Public report

Institute for
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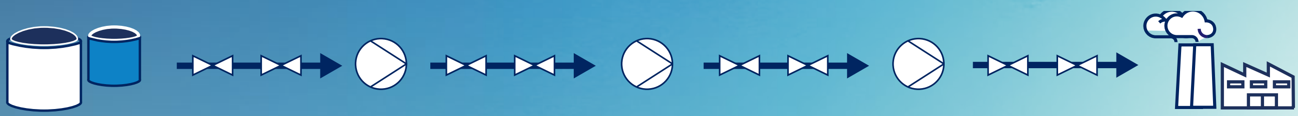
Process Technology

Design and Safety Aspects for large-scale Clean Ammonia Pipelines

Clean Ammonia Innovation Platform



Port of Rotterdam

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EnBW

chane

gasunie

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Acknowledgements

We are delighted to share this report with you to increase awareness and knowledge of a future low carbon and renewable energy system with clean ammonia as its energy carrier. The development and execution of the Ammonia Pipeline Safety project was a team effort by ISPT and its project partners from the industry, supported by DNV for the execution. The project partners consisted of Aramco Europe, Chane Terminals, EnBW, Equinor, Fluxys, Gasunie, Shell and OCI. The cooperation was intensive with multiple workshops, a site visit to OCI in Geleen (NL) and about 30 meetings which combined knowledge and experience from both the team and externals. The cooperation with Dutch and German government stakeholders and other Clean Ammonia Innovation Platform partners was also important.

We would like to express special thanks to the following project partners who made important contributions to the project's findings, results and benefits:

Aramco Europe/John Henn, Miguel Tapias Rojas, Mohamed ElReheem, Chane terminals/Tamme Mekkes, Bilfinger/Freddy Weessies, Aron Khan, EnBW/Greg Stace, Equinor/Hroar Andreas Nes, Sandra Hennie Nilsen, Petter Henrik Holmström, Vahid Alipour Tabrizy, Fluxys/Willy Vanhorenbeek, Gasunie/Annelies Buist, Adriaan de Bakker, ISPT/Rob Stevens, Gijs Tubben, Carol Xiao, Hans van 't Noordende, Franka Wijnbergen, Otto Tobé, OCI/Filip Raemaekers and Jan-Jaap Nusselder, Port of Rotterdam/Mark Stoelinga, Klaas-Jan Bosch, Edwin van Espen, Alan Dirks. Shell Global Solutions/Wouter Koopman.

And special thanks to the DNV team: Victoria Monsma, Lars Even Torbergsen, Eric Kervezee, Shawn Murray, Niek Wessels and Afzal Hussain.

Also we would like to thank the Ministry of Climate Policy and Green Growth/David Bolsman, Jeroen van Bochhove, Kees Theune, the Ministry of Infrastructure and Water Management/Victor van de Pas, Ammonia Energy Association/Kevin Rouwenhorst.

The goal of sharing our project results is to stimulate knowledge sharing to make the energy transition happen. The main results presented in this report provide the facts and figures pertaining to how the pipeline transport of clean ammonia can be effected in a safe way, meeting all the requirements applicable to the energy transition.

Authors

Foreword

The energy transition and the hydrogen economy have almost become synergistic terms, but there are real concerns and challenges that need to be addressed when it comes to achieving this relationship's promise. The efficacy of scaling-up hydrogen production faces logistical and practical challenges if it is not paired with the scaling-up of hydrogen derivatives as carriers as these often have a higher volumetric energy density than hydrogen itself.

Saying that scaling-up a hydrogen economy will require effective hydrogen carriers does not ignore the simple fact that the best application is also the most direct one. Evaluating the above with the merit order in mind, when we have reached the molecules after the world of electrons, the direct use of these molecules is the most efficient. This also holds true for ammonia.

To me it is clear: the hydrogen economy will not happen without ammonia as the molecules go hand in hand. The large-scale production and transport of hydrogen is only possible if ammonia is in the picture given the energy density it can store and transport.

The direct use of ammonia energy requires additional transport modes from the production or import location to the end-user. This is why it is absolutely urgent to introduce ammonia pipelines in Western Europe as an alternative to road, rail or water-based transport. Pipelines are how today's energy is transported, for instance using the national gas grids.

ISPT and its partners have benefited from their collaborative investigations into the potential of ammonia pipelines though there was a steep learning curve. I believe this report shares knowledge on the opportunities ahead for ammonia as a new energy vector.

New energy vectors entail a variety of risks and logistics costs, and I hope this report helps put the questions from the readers into context.

Rob Stevens

Summary

Challenges

Taking the announced and confirmed investments in clean ammonia production and import into Europe as reported by the Ammonia Energy Association into account, the demand for clean ammonia is expected to skyrocket. Large-scale clean ammonia transport from deep sea ports to inland terminals and consumers is anticipated as was suggested by the ISPT Clean Ammonia Roadmap. However, as of yet, nowhere has the large-scale, onshore transportation of clean ammonia been achieved. Nor have the safety aspects of the pipeline transportation of clean ammonia been explored yet. One aspect concerns the release of a toxic gas cloud in the event the pipeline is breached. More background on clean ammonia is provided in the box below.

Clean ammonia in brief: what is it, why is it important to Europe and can it be handled safely?

Ammonia is a molecule (NH_3) having 83% (weight) of nitrogen and no carbon. Ammonia has been a key component in agricultural fertilisers for over 100 years. New technological opportunities have re-cast ammonia as a low carbon fuel and hydrogen carrier.

Clean ammonia is made by combining green or low-carbon hydrogen and nitrogen from the air. It is produced by splitting water into green hydrogen and oxygen, using electricity from renewable sources (solar, wind or hydro power) followed by ammonia synthesis using nitrogen. Another route to creating clean ammonia is through hydrogen production from natural gas (or low carbon gas from waste or biomass gasification) that involves the capture and storage of the CO_2 emitted, called blue or low-carbon hydrogen. Clean ammonia has the potential to significantly reduce the carbon emissions that contribute to climate change.

As such clean ammonia can play a key role in the transition to a sustainable low-carbon economy, especially because ammonia is relatively easy to store and transport. It has potential as a carbon-free fuel for maritime shipping, a substitute for gas, oil and coal at electric power stations and as an efficient hydrogen carrier for new industrial markets such as green steel. Clean ammonia could also be used as a simple 'feed' for hydrogen in pipeline-based energy distribution systems.

According to the European Commission, contemporary high energy prices are undermining the global competitiveness of Europe's industry. In due course, clean tech and low-carbon energy solutions including clean hydrogen and clean ammonia will help reduce Europe's energy dependence, lower energy prices for both industry and households as well as increase its resilience and energy security. As the President of the European Commission Von der Leyen stated: "Decarbonization in Europe will also strengthen our competitive power". Green hydrogen and clean ammonia are critical to Europe's economic survival.

Ammonia requires careful handling by parties that prioritize safety. Ammonia poses high health hazards because it is corrosive to skin, eyes and lungs. Over many decades, the fertilizer industry and authorities have cooperated closely on stringent safety regulations, high industry standards and training & competence programmes for staff to ensure the safe production, storage, distribution and use of industrial ammonia. Ensuring safety for this new industrial application of ammonia in the energy transition will require intensive cross-industry collaboration on leveraging safety standards, sharing best practices and sound safety risk assessment and management. New safety design solutions and extra safety standards are now being developed by multidisciplinary teams of engineers under scrutiny of (inter)national authorities.

ISPT and Industry Partners

ISPT and partners from industry, supported by DNV, joined forces to do fact finding on this topic. The industry partners consisted of Aramco Europe, Chane terminals, EnBW, Equinor, Fluxys, Gasunie, OCI, Port of Rotterdam, Shell. ISPT is an independent and leading open innovation platform for the process industry focusing on the energy, materials and food transition.

Aim and Scope

The Clean Ammonia Pipeline Safety study assesses the necessary design and safety aspects for the long-distance pipeline transportation of large volumes of ammonia through rural as well as densely populated areas. On the basis of the ISPT Roadmap such a pipeline would be assumed to transport some 7 million tonnes per annum (mtpa) equivalent to roughly 1 mtpa hydrogen. For the sake of this study, a 550 km pipeline was considered, which is in line with the projected Delta Rhine Corridor from the Netherlands to Germany. The information generated by the project can nevertheless be applied to other pipeline routs and countries. The scope comprises a pipeline system with a single pipeline, booster pump stations, valve stations and interfaces to importing and receiving terminals, see Figure S1.

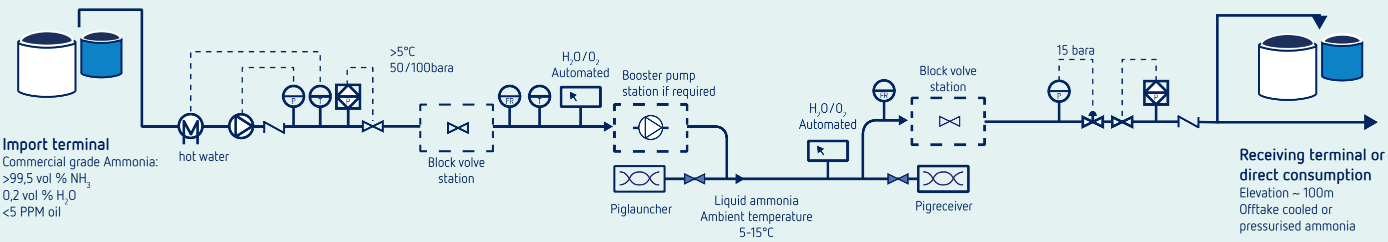


Figure S1: Clean ammonia pipeline system

Legal Framework

The impact of accidents with pressurised ammonia transfer through pipelines on society is evaluated in terms of risk contours and maximum effect distances, defined as focus areas. It was determined that all risk reduction measures in place should be in line with applicable laws, regulations, codes and standards. The Netherlands and Germany's legal frameworks were studied and compared to this end. At first sight, the two country's approaches seem different, as the Netherlands has a risk-based approach whereas in Germany the approach is based on avoiding adverse effects (risk) to people and nature. The translation of state-of-the-art technologies into design, practices and methods in Germany has also been adopted in the risk reduction measures and factors incorporated into the Dutch calculation modules.

Pipeline Sizing

Three case studies were considered for pipes with different diameters (32", 20", 18"), see Table S1. This resulted in different pressure ratings, wall thicknesses and number of intermediate booster pumping stations in addition to the pumping station at the import terminal. The hydraulic design is based on a mass flow of 222 kg/s liquid (anhydrous) ammonia and an assumed route. The proposed design reflects the 20" base case because this is a proven pipeline design pressure, requiring 3 booster pumpstations. As follows from this study this design case can be compliant. The alternative case with 18" pipes can also be made compliant, however the 100 barg design pressure – although technically feasible – is not common practice. According to this study, the 32" reference case with single pipeline and only pumps at the import terminals is not compliant as it exceeds the 5-metre risk contour.

Table S1: Hydraulic design with three cases

Case	Line size (inch)	Design pressure (barg)	Wall thickness (mm)	No. intermediate pump stations	Description
Base	20	50	15	3	Recommended and proven pipeline design
Alternative	18	100	19	2	Possible pipeline design
Reference	32	50	15	0	Direct transfer pipeline design

Safe Design

A safe design was proposed based on the above cases, hazard identification workshops, credible scenarios and risk reduction strategies. The risk reduction in preceding order is: inherent safe design, preventive reduction measures, mitigating measures, emergency response, and crises management. The design incorporates emergency shutdown systems (ESD), the segmentation of ESD valves, flow assurance modelling for pipeline sizing, material selection and external corrosion-addressing coatings, booster pump stations with collection systems, pig launch receivers, leakage detection, burial depth and trench design, see Figure S2. The proposed design includes the necessary risk reduction measures from this project's safety study.

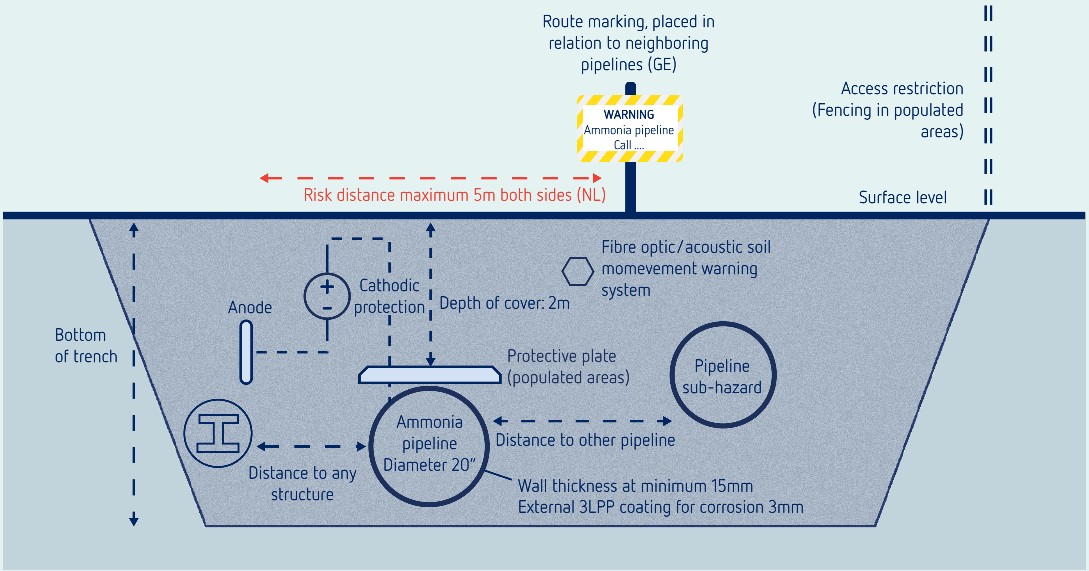


Figure S2: Pipeline Trench

Safety study results

The safety study's main objective was to assess the hazards to society in terms of process safety and external safety risks associated with operating a clean ammonia pipeline. Two pipeline rupture and leakage scenarios were used for the three pipeline designs in Table S1 as the basis for the quantitative risk assessment (QRA) calculations. The QRAs were prepared for the pipeline and pumping stations using SAFETI.NL software to determine the risk contours of an accident with a probability of 1 in a million years. The maximum effects distances defined as focus areas for protecting groups of people were determined on the basis of the worst-case release scenario i.e. a pipeline rupture. Several sensitivity analyses were performed to assess the impact of various parameters such as, for instance, segmentation through variable distances between ESD valves.

The proposed design and selection of risk reduction measures – including a minimum soil cover of 2 metres and protective plates – can reduce the risk contour of a 20" pipeline to below the legally required 5 metres. A pumping station's risk contour is around 1,800 metres. Its design and operation should follow the SEVESO III requirement. The pumping station should preferably be situated at a site with heavy industry zoning. The large-scale clean ammonia pipeline from Rotterdam to Germany can be made compliant with Dutch standards and interpretations of German state-of-the-art techniques. It is suggested by this project that when it comes to large-scale ammonia transportation, the protection of civilians from a pipeline rupture with a subsequent toxic gas cloud can be enhanced by reducing pipeline inventory. The latter can be achieved by optimising pipeline sizes from 32" to 20", requiring two booster pumping stations and shorter segmentation lengths between ESD valve stations (e.g. 5km).

CAPEX and OPEX

The CAPEX estimate for the 20" pipeline is 2,100 Mio EUR, based on the proposed safe and compliant design. By comparison, a cost estimate for a basic design, based on common practices, amounts to 1,600 Mio EUR but this design appears non-compliant for this ammonia service. The 500 Mio EUR difference provides an indication of the additional CAPEX required to make such a clean ammonia service safe and compliant. This would amount to a 31% CAPEX increase. The annual costs, comprising OPEX and annualised capital costs, are 310 and 240 Mio EUR/a respectively for the proposed and the basic design. The annual costs increase is estimated to be 70 Mio EUR/a or 29% higher. The pipeline material and installation costs followed by the building of 110 valve stations are the dominant items increasing costs.

Based on these figures, transportation costs are estimated to be 0.50 EUR /ton H_2 equivalent/km. According to a European hydrogen backbone study (2021) and corrected for inflation and escalation, the transport costs for hydrogen today would also be around this figure of 0.5 EUR /ton H_2 /km.

Recommendations

A front-end engineering and design study is necessary for each project to agree on the starting points, evaluate the legal and permit issuing requirements, improve the project definition and increase the cost estimate's level of accuracy. This project's key findings with regard to safe, compliant design and accurate cost estimates can be used as guidance for future clean ammonia pipeline projects in Western Europe and elsewhere.

The modelling results for risk contours and maximum effect distances were determined but should be taken with care. Validation of the model for large volume ammonia release caused by pipeline rupture is crucial. The QRA and dispersion model has limitations and uncertainties, which need to be addressed. In general, validation is required for the mechanism observed and dispersion of a toxic gas cloud.

At the same time, the approach to and emphasis on including safety aspects in the design is paramount to ensuring the safe operation and maintenance of a long distance, large volume clean ammonia pipeline.

A common approach for the Netherlands and Germany, and the EU with regard to long-distance (cross border) ammonia pipelines as well as hydrogen and other energy carriers is needed to meet the energy transition challenges in Western Europe. This common framework could be provided by the application of design practices alongside the development of state-of-the-art techniques and a risk-based approach with risk reduction measures.

List of abbreviations

Reference	Definitions and clarifications
ALARP/ ALARA	As Low As Reasonably Practical/ Achievable
Bal	Activity Environmental Decree (Besluit Activiteiten Leefomgeving)
Bkl	Quality Environmental Decree (Besluit Kwaliteit Leefomgeving)
BEVB	External Pipeline Safety Decree (Besluit Externe Veiligheid Buisleidingen)
BNatSchG	Bundesnaturschutzgesetz
BW	German State Baden-Würtenberg, relevant stakeholder due to trajectory to Karlsruhe
CAPEX	Capital Expenditures
DCS	Distributed Control System
DN	Diameter Nominal
DRC	Delta Rhine Corridor
EIA	Environment Impact Assessment
ESD	Emergency ShutDown,
FID	financial investment decision
ICCP	Impressed current cathodic protection system
HAZID	Hazard Identification
HAZOP	Hazard and Operability
HDD	Horizontal Directional Drilling of pipelines, e.g. for river crossings
HNS	Hydrogen network Service
KGG	Ministry of Climate and Green Growth (Klimaat en Groene Groei)
LOPA	Level of Protection Assessment
KAS-18	Committee for safety of installations (Kommission für Anlagensicherheit)
LBW	Lethality threat value (Levens Bedreigende Waarde)
LHV	Lower Heating Value
LOC	Loss Of Containment.
LOPA	Level of Protection Analysis
LSIR	Location-specific Individual Risk
MAOP	Maximum Allowable Operating Pressure
MTBF	Mean Time Between Failures, representing the inverse of the total (aggregated) failure frequency
mtpa	Million Tonnes Per Annum
MW	Mega Watt
NG	Natural gas
NRW	North Rhine-Westphalia
OPEX	Operational expenditures
PFD	Process Flow Diagram
PGS	Storage and Loading Guidelines
PLR	Pig Launch Receiver
PR	see LSIR (Plaats Risico)
PFD	Process Flow Diagram
RCR	Government Coordination Scheme (Rijks Coördinatie Regeling)
RFNBO	Renewable Fuels of Non-Biological Origin (RFNBO)
RIVM	National Institute for Public Health and Environment (Rijksinstituut voor Volksgezondheid en Milieu)

RohrFLtgV	Pipeline ordinance (Rohrfernleitungsverordnung)
SAFETI	SAFETI is a QRA software solution
SIL	Safety Integrity Level
SIS	Safety Integrity System
SMYS	Specified Minimum Yield Strength
SRA	Safety relevant plant inventory (Sicherheitrelevante Anlageteile)
QRA	Quantitative Risk Assessment
SCC	Stress Corrosion Cracking
TRV	Thermal relief valves
TRFL	Technical regulations for pipeline system (Technische Regeln für Rohrfernleitungsanlagen)
UPS	Uninterrupted power supply
UVPG	According to the Environmental Impact Assessment Act (UVPG: Umweltverträglichkeitsprüfungsgesetz)
WT	Wall thickness

Contents

1 Introduction

EU Competitiveness

Today, according to the European Commission, high energy prices and geopolitics are undermining the global competitiveness of Europe's industry.[1] The EU needs to increase its resilience, energy independence and economic security. There is an urgent need for a joint roadmap for decarbonisation, innovation and competitiveness. This Clean Industrial Deal for competitive industries puts the European Green Deal in a completely different perspective as it provides an opportunity rather than a problem to reduce net greenhouse gas emission by 55% in 2030 in comparison to 1990. Significant quantities of fossil fuels need to be replaced by energy from renewable sources such as wind and solar to successfully decarbonise industry. The EU alongside manufacturing companies, the process industry and the logistics chain need to invest in renewables, electrification and the import of affordable clean energy carriers. According to many public sources and fact findings of the ISPT Clean Ammonia Roadmap, we have seen that clean ammonia is needed and going to play a pivotal role in the energy transition.[2, 3, 4, 5]

The Energy Challenge

There is an urgency to supply large volumes of reliable, affordable clean energy to Western Europe from other parts of the world with an abundance of renewable energy, as illustrated in Figure 1. Massive increases in renewable sources of energy in North-Western Europe are crucial to Europe's independence.

Figure 1: The Energy Transition and the Circular Economy

1 EU competitiveness: Looking ahead - European Commission
2 https://ispt.eu/publications/power-to-ammonia-2017/
3 Download: Clean Ammonia Roadmap, ISPT, 2024
4 Innovation Outlook Renewable Ammonia, IRENA, 2022
5 Low-Emission Ammonia Data (LEAD) - Ammonia Energy Association

Major investment in the grid requires a coordinated European approach. However, this growth is expected to be insufficient to accommodate the increased demand for electricity as a result of society and industry's decarbonisation at the required pace. Also, energy from solar and wind turbines fluctuates making importing energy from overseas and storage necessary. There is simply not sufficient renewable energy available in the short and long term to decarbonise industry in Europe. So importing clean energy from other countries is necessary to create energy security in Western Europe.

Energy Carriers

The main clean energy carriers are: electricity, gaseous and liquid hydrogen, ammonia and methanol.[6] Using electrons instead of molecules is generally considered the best option as far as the energy losses and CO_2 footprint are concerned. Molecules can be used for energy storage and as a carrier in the energy transition, especially since renewable electricity is not always sufficiently available at the right time and place. All the energy carriers experience energy losses during conversion, transport and storage, which need to be taken into account as these lead to differences in CO_2 footprints. Energy mix differentiation depends on region, scale, environment and price as well as how and where it is to be used. As explained above, all of these carriers are essential.

Gaseous hydrogen can be used directly for the production of biofuels, ammonia synthesis and chemicals but has a low energy density by volume, which is unfavourable for storage and transport. Liquid hydrogen increases the energy density significantly but still has about 50% less energy density than liquid ammonia and 80% less than methanol. Ammonia and methanol can act as large-scale energy carriers, which makes them very attractive to hard to abate sectors such as the maritime and aviation industries. Ammonia can be used as a chemical building block or fuel, e.g. for shipping, and it can be cracked back into hydrogen later on, at its destination. Methanol has an advantage as a drop-in fuel replacing fossil fuels, for example, kerosine in aviation and as a chemical building block. Methanol is synthesised from hydrogen and CO_2 (or carbon monoxide CO), which can be biogenic, captured from industry or directly from the air. Avoiding net CO_2 emissions to the atmosphere from burning methanol is only possible with the direct air capture of CO_2 or by using biogenic CO_2.

Clean Ammonia

Clean ammonia is made of green or low-carbon hydrogen and nitrogen from the air. Ammonia synthesis from hydrogen and nitrogen is known as the Haber-Bosch process and is an efficient process that has been in use for a century. Hydrogen plays a dominant role in clean energy system as green, blue or biogenic hydrogen. Green hydrogen is produced using water electrolysis from renewable electricity. Low carbon or blue hydrogen is based on natural gas with CO_2 capture and storage which can be a competitive low-carbon solution in terms of CO_2 abatement costs. Also, low-carbon hydrogen can be produced through the gasification of (biogenic) waste or biomass to syngas: hydrogen and carbon monoxide (CO). Green and low-carbon hydrogen should adhere to EU requirements as laid out in the RFNBO declarations.[7]

6 Other carriers, like Synthetic Natural Gas, Liquid Organic Hydrogen Carriers, Sodium Borohydride (NaBH4), Biogas, Biofuels, Synthetic Aviation Fuels (SAF) are not discussed here.

7 Renewable hydrogen - European Commission

Clean ammonia has potential for CO_2 abatement because it does not contain any carbon. Next to ammonia cracking, clean ammonia could also be used directly as a chemical building block. This could already happen today with clean ammonia gradually replacing grey ammonia in the fertiliser and chemical industry. Clean ammonia has even larger potential as a fuel for shipping replacing marine diesel oil. In addition, ammonia can also play a role in the energy system for electricity generation ('Dunkelflaute') or producing heat in industrial processes offsetting renewables. In the case of combustion of ammonia NOx emissions should be controlled, which is an available standardised practice. The longstanding experience, underlying existing infrastructure and relatively fast investment planning with production sites, large ships and storage tanks and retrofitting for utilisation, would make clean ammonia more interesting than other energy carriers. [3, 4, 5] It is suggested therefore that clean ammonia production in other regions and import to Europe will grow in the near future. It is anticipated that will unlock the demand for clean ammonia. The number of firm projects with financial investment decision (FID) and traded volume are expected to grow fast in this decade, see Figure 2.

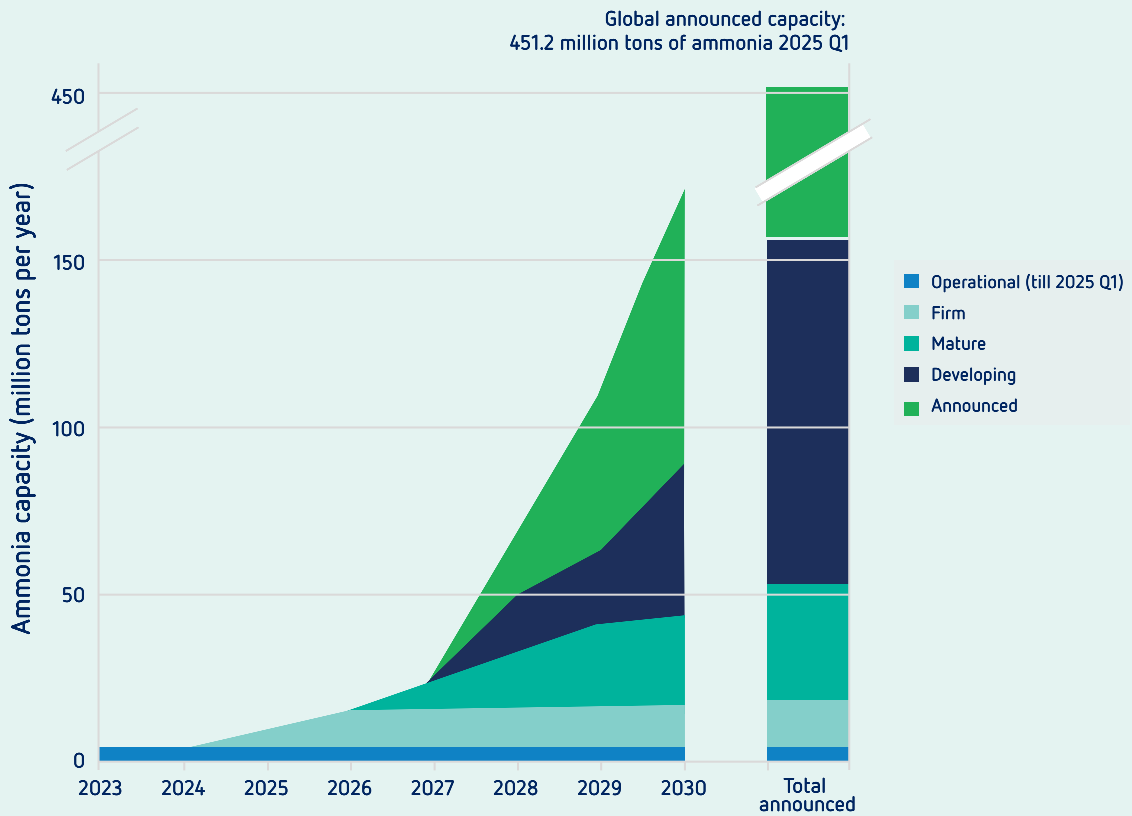


Figure 2: Clean Ammonia Market Announcements [5]

Ammonia Transport Modes

The scale required demands major investment in supply chains for maritime transport, port and inland infrastructure. Ammonia is currently predominantly transported by rail and barge in Western Europe and both have future potential for growth. The latter could entail several safety risks to society and nature, as well as involving major logistics efforts. Transporting ammonia using onshore pipelines has been demonstrated to be a safe. [8, 9] Ammonia pipelines are typically limited to industrial clusters in Europe with pipeline lengths generally measuring 10 km or less though there are longer pipelines in more sparsely populated areas. An example is an 8" pipeline from an inland port to a site operated by OCI in Geleen, the Netherlands. Another notable example is Nustar Energy's ammonia pipeline in the United States, which spans approximately 3,220 km and transports 1.5 million tonnes per annum (mtpa). In Europe, the longest pipeline is the Togliatti-Odesa ammonia pipeline, which spans approximately 2,500 kilometres from the Russian city of Togliatti to Odesa. Before this pipeline ceased operations during the Russian invasion of Ukraine, it exported 3 to 5 mtpa.[10] Ammonia transport using pipelines is a crucial aspect of the global ammonia supply chain.

Health, Safety and Environmental Aspects

Ammonia is toxic. Its effect depends on the extent of exposure after a release caused by, for example, damage to a pipeline due to excavation work. It is also harmful to aquatic life, e.g. in case of a leak. Ammonia should therefore be handled with professional care. The flammability range of ammonia in (dry) air is between 16 - 25 vol% though ammonia is difficult to ignite. The industry has over a century with experience and knowledge of ammonia and the accompanying practices. [3, 11, 12]

The safety, health and environmental aspects should be studied and addressed when a new chemical is introduced. This is also holds true for new energy carriers such as ammonia. It is important to assess the risks involved for society and nature as civilians should be protected from exposure to a toxic gas cloud or, better yet, accidents should be prevented. Given current investment in overseas clean ammonia production and the decision to build import terminals in Western Europe, it is a prerequisite that adequate international practises, laws and regulations are put into place for the safe storage, transport and utilisation of ammonia. Storage, has already been covered by an updated best practice for the Netherlands (PGS12) which recommends large, gas-tight, double-walled concrete tanks.[13] Fertilizers Europe has a best practice for the transportation of ammonia in pipelines, however this does not suffice for large-scale application.[12]

8 Accident Search Results | Occupational Safety and Health Administration osha.gov
9 UROPA - eMARS Accidents Search - European Commission
10 DNV Ammonia Safety Pipeline study report for ISPT, Report No.: 25-0127, Rev.0 Date: 2025-01-23 (confidential)
11 hazards-26-paper-34-review-of-global-regulations-for-anhydrous-ammonia-production-use-and-storage.pdf
12 Guidance_for_inspection_of_and_leak_detection_in_liquid_ammonia_pipelines_FINAL_01.pdf, Fertilizers Europe, 2013
13 PGS 12:2024 versie 0.3 (July 2024)

The Aim and Scope of the Ammonia Pipeline Safety Study

The onshore transportation of ammonia at this scale has not been implemented anywhere in the world. In addition, the safety aspects of the pipeline transportation of clean ammonia have not fully been explored yet. This Ammonia Pipeline Safety study assesses the necessary design and safety aspects for the long-distance pipeline transport of large volumes of anhydrous ammonia through rural and urban areas. The aim is twofold, to:

- assess the impact of accidents involving pressurised ammonia pipelines on society
- determine which risk reduction measures should be implemented to meet the applicable regulations, codes and standards.

A pipeline transporting 7 million tonnes per annum (mtpa) was assumed on the basis of the ISPT Clean Ammonia Roadmap. A 550 km pipeline was considered as this is akin to the projected Delta Rhine Corridor from the Netherlands to Germany. The study's scope comprises a single pipeline, booster pumping stations, valve stations and interfaces for the importation and receiving terminals.

Delta Rhine Corridor Route

The Delta Rhine Corridor (DRC) was considered in this study, as initially an ammonia pipeline from Rotterdam to Karlsruhe was also part of the DRC. Recently, the Dutch Ministry of Climate and Green Growth has decided to prioritise the development of the Delta Rhine Corridor's first phase and H_2 and CO_2 pipelines from the Port of Rotterdam to Venlo close to the German border. [14] These pipelines can then be extended into Germany during phase two. Some other parts of the hydrogen backbone developed by Hydrogen Network Services (HNS) are already under construction.[15] In Germany, a similar decision has been taken to develop a 19 B Euro hydrogen core network.[16] According to the Min. KGG, there is room available within the DRC for a potential ammonia pipeline.[17] An ammonia pipeline to Germany can be continued as a project next to the DRC.

ISPT and Clean Ammonia Innovation Platform

A collective of industrial partners collaborated on this study. On behalf of the partners, ISPT commissioned DNV to execute the study. ISPT compiled this public report partly on the basis of DNV's work.[9] Our industry partners are: Aramco Europe, Chane terminals, EnBW, Equinor, Fluxys, Gasunie, OCI, Port of Rotterdam, Shell.

ISPT is an open innovation platform for industry focusing on the energy, materials and food transition in the Netherlands. ISPT leads a Clean Ammonia Innovation programme as well as Circular Carbon, Green Hydrogen and Circular Plastics programmes. These platforms bring the industry and stakeholders together to share and develop knowledge aiming at decarbonising industry.[18] ISPT is an independent, non-profit organisation.

14 Delta Rhine Corridor | DRC
15 Hynetwork
16 Bundesnetzagentur - Hydrogen core network
17 Kamerbrief over scope en vervolg Delta Rhine Corridor | Kamerstuk | Rijksoverheid.nl
18 Clean Ammonia Platform

How to Read this Report

This report intends to provide facts and figures to determine the social/technological/economic feasibility of large-scale clean ammonia pipelines in various locations, of various lengths and transporting lower/higher volumes. ISPT and its partners are also interested in the follow-up to this study for enabling clean ammonia on the agenda of the energy transition. This study was conducted on the basis of the current legislation in the Netherlands and Germany and the potential route of the DRC. The results will nevertheless be applicable to other routes and countries. To what extent the reduction measures lead to tolerable risks and/or the design is acceptable with regard to maximum effects is a more complex discussion in society. With these uncertainties and discussions in mind, this study's facts and figures can indicate what the industry should do to develop next level industrial practices in a dialogue with the authorities. This dialogue can contribute to a coordinated approach between countries to make Europe more competitive and innovative in the energy transition.

List of Explanations and Clarifications

The report uses abbreviations, synonyms, technical guide words and references to regulations, which are explained and clarified in Annex 1.

Clean ammonia will help to decarbonise industry and shipping whilst boosting EU's energy security and global competitive power

2 The Approach to Ammonia Pipeline Safety Study

Iterative Design

The approach followed in this study is depicted in Figure 3. It is an iterative approach that incorporates the lessons learned from the safety studies pertaining to pipeline design and includes these in the economic assessment. This feedback loop represents a sensitivity analysis for design variables and risk reduction measures. One example of this iteration is the adjustment of the pipeline sizing from larger to smaller bores based on safety study results.

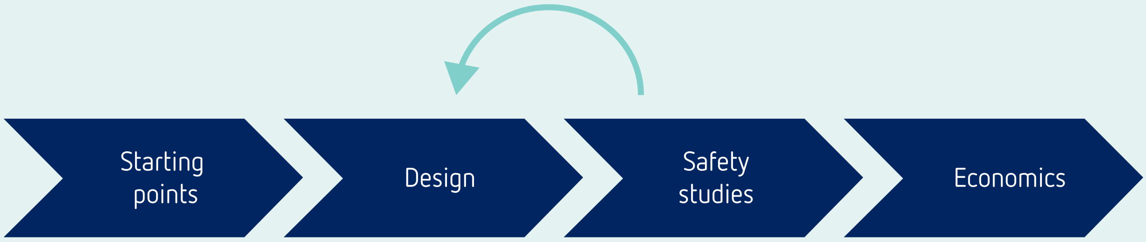


Figure 3: Approach to the Ammonia Pipeline Safety Study

The starting points will be addressed in Section 3 and consist of requirements, a process and a scope description. These requirements basically entail: user requirements from owner-operators, requirements, industry codes, standards and compliances. Important applicable regulatory and permit issuing requirements with regard to pipeline safety will be further defined in Section 4 on The Legal Framework in the Netherlands and Germany. These requirements constituted the basis for the process, scope, pipeline design and engineering that were prepared and verified, see section 5. The safety studies' results were incorporated into the design.

Inherently Safer Design

Inherently safer design principles were adopted for the pipeline system's design, for instance:

- preventing an ammonia release from the pipeline otherwise referred to as loss of containment (LOC) leading to a gas cloud in the atmosphere
- reducing the actual content (inventory) of a pipeline segment
- simplifying the design.

The study focused on preventing an LOC from happening, for example by burying the pipelines deeper to avoid accidental damage due to ground work. In the event that an LOC accidently happens, the intent is to minimise the volume which can be release thereby reducing the effect as much as possible. In the event of an emergency shutdown (ESD), this can, for example, be achieved by ESD valves automatically isolating a segment of pipeline.

Engineering Methods and Tools

This project is a feasibility study at a level of engineering detail known as Identify&Assess. During the project phase, engineering methods and tools were used as follows:

- The preferred route and options were verified spatially using a Geographic Information System tool (QGIS) and web-based mapping tools to sufficiently optimise and refine the corridor.
- Hydraulic simulations (steady state) were performed using the Unisim R480 process simulator to screen and determine minimum pipeline diameters, wall thicknesses and intermediate pumping requirements.
- The minimum wall thickness was based on requirements for operational pressure containment and pressure testing (Design factor 0.67, Factor 1.4 MAOP).[19]
- No location classes were used for the pipeline except for the pumping stations. Also, the above design factor was not altered for densely populated areas. Instead external safety distances were applied, including risk reduction measures.
- Liquid hammer calculations and ramping up/down characteristics were included.
- Simple Process Flow Diagrams were prepared for the design of the pipeline's main elements and as input for the safety studies.

Safety Studies

The safety studies comprise process and external safety. Process safety concerns the safe design, operation and maintenance of the pipeline and its facilities to reduce the frequency and consequences of accidents whereas external safety is mainly for the protection of people living in the vicinity of the pipeline and its facilities.

One should bear in mind that safety in design always takes priority over preventive and mitigating safeguards. Next to this, repressive measures and emergency response and preparedness should be in place. Also crisis management planning by authorities has to be organised but this is not further detailed in this project .

An important key success factor for this project was the cooperation between industry partners, ISPT and DNV at several workshops and by means of regular biweekly meetings. Experiences and knowledge were shared concerning preparing the design and conducting the safety studies.

Process Safety

In this project, safety studies were conducted in a structured manner using methods and tools commonly applied in industry, as follows:

- Developing a process safety management system, including process hazards assessments, prevention, safeguarding, procedures, training and emergency responses.[20]

19 According ISO 13623, NEN 3650 series, TRFL, ISO 1362

20 CCPS | for Chemical Process Safety

- Preparing bow tie diagrams, which are a widely used methodology for hazards assessment to visualise credible hazardous scenarios, see Figure 4. The bow tie provides an intuitive and clear, causal illustration of events (threats or causes) resulting in a top event, usually an LOC, and its consequences. An important aspect of bow ties is identifying barriers to breaking the chain of events. Risk reduction can be achieved using control (preventive) measures, prevention and mitigation measures.
- Performing hazards (risk) assessments for the safeguarding of processes, minimising failure frequencies and reducing the effect of a release through reduction measures. Three hazard identification workshops (HAZID) were held for this study, addressing typical preventive and mitigating safeguarding for pipelines. More detailed risk assessments such as HAZID, HAZOP, SIL, LOPA are necessary but these are part of next project stages, i.e. Concept Select and FEED (Front-End Engineering Design).[21]
- This study references SIL(Safety Integrity Level), since the latter assessment was used specifically to assign reduction factors to instrumental safeguards. The instrumental safeguarding should meet the functional requirements (self-diagnostics, reliability, verification, etc.) in accordance with the required SIL level. Four SIL levels are defined, ranging from SIL 4 which has a reduction factor of 10,000 – 100,000 to SIL 1 having a factor of 10 – 100.[22]
- A scenario's risk is often represented as a combination of the frequency of occurrence and the severity (impact which can be related to HSE, damage and reputation) and is often plotted in a risk matrix or risk graph. No nationally or internationally agreed risk acceptance criteria are currently available. For this reason, and because the exact risk will be project specific, no risk rating has been undertaken for the generic hazardous scenarios identified. Companies should define their own risk assessment method and criteria for each specific project.

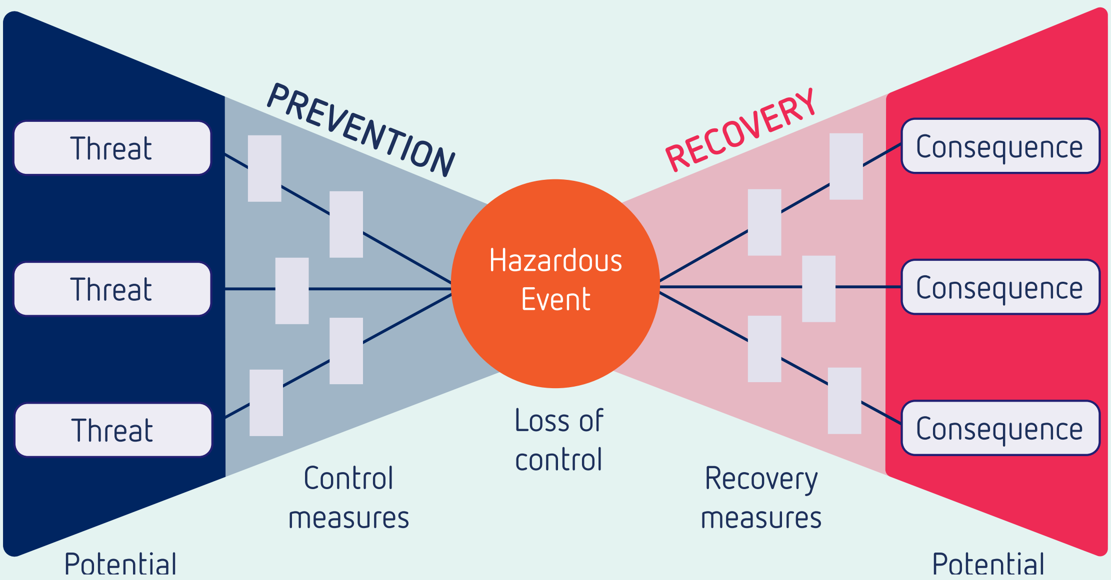


Figure 4: Bow Tie Method

21 CCPS Process Safety Glossary | AIChE
22 Applicable codes for SIL requirements are IEC 61508 and IEC 65811

External Safety

The external safety studies are basically compliance driven based on a legal framework, which can be different between the Netherlands and Germany, and other countries. This will be discussed in more detail in Section 4. This project carried out the following modelling work:

- Developing scenarios based on Quantitative Risk Assessment (QRA)
- Determining risk contours or external safety distances around a pipeline location or around facilities expressed as location-specific individual risks (LSIR) by calculating QRAs
- Assessing focus areas to protect groups of people (alongside LSIR) based on worst case scenarios and dispersion modelling to meet certain intervention values in accordance with Dutch Law.
- QRA modelling of the focus areas and the risk contours was carried out using the prescribed SAFETI.NL 8.1 software [23] and in accordance with Calculation model V *(Rekenvoorschriften)* for pipelines and Modules I & II for the pumping stations [24, 25, 26]
- The abovementioned software was also used for dispersion modelling based on a case involving a long pipeline with vertical upward flow after rupture and a burial depth of 1.2 m
- SAFETI.NL assumes a leak will be controlled inside 1,800 seconds. The model stops the outflow that time, irrespective of the inventory left inside the isolated section. This should be reconsidered and potentially adjusted until the isolated section is emptied
- Weather type D1.5 was used for the QRA dispersion calculations, since it has been shown to be the worst-case weather type for the consequences concerned in this project.

Cost Estimation

Section 7 provides the estimated costs for the ammonia pipeline service, clearly stating the project's financial requirements and providing a basis for early decision making. The aim being to assess the additional costs involved to safely designing, building, commissioning, operating and maintaining a large-scale ammonia pipeline.

The estimate 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 have been factorised at a budgetary (Class V) level according to AACE guidelines. The estimates' accuracy range lies between -50% and +100%. The cost estimate include a 50% contingency as this accounts for risks such as delays, uncertainties (e.g. permit issuing, design changes) providing a robust financial buffer.

The OPEX includes cost of capital based on 8% IRR, electricity (100EUR/MWh, including grid fees), other utility costs, and 5% (of CAPEX) for operation & maintenance annual costs.

A sensitivity analysis has been carried out to check the main cost drivers in the cost breakdown.

23 Risk calculation methods | RIVM
24 Rekenvoorschrift Omgevingsveiligheid Module V
25 Rekenvoorschrift Omgevingsveiligheid Module I - versie januari 2025 | RIVM
26 Rekenvoorschrift Omgevingsveiligheid Module II - versie januari 2025 | RIVM

3 Requirements and Scope of the Ammonia Pipeline Safety Study

Ammonia

Ammonia is usually stored and transported as a liquid because of it this has a higher density than gaseous ammonia. Liquid ammonia can be stored cold (<-33° C at 1 bara) in atmospheric storage tanks, then pressurised (>10 barg at 25° C) for transportation. Shorter pipelines can be operated at lower pressures as long as the temperature remains above zero. Imported ammonia is assumed to be trade quality anhydrous ammonia (>99.5 vol% NH_3 and < 0.5 vol% water).[27] Pipeline service operators would then transport and distribute the same quality to its clients.

Scope of this Study

The emphasis of this report is on the pipeline system as a whole consisting of a single (underground) pipeline, booster pumping stations, valve stations and interfaces for the import and receiving terminals, see Figure 5. Terminal operation and utilisation is not included except for the conditioning and transfer of ammonia. The study comprises the complete lifespan of the pipeline system, from design, construction and first filling to operation, maintenance and decommissioning.

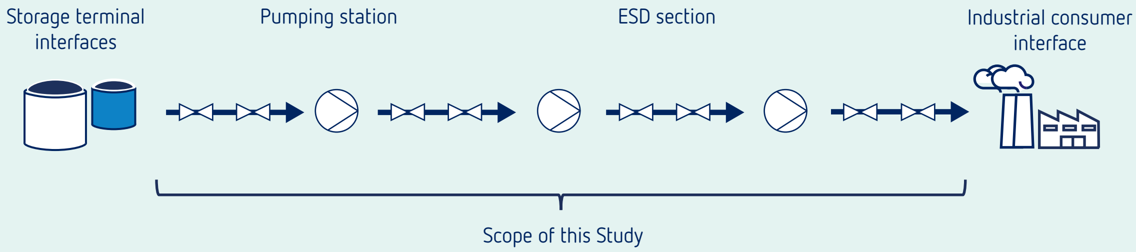


Figure 5: Pipeline Safety Study's Scope

Figure 5 indicates the pumping stations that help transport the ammonia up elevations and compensate for pressure losses in the system due to friction in the pipeline. In addition, the pressure should remain sufficient over the entire length of the pipeline to avoid flashing and two-phase flow. The first pumping station at the terminal could provide sufficient pressure for transport, which is why no booster pumps would be needed. Emergency Shut Down (ESD) sections between two isolation valve stations are required to close the system (and stop the pumps) immediately in the event an LOC is detected.

27 OCI-Nitrogen-Product-Specification-Sheet-Anhydrous-Ammonia-en-1.pdf

Other Ammonia Pipeline Safety Studies

Other ammonia studies – mainly conducted in the Netherlands – provide important insights into the feasibility and safety aspects of single pipelines for large scale transportation, diameters are in the range of 24 " to 36".[28, 29, 30] The main difference being that the ISPT study used a single pipeline with booster pumping stations as its starting point and that it assessed the safety aspects of the pipeline system's design in its entirety.

Alongside the studies that examined single-pipe pipelines, others studied pipe-in-pipe or double walled pipes (PiP) with regard to their potential to reduce the effects of pipeline failure. PiP received increasing attention as a potential best practice for the transport of toxic chemicals e.g. chlorine and ammonia. The advantages stated include possible external damage or external corrosion not immediately affecting the inner pipe as well as the servicing of and repairs to the external pipe could be effected during operation.[31, 32] A disadvantage is that pipeline integrity has not been proven yet, particularly when it concerns the product and welding quality, testing and lifespan. Challenges remain with regard to inspections and maintenance. So far, these PiP solutions have not been used for ammonia pipelines nor at such a large scale with this number of valve stations and over such distances. It would be a more expensive solution and should therefore, be studied in more detail.

Over the course of the DRC project, two parallel pipes in a single trench was suggested as a solution to reduce the volume of a pipeline by half. As a result, the risk contour would be smaller due to reducing the inventory of a pipeline segment, which could be released in case of a rupture. In this solution, a single pipeline can take over services from the other pipe in the event of damage or maintenance. This solution is however not recommended due to its expected complexity, which could have adverse effects, perhaps even increasing the risk contours.[33, 34]

Capacity

The capacity was fixed at 7 million tonnes of clean ammonia per annum (mtpa), equivalent to about 1 mtpa hydrogen throughput, assuming losses for ammonia cracking.[35] This scale was derived from market outlooks as suggested in the ISPT Roadmap report.[11] For the purpose of this study, it was assumed that the mass flow rate of 222 kg/s is calculated as an annual average based on full time running hours and full capacity for the entire length. No logistical margins and mean times for (preventive) maintenance and inspections were taken into account.

28 Transport van waterstofdragers door buisleidingen en bijbehorende risico's | Rapport | Rijksoverheid.nl, Antea, 2023.
29 veiligheid van ammoniak door buisleidingen, AVIV, 2024.
30 IT56673_3461002_RevA_QRA EnBW NH3 buisleiding, Bilfinger Tebodin 2024 (confidential)
31 Presentation Quickscan QRA_Rev02 PiP, Bilfinger Tebodin 2024 (confidential)
32 Memo Double Walled Chlorine Pipeline, Port of Rotterdam, 2024 (confidential)
33 57568-1934001 Analyse optie ammoniakleidingsysteem - rev D, Bilfinger Tebodin 2024 (confidential)
34 Analyse optie ammoniaksysteem: Processimulatie dubbele leidingconfiguratie, Bilfinger Tebodin 2024 (confidential)
35 Stoichiometric factor hydrogen/ammonia 3/17=5.6 and 79% ammonia to hydrogen cracking efficiency

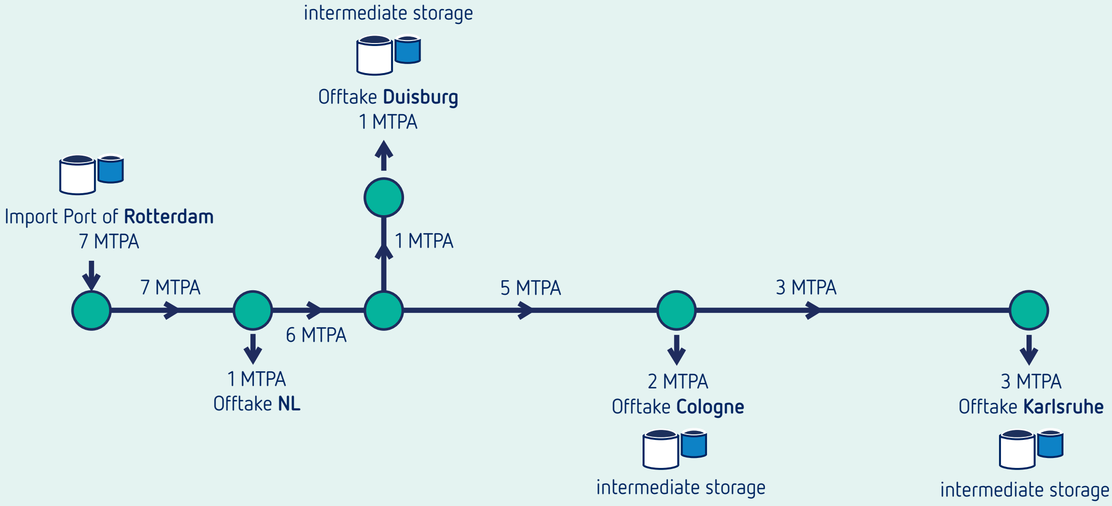


Figure 6: Pipeline Capacity [10]

The entry point assumed is an import terminal at the Port of Rotterdam and, at the exit points, there are (intermediate) receiving terminals with connection to off-takers for utilisation, see Figure 6. For the sake of the study, the total pipeline length was assumed to be approximately 550 km and it was dimensioned for the maximum capacity over its entire length. Potential offtake could be 1 mtpa within the Netherlands and in Germany offtake of 6 mtpa, distributed as 1 MTPA to Duisburg, 2 MTPA to Cologne and 3 MTPA to Karlsruhe. The entire pipeline system will however accommodate the total transfer capacity of clean ammonia from Rotterdam to Karlsruhe.

Rotterdam to Germany Route

A virtual route from Rotterdam to North Rhein Westfalia (NRW) and Baden-Würtenberg (BW) in Germany was created that resembles the proposed DRC. The pipeline was predicted to cross residential, industrial and commercial areas as well as canals, rivers, roads and railways. Horizontal directional drilling (HDD) can be applied for some complex crossings. This study also considered intermediate pumping stations as these are also part of the pipeline.

In the Netherlands the route basically follows the projected DRC route which includes many complex, sensitive crossings as well as passing through nature reserves (Natura 2000) and densely populated areas, which prove difficult to avoid. The virtual route in Germany was, in principle, based on a corridor of minimal length, with as few river/road crossings as possible as well as avoiding (densely) populated areas and nature reserves, see Figure 7. In this project it was assumed that there will be sufficient space at industrial sites along the route to build intermediate pumping stations. The route includes elevations to approx. 400 metres and ends at an elevation of a little over 100 metres.

Figure 7: Route and Elevations [10]

4 Legal Framework Concerning Pipeline Safety Risks

Vision

To ensure health, safety and environment of the workers, the population and nature, applicable lawws are implemented. European guidelines such as Natura 2000, IPPC and ATEX are harmonised by all EU members. Specific acts and regulations are applicable to pipeline safety. This is the case for natural gas, chemicals but also for new energy carriers such as hydrogen and ammonia. In the Netherlands, Germany and EU, the impact of the energy transition on legal framework is under development.

In a vision document on hydrogen carriers and the energy transition, the Dutch Ministry of Climate and Green Growth (Min. KGG) considered ammonia as an important energy carrier, particularly at ports that would crack and use it as a building block for other products, and potentially as shipping fuel. The ministry recognises that pipeline transport is the preferred method for large-scale ammonia transportation to the hinterland, although it does not actively support ammonia transport to the hinterland.[36] In Germany, a similar vision has not been developed yet.

Laws and Regulations

Industry and the government have over a century of experience with compliance regarding the production, storage, transport, handling and utilisation of ammonia, mainly at industrial sites. There are a wealth of safe designs, permits, operations, inspections and maintenance requirements. However, long-distance, cross-border pipelines transporting large volumes in public areas introduce new risks, and the laws, regulations and compliances need to be aligned nationally as well as across the EU, particularly between neighbouring countries. This regulatory framework will constitute the basis for the permit issuing procedures for ammonia pipelines or pumping stations, to protect people and nature for the impact of a toxic gas cloud or soil/water pollution. The emergency responses should be coordinated by the authorities, particularly in border areas, in the event a leak happens to protect people and aquatic life. These developments and new risks require understanding the differences and commonalities in approaches, principles and requirements between the two respective countries in this project. A review of the legislative context regarding pipeline safety for the Netherlands and Germany is presented in Table 1.

Table 1: Main Regulatory Framework for Pipeline Safety for The Netherlands and Germany

	Netherlands	**Germany**
Environmental	Environmental Act (Omgevingswet)	Environmental Impact Assessment Act (UVPG) Soil protection Act (BNatSchG) Climate change Act (KSG)
Spatial planning	Environmental Act (Omgevingswet)	Spatial planning procedure (Raumordnungsverfahren) Planning approval procedure (Planfeststellungsverfahren)
Pipelines and safety	Environmental Quality and Activity Act (Bkl and Bal) NEN 3650 series for transport pipelines Calculation modules (Handboek RIVM Rekenvoorschift)	Pipeline Ordinance (RohrFltgV) Technical regulations (TRFL) SEVESO III (KAS)

36 Verdiepingsdocument beoordeling waterstofdragers | Rapport | Rijksoverheid.nl

The Risk Approach in the Netherlands

In the Netherlands, a process is ongoing with the Min I&W and KGG to develop new and review existing safety policies, with a view to the introduction of new energy carriers.[37] In several countries, including the Netherlands, Belgium, France and the UK, a risk-based approach is followed, subdivided into:

- compliances aimed at reducing process safety risks for operations to ALARA (as low as reasonably acceptable)
- legal requirements concerning focus areas for protecting people living in nearby villages or cities
- imposing an external safety distance for anyone present in the immediate vicinity.

The Environmental Act

Recently the relevant legislation was changed due to the implementation of the Environmental Act (Omgevingswet) as part of spatial planning and permit issuing procedures. The External Pipeline Safety Decree (BEVB) is therefore no longer applicable. The Quality Environmental Decree (Bkl) and the Activity Decree (Bal) which are elements of the Environmental Act determine the permit requirements for external safety risk, focus areas and risk contours.[38]

The risks must be calculated using QRA and the National Institute for Public Health and the Environment's calculation models, which prescribes failure rates and risk reduction factors. [22, 23, 24] The risk reduction factors are based on a selection of risk reduction measures listed in the calculation modules. Pipe in pipe (PiP) solutions are not included in the latter. Interaction/domino effects from one pipeline to another were also not considered. The Bal states that a pipeline may not cause a risk (LSIR) higher than once in 1,000,000 per year (10^{-6}/year) for vulnerable and very vulnerable buildings, and vulnerable locations. This means that the risk contour must be less than a 5 metre distance from the pipeline. The operator is responsible for meeting this criterion.

An Environmental Impact Assessment (EIA) applies for long-distance pipelines. The permit issuing can be part of a Government Coordination Scheme (Rijks Coördinatie Regeling-RCR), which is also the case for the Delta Rhine Corridor. Political support for the Delta Rhine Corridor (DRC) project to be extended into Germany to Duisburg and Cologne is present as declared by the Netherlands and North Rhine-Westphalia.[39]

As for the pumping stations, these are expected to be viewed as separate entities, potentially classified as SEVESO III sites and are therefore expected to comply to different permit issuing processes and legal requirements such as those for fatality risk contours.[40] The fatality risk contour, for example, may be agreed with the authorities based on local zoning.

37 Veiligheidsrichtsnoer waterstofdragers, eerste versie

38 The Guidelines for Environmental Safety Assessment are outlined in Appendix VII and section 5.1.2.5 of the Quality of Living Environment Decree (Bkl) of the Environmental Act in the Netherlands.

39 "Joint Declaration of Intent on cooperation regarding the cross-border connection of pipeline infrastructure of carbon dioxide and hydrogen in the Delta Rhine Corridor project" (14-11-2023).

40 Directive - 2012/18 - EN - Seveso III - EUR-Lex

Focus Areas [41]

The Environmental Act is explained in the Bkl as it pertains to the planning process and general obligations in the Bal. This means that focus areas have been introduced to protect people in the event of accidents leading to a potential toxic cloud drifting to a (densely) populated area. The focus areas also include fire and explosion, but these are not relevant for ammonia due to its properties. The implementation of focus areas for toxic substances is planned for July 2025 with a modification to the Bkl. However, the implementation of focus areas for fire and explosion for determining safety distances has not been planned yet and the existing procedures in accordance with the Environmental Act remain in place. The competent authority makes and motivates its choices with regard to environmental and spatial planning as to what is sufficiently safe and how health and the environment should be protected. The focus areas for ammonia can be calculated for a release of a certain volume of ammonia due to damage, assuming that this worst case scenario happens, adopting lethality threat values (LBW). The focal areas are expressed in distances from a pipeline and pumping station, which the Bkl caps at 1,500 m. This cap is only for spatial development and not for granting a possible permit for the pumping station itself. Beyond this distance, the local and regional authorities are responsible for emergency response and crisis management.

Thresholds

Health hazards and thresholds for intervention values are presented in Figure 8. The focus area is based on the intervention value for (gaseous) ammonia, expressed as a lethality threat value (LBW) of 1,100 ppm (780 mg/m^3) with 60 minutes of exposure.[42, 43] The Level Odour Awareness (LOA) or Public Threshold Value (PGW) is however much lower at around 2 ppm. In addition, the intervention value for warning people (VBR) is 30 ppm, roughly a factor of 20 - 30 above the LAO and below the LBW. Internationally, the Immediately Dangerous to Life or Health (IDLH) standard is referred to, which uses a value of 300 ppm for ammonia.[44] This is similar to the Alarm Threshold Value (AGW) in the Netherlands.

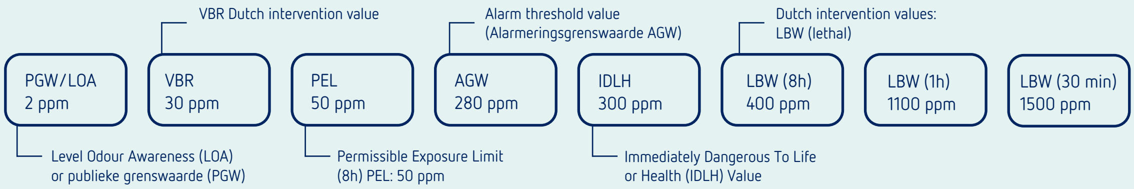


Figure 8: Ammonia Health Hazards [2]

41 Ontwikkelingen aandachtsgebieden | Informatiepunt Leefomgeving
42 Interventiewaarden ed 2023-1 alfabet
43 Ammoniak-IVW-2009.pdf (rivm.nl)
44 AMMONIA | Occupational Safety and Health Administration

The size and duration of the gas cloud depends on the actual volume that escaped, the pipeline's operating pressure, the temperature, ammonia's properties, the pipeline's damage reduction features such as, for example, deeper placement, soil and weather conditions. There are no legal criteria for the lethality and LBW distances in the Netherlands (and Germany) or for scenario durations. During the permit issuing phase the authorities may discuss additional mitigating requirements for the design, operation, emergency control and response with the owner-operator.

German Approach: Avoidance and State-of-the-art Technology

Germany has a deterministic approach employing state-of-the-art solutions. The safety philosophy is based on avoidance of damage, and the subsequent adverse effects for the population and the environment, which is reflected in the German EIA Act (UVPG), the Pipeline Ordinance for Hazardous Substances (RohrFltgV) and the Technical Regulations for Pipeline Systems (TRFL). The RohrFltgV and TRFL specify the state-of-the-art technologies to be employed whereby risk-based approaches can also be taken into account for individual cases. TRFL states the pipeline must be installed in a protective strip or corridor.

Pumping stations and other pipeline elements are also subject to the RohrFltgV and TRFL and requirements on state-of-the-art techniques are therefore applicable. The Committee for Safety of Installations (KAS-18) recommends, as starting points, a green field ammonia site distance of 500 metres for pumping stations subject to SEVESO III.[45] Intermediate pumping stations must be viewed as integral parts of the pipeline. There are no legal guidelines for risks. Germany employs an additional safety assessment regarding SEVESOIII facilities, the *Sicherheit Relevante Anlageteile* (SRA) as part of KAS 1 *(Störfall-Verordnung)*.[46] This regulation requires additional safety assessments and stricter oversight for plant parts with special material content or special functions. For ammonia the limit is set at 2% of the lower Seveso limit which equals 1,000kg.[47] By comparison, for hydrogen, this is 100 kg (or a flow rate of 100 kg/10 min).

As described in the UVPG, contact should be established with the responsible (regional) authorities *(Bundesländer)* at an early stage in order to coordinate the further EIA procedure and define concrete requirements. For example, for the Environmental Impact Assessment Act in the state of North Rhine-Westphalia, the UVPG is harmonised into the UVPG NRW. In addition, a planning approval procedure *(Planfeststellungsverfahren)* and a spatial planning procedure *(Raumordnungsverfahren)* should be expected. These are also part of the permitting process *(Genehmigung)*. This is arranged separately for the hydrogen core network.[48] The approval and permitting procedures require verification *(Prüfung)* and certification through independent accredited organisations, so called notifying bodies (NOBO).

45 umwelt-online-Demo: KAS-18 Leitfaden - Empfehlungen für Abstände zwischen Betriebsbereichen nach der Störfall-Verordnung und schutzbedürftigen Gebieten im Rahmen der Bauleitplanung Umsetzung § 50 BImSchG - Kommission für Anlagensicherheit (KAS)
46 GRS-A-Bericht
47 GRS-A-Bericht Tabelle 1
48 Genehmigung Wasserstoff-Kernnetz

Common Approach for NL and DE Legal Framework

An internationally acknowledged legal framework for ammonia concerning (cross-border) pipeline safety risks is not available yet. Zooming out, the legal framework of the Netherlands and Germany is largely similar, see Table 2. The requirements from the EU guidelines EIA, SEVESO and for CE marking as well as some parts of the spatial planning procedures and the pipeline ordinances seem similar. There are differences in the approach and principles in both countries. In the Netherlands the risk-based approach is prevalent whereas in Germany this is only allowed in individual cases.

Table 2: Approach to External Safety for Pipelines in the Netherlands and Germany

	The Netherlands	Germany
Approach	Risk-based approach largely based on safe design, technical standards, confirmed using QRA and focus areas.	A deterministic approach based on state-of-the-art methods, technology and practices. In individual cases, a risk-based approach for the design of reduction measures is allowed.
Principle	Safety risk contours are based on QRA and expressed as 10^{-6}/yr for external safety. In addtion, focus areas are applicable to protect the public from possible accidents.	Avoidance of damage and subsequent hazardous effects on people and the environment.
Practices	Risk reduction and inherently safer designs Process safety management requirements	Proven state-of-the-art techniques
Distances Pipelines (LSIR)	Distances (10^{-6}/yr risk contour) from pipeline to sensitive objects should be <5 m	No distances defined for pipelines
Distances Pipelines Focus Areas)	Distance focus area is limited to 1.5 km as per Bkl. This cut-off only applies to spatial developments in the vicinity of the ammonia pipeline, but not to granting a possible permit for the pipeline itself.	Not applicable
Burial depth	Minimum 1.2 metre to top of chemical pipeline (or protective plate)	Minimum 1 metre according to TRFL These must be viewed as integral parts of the pipeline. There are no legislation-based guidelines pertaining to risk.
Distances intermediate Pumping Stations	Separate permit issuing procedure (Bkl) Distances (10^{-6}/yr risk contour) from pumping station to sensitive object should be > 10^{-6}/yr risk contour.	KAS-1 imposes a safety assessment for SEVESO actities, but tthis does not apply to pumping stations. KAS-18 recommends, as starting points, a green field ammonia site should be 500 metres from communities, however this does not apply to pumping stations.[49]

State-of-the-art Practices

Examined more closely, the approaches can also be interpreted as similar as in both countries as these are based on state-of-the-art design and safety in design practices. At first sight, the approaches may seem different with the Netherlands utilising a risk-based approach whereas the German approach emphasises avoiding adverse effects on and risks to people and nature. The principles with focus areas and avoidance criteria can both be considered effect-oriented, although they take different angles reducing/respectively avoiding effects. Both countries require a corridor and obstruction areas for maintenance access and protection against accidental impact from excavation and construction.

49 or a credible accident release area of 490 mm2 with an assumed endpoint of ERPG-2 (150 ppm).

In Germany, the route planning and design of a pipeline system is not approved on the basis of risk criteria as is the case in the Netherlands. The extent to which the state of the art is fulfilled would require clarification. The incorporation of state-of-the-art techniques into designs, practices and methods would provide room for a more risk-based approach and risk reduction measures. Safety in design and compliance with regulations, as stated and interpreted by the submitting party, must be validated by the competent authority. There is no legal basis for a guideline on criteria for 'avoidance' levels of accidental exposure of the public, such as the implementation of the SEVESO guideline. Because of this and other studies with ammonia transport it is therefore suggested that state-of-the-art techniques should be defined on the basis of the Netherlands' risk-based approach with required reduction measures and factors. As such this could be applicable to German state-of-the-art techniques in accordance with the Pipeline Ordinance (RohrFltgV) and Technical Regulations (TRFL). A more design oriented approach, following inherently safer design practices is recommended.

Key finding

A common approach for the Netherlands, Germany and, more generally speaking, the EU is needed for long-distance (cross-border) ammonia pipelines (as well as hydrogen and other energy carriers) to meet the challenges of the energy transition in Western Europe. The application of inherently safer design practices using state-of-the-art techniques and a risk-based approach employing risk reduction measures could provide this common framework.

5 Pipeline Integrity: Design and Operation

Pipeline System

The pipeline system for transporting ammonia with interfaces to the import and receiving terminals is depicted in Figure 9. This process flow diagram (PFD) schematically describes the pipeline system's design, including two isolation ESD valve stations, one intermediate (booster) pumping station, pig launcher receivers for internal inspection and the typical instrumentation. The actual number of valve stations will be determined by a safety study and the number of pumping stations which, in turn, depends on the hydraulic design.

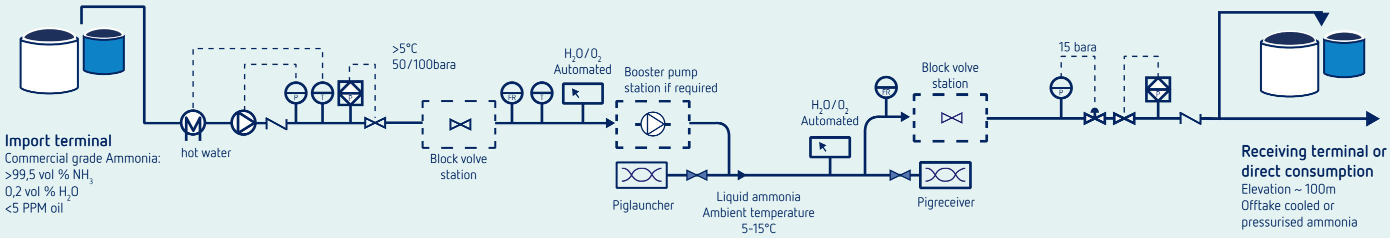


Figure 9: PFD Pipeline System [7]

Clean ammonia transfer of 222 kg/s in liquid phase at ambient temperature was assumed. Two phase flow should be avoided at all costs as this can lead to sluggish flow and pressure issues, which could damage the pipes and valves. Controlling the minimum temperature at the entry point to 5° C and the minimum pressure at the exit point at 15barg. The refrigerated ammonia in the import terminal should be heated, e.g. with surface/hot water from -33° C to a minimum of 5° C or in practice 15° C, which is close to average soil temperature. At the receiving terminal the ammonia should once again be refrigerated for storage.[50] Alternatively, the ammonia can be immediately transferred to its users. The operation should be fully automated and overseen by operators located at a central control room.

Main Hazards

The hazards were investigated during HAZID workshops. Pipeline integrity, including barriers, was analysed using the bow tie method. An overview of the hazard assessment is provided in Annex 2 and the bow ties in Annex 3. The main concerns are a loss of containment and the release of an ammonia cloud. The major hazards identified are summarised below:

- Excavation accidentally damages the pipeline causing rupture
- Corrosion, internal and leaks through holes or ruptures
- Corrosion external and leaks through holes or ruptures
- Leaks through valves, flanges, instruments, etc.
- Natural disasters including landslides, floods, earthquakes, etc. causing a rupture
- Liquid hammering leading to pipeline damage and causing a rupture
- Overpressure due to expansion as a result of the temperature increase of a blocked-in volume
- Control failure up/downstream (pressure, temperature)
- General failures during the commissioning, operation and maintenance of the pipelines, pumps, valves and other equipment, e.g. relief valves and vents.

50 The process for conditioning, refrigeration, liquefaction is described as the Joule-Thomson effect

Scenarios

This report considers two external safety scenarios:

- The worst case scenario i.e. an accident leading to a full bore pipeline rupture, a release of ammonia and the subsequent formation of an ammonia cloud
- Or leaks leading to an ammonia release, a smaller gas cloud and a smaller expected impact.

Here, a rupture is defined as a pipeline breaking into at least two pieces with outflow from openings similar to the diameter (full-bore line size). The hazard assessment was based on the assumption that leaks occur through what are typically 20 mm holes (10% of the diameter). Fugitive (gaseous) emissions can occur, however these were not considered by this study.

The extent of the hazardous effect on people is a function of the weather (wind direction), the event location and the distance to people as well as the duration of the exposure combined with the concentration at a certain distance. This will be discussed in further detail in Sections 2 and 6.

Risk Reduction Strategies

Concerning the pipeline's design, the following risk reduction strategies have been used, based on the approach outlined in Section 2 and the abovementioned hazards and scenarios:

- Preventing an event, for example, avoiding routing through urban areas or digging deeper trenches for the pipeline
- Preventing an event, for example, corrosion and overpressure, which can potentially lead to an LOC, through inherently safe design measures, e.g. materials and mechanical design features
- Controlling an event i.e. finding issues before they cause problems, e.g. using the X-ray verification of welds on the pipeline during construction and in-line inspections during operations and maintenance
- Minimising the probability of failures, for example, the likelihood of excavation damage, the failure rates of instruments or controls
- Reducing the inventory, for example, by reducing diameters and increasing segmentation using isolation valves, therefore minimising the consequences should an accident leading to a gas cloud occur
- Mitigating the LOC, for example, by applying safety distances, leakage detection and reducing the effect of a release through reduction measures
- Emergency response, for instance, installing a scrubber, crises management planning thereby reducing the consequences.

The necessary risk reduction measures, prevention and mitigation as well as instrumental and mechanical safeguarding should meet the requirements listed in Sections 2, 3 and 4. The risk reduction measures will be described in Section 5 and further assessed in Section 6. The proposed pipeline integrity system with risk reduction measures needs to be confirmed and further detailed in a design and engineering study.

Obviously, alongside risk reduction measures, emergency control is also essential and should feature collection, scrubbers, water curtains, emergency response by the fire department and crisis management by the authorities.

Emergency Shutdown System

An emergency shutdown system (ESD) is compulsory for safeguarding hazardous operations and will therefore also be applicable to ammonia pipelines. The ESD functions are usually part of a Safety Integrity System (SIS) that is separated from a Distributed Control System (DCS), and operated from a control room. The ESD system overrides the basic control system if abnormal operating conditions occur such as, for instance, a sudden drop in pressure. Temperature and pressure sensing instruments are required at each pumping station and valve station for monitoring, control and safeguarding. An uninterrupted power supply system (UPS), usually batteries, should be available at each pumping and valve station to ensure ESD functions in the event of a power cut. An automated leak detection system has also been proposed for the ammonia pipelines as well as the pumping and valve stations. In the event of a problem, pressure transmitters and/or the detection system will trip the pumps and automatically close the ESD valves for the relevant section of pipe. These and other safety integrity functions need to be engineered as part of the HAZOP-SIL-LOPA risk assessment methodology to ensure process safety for ALARA. However, on the basis of this study's QRA (see Section 6) a SIL level should be added on top of the engineered SIL level (SIL+1) as an extra risk reduction measure with a factor 10 to meet the required 5 metre risk contour. The SIL level classification should be assessed and verified during the FEED phase of a dedicated project.

Hydraulic Design and Pipeline Sizing

Pipeline diameters can be reduced by increasing velocity. Reducing pipeline diameter (line size) using higher velocities reduces the inventory significantly. The volume is proportional to the square root of the line size. For instance, if the pipeline diameter decreases by a factor of 2, the volume reduces by a factor of 4. As a consequence of the increased pressure drop, the design operating pressure may need to be increased or a number of pump stations is needed.

Table 3 presents the hydraulic study's results for pipeline sizing to accommodate the specified transfer capacity, the number of intermediate pumping stations and the design pressure. The recommended (base case) pipeline sizing is based on both 50 barg design pressure, with the maximum permissible pipeline operating pressure (MAOP) expected to be moderately below the specified design pressure i.e. 46 barg. The 50 barg design pressure is in line with current industry practices for onshore ammonia pipelines and suggests a line size of 20" (inch) or a diameter around 500 mm (DN500) and a velocity of 2.0 m/s. The wall thickness (WT) is 15 mm, which is in line with the minimum (regulated) wall thickness to lower the frequency of failure due to external damage, see Section 6. The pipeline failure statistics demonstrate that no external interference or accidents have occurred with wall thickness (WT) above 15 mm for chemical pipelines.[51] For this project's proposed ammonia pipeline and with reference to the RIVM Calculation Model, additional requirements for mechanical strength (SMYS) should be applied to meet the 5 metre contour.

In line with standard practices, 1 mm of corrosion allowance was also added to the WT design. In the case study, the number of required intermediate pumping stations for the pipeline size recommended is three. An alternative case study concerning a 100 barg design has also been proposed. This is at the higher end of the pressure scale, but would be technically feasible.

51 EGIG, Gas Pipeline Incidents, 11th Report of the European Gas Pipeline Incident Data Group (period 1970 – 2019)

In this case an 18" (DN450) pipe diameter at 2.6 m/s velocity with 19 mm WT and two pumping stations would be required. For reference, a 32" (DN850) pipeline with its design pressure at 50 barg and 15 mm WT with no intermediate pumping stations is also shown. In the latter reference case, the ammonia is directly transferred to a receiving terminal in Germany. This design's intent is to minimise average pipeline diameters. Reducing the line size from 32" to 20" leads to a factor 2.6 lower inventory per km of pipeline.

Table 3: Three Hydraulic Design Case Studies

Case	Line size (inch)	Design pressure (barg)	Wall thickness (mm)	No. intermediate pumping stations	Description
Base	20	50	15	3	Recommended and proven pipeline design
Alternative	18	100	19	2	Possible pipeline design
Reference	32	50	15	0	Direct transfer pipeline design

The total (extra) pumping power consumption for the intermediate pumping station is estimated at 3 MW for the base case, 3.3 MW for the alternative case and does not apply for the reference case. The power consumption is 0.07% for base and alternative case compared to the actual energy (LHV) conveyed by the ammonia flowing through the pipeline.

Corrosion

It is known that corrosion may occur in liquid ammonia pipelines, tanks and vessels. The main corrosion mechanism is the formation of cracks due to stress corrosion cracking (SCC).[52] The water concentration should therefore be kept at between 0.1 and 0.5 vol%, typically 0.2 vol% to inhibit corrosion (SCC). Pipeline design and operation must strive to avoid any transition to the vapour phase, even during transient phases of operation. Contamination of ammonia with oxygen from the air must be avoided by using nitrogen for example during commissioning. Since ammonia is highly corrosive to copper and zinc, the materials selected should not contain these elements.[7]

Material Selection

The materials selected must show good resistance to cracking and certified welding procedures must be employed to this end. Typically this is achieved by requiring high toughness and elongation, alongside limiting hardness. These properties are easier to achieve in lower-grade steels and with upper limits for yield and tensile strengths. Low alloy carbon steel is therefore usually selected. Line pipe grade API 5L X52N (L360N) was selected for this project and has also been used for operational ammonia pipelines in Italy and Poland.[5] ASTM A333 Gr.6 was selected for several other European ammonia pipelines (in the Netherlands, Spain and Portugal) whereas in the USA the material choices specified for ammonia pipes are ASTM A53 Grade B or ASMT A106 Grades B or C.

52 A. W. Loginow (1989) Stress Corrosion Cracking of Steel in Liquefied Ammonia Service— A Recapitulation. National Board Classic Series, National Board Bulletin.

All the types mentioned are low alloy carbon manganese steels with a specified yield strength of a minimum of 240 MPa and that are resistant to Stress Corrosion Cracking (SCC). It must be noted that ASTM A53 and A106 grades, along with A333 Grade 6 are allowed to contain 0.4% copper. This should be restricted for ammonia pipelines et al, due to the risk of corrosion. The selected yield strength of 360 MPa is chosen to slightly optimise pipeline design in comparison to the reference projects, since those pipelines were generally less than 8" in diameter as well as shorter, and so required much lower operating pressures.

Segmentation of Pipelines using ESD Valve Stations

Ammonia pipelines should be segmented to limit the amount of ammonia released into the atmosphere in the event of an LOC caused by a pipeline or equipment leak or due to accidental rupture. Pipeline segments are defined by the blocked-in volume between 2 automatic, electrically actuated ESD isolation valves. The segmentation distance should be based on the safety requirements (QRA), design codes and maintainability. The maximum block valve segment given in ASME B31.4 is 12 km for NH3 and LPG. This is independent of pipeline diameter (i.e. not directly linked to volume) and area designation, i.e. populated areas. A PTX guide makes reference to 16 km representing 400 tonnes of NH3.[53] In another study based on 36" pipelines a distance of 3 to 5km was recommended for densely populated areas. For rural areas this would be 10 km, due to modelling uncertainties.[29] For this study 5, 12 and 16 km were therefore studied. The proposed segmentation depends on the external safety distances and economics, see Section 6 and 7. At this stage, it is recommendable to conservatively assume a 5 km distance between ESD valves. This means roughly 110 ESD stations over the entire length of the proposed corridor to Germany.

ESD Valve Stations

The isolation ESD valves are automatic, electrically actuated ESD valves. These full bore (20") ESD valves are mounted in the main pipeline with the spindle for the electrical actuator above ground in a housing, see Figure 10. The latter for weather protection, leakage detection, communication and security reasons. Instrumentation for monitoring and safeguarding, a nitrogen tank for inertisation and, if need be, a (mobile) scrubber should be installed. All pipeline and piping sections between isolation valves should be open towards a thermal relief valve (TRV). Overpressure exceeding the design pipeline pressure should be prevented since this could lead to valves leaking. Overpressure can be caused by heat ingress from the soil, a subsequent temperature increase and expansion of the liquid ammonia (typically associated with a shut-in condition). Thus release to atmosphere will be avoided in case a TRV opens the inventory of one segment is transferred to the next segment.

Response Time for Closing ESD Valves

Usually, the response time for closing isolation valves in the event of an ESD being tripped is set at 3,600 seconds (one hour) to allow the operator to initiate an ESD manually. One of the starting points for the safety assessment was the presence of semi-automatic ESDs. This means the leak is automatically detected, but that the ESD system must be initiated manually from a control room.

53 PtX Hub, AMMONIA TRANSPORT & STORAGE, 2024 /3/ 16

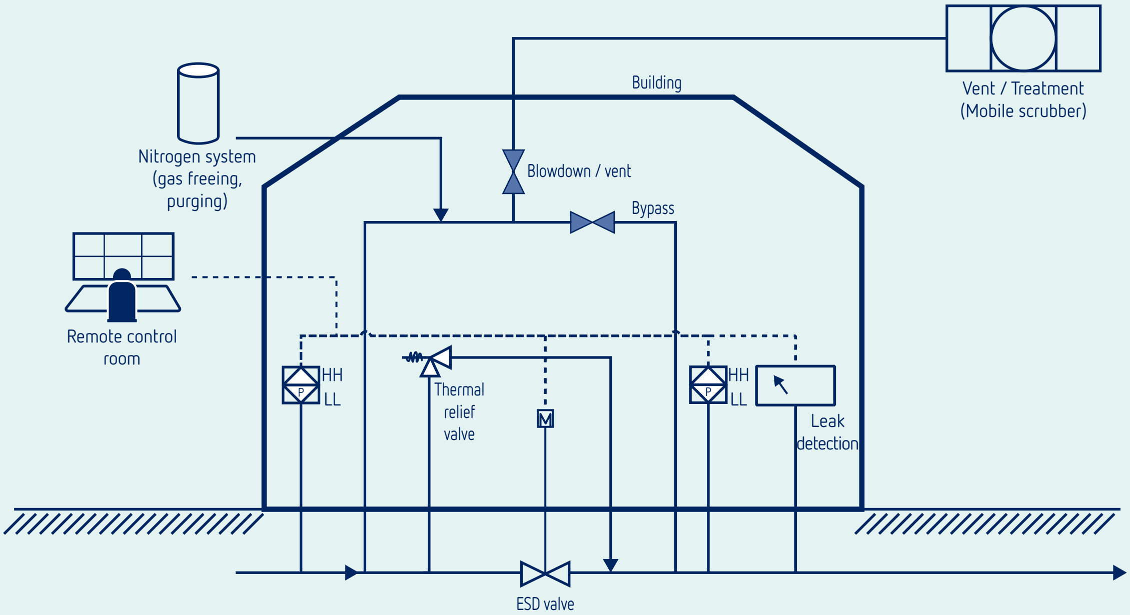


Figure 10: PFD Isolation ESD Valve Station [10]

The response time is important since this will limit bidirectional flow in the pipeline segment in the event of a pipeline rupture (or leak). Typically, a minimum automated closing time is calculated using 1" per second, so at least a 20 second response time for closing of a 20" ESD valve in a pipeline. Some time passes between detecting the leak and activating the ESD. An ESD time faster than 60 seconds is considered unrealistic. To this end, the safety assessment in Section 6 simulated the use of automatic ESD valves with a 60 – 120 second response time.

Liquid Hammering

Liquid hammering effects could potentially occur due to the impact (momentum) of the inventory of a pipeline segment on a closing valve. A preliminary calculation shows that up to 18 bar pressure surges could be observed depending on the segment's length and particularly during the final stages of closing, which can lead to serious vibrations, damage and LOC. Liquid hammering can be prevented using slow-acting automatic ESD valves. At the moment, the assumption is that the valve closing time is sufficient to prevent hammering effects.

Pumping Stations

The assumption made for the pumping stations is that the line diameter, operating pressure and temperature will be the same as for the pipeline. A generalised schematic of a pumping station is provided in Figure 11. Due to safety, operational, and security reasons , the pumps and electrical and control systems, are preferably located indoors. The assumption is that each pumping station will be configured to have multiple pumps in parallel (e.g. three pumps and a back-up). Only one pump has been included in the drawing and the valves (double-block and bleed). Pumping stations should preferably be located as far away as possible from populated areas, in line with spatial planning requirements and the QRA (see Section 6). Any venting associated for the benefit of pump operation, safeguards (e.g. TRVs), inspection or maintenance may need to be contained or relieved into a lower pressure segment (i.e. an upstream section). Nitrogen skids, scrubbers and pig launchers/receivers need to be facilitated for maintenance activities. The pumps should be isolated in case of an ESD due to a leak and detection in the building. Sprinklers and a basin for collecting ammonia water should also be present. A 20 to 30 metre, arbitrary typical ESD distance along a pipe segment around the pumps was considered. The shut-off head pressure (approaching zero flowrate) of the centrifugal pumps should remain below the design pressure of 50 respectively 100 barg.

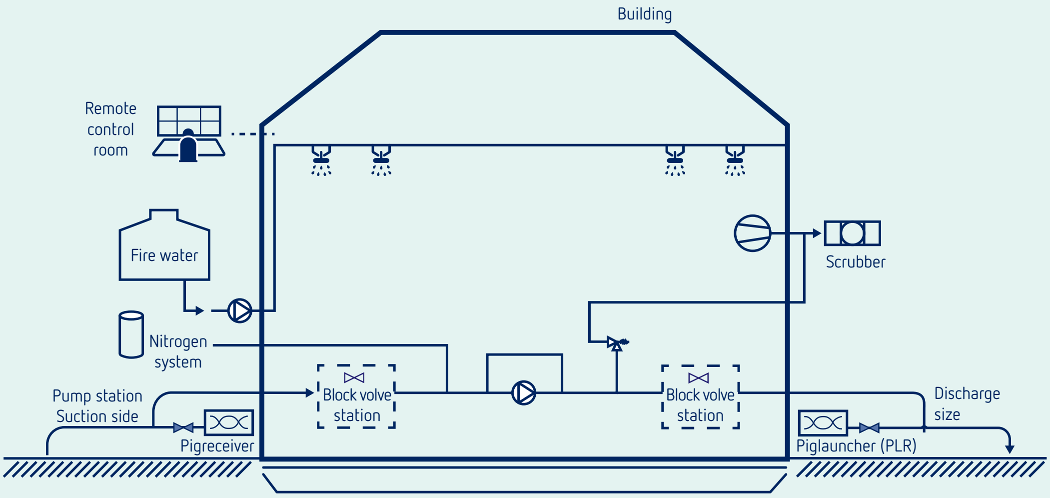


Figure 11: PFD Pipeline System [10]

Pig launchers/receivers and In-line Inspections

A pigging device is an electronic device inside the pipe. It is used to clean, maintain and inspect new or existing pipelines for hazardous substances including ammonia. An example of a pipe cleaning pig is given in Figure 12.

Figure 12: Example of Pipe Cleaning Pig [54]

54 T.D. Williamson PITBOSS Cleaning Pig

A pig launcher/receiver (PLR) is used as an entry/exit point in the system. Each pipeline segment should be individually piggable by installing PLRs at each pumping station and preferably also at each valve station. Pigging should be used for internal line inspection (ILI). For cleaning upon commissioning and to combat the displacement of ammonia during start-up, a separation pig can be used, pushing product into the pipeline and emptying out nitrogen.

The PLR equipment pool may benefit from a uniform pipeline size for all sections. As pigging devices may contain copper, corrosion can occur, which may impact the inspection's reliability. There is a need for the development of reliable pigging devices that do not contain copper for the cleaning of ammonia pipelines.

Pipeline Trench

The corridor's routing and the geotechnical design are part of a dedicated project. The routing and design should take natural disasters into account to the greatest extent possible. The design should also address other pipelines and cables. A typical trench and pipeline are shown below in Figure 13. The reduction measures indicated have been proposed to meet the safety distance of 5 metres, see Section 6 for clarification.

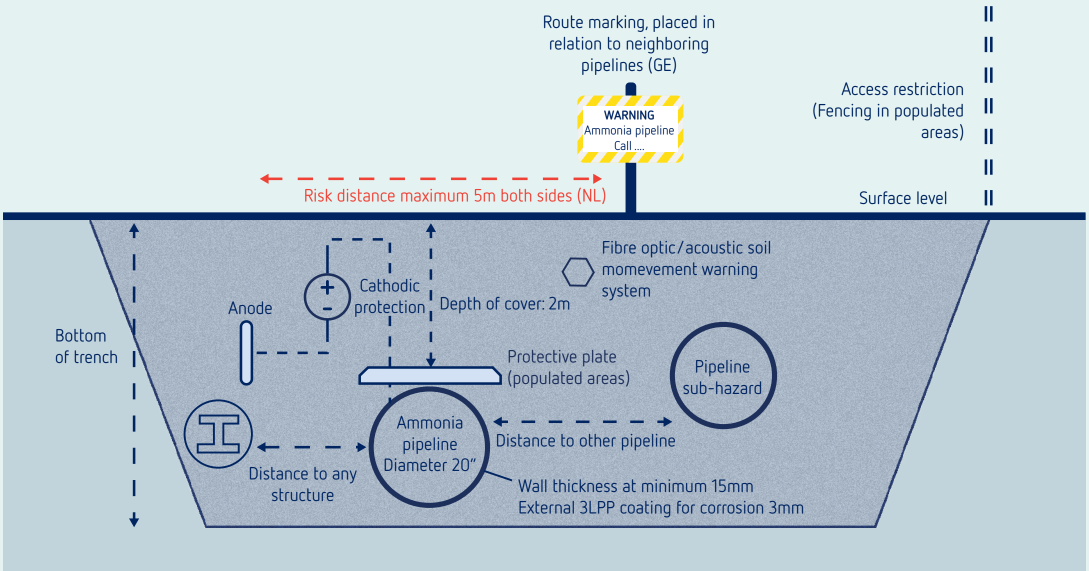


Figure 13: Pipeline Trench[10]

In practice, this safe distance could be created in a corridor's protective strip (for the DRC a 60 metre strip has been reserved). Common practices include (buried) warning ribbons, signposting of the corridor as well as rules for the approval of excavation and construction. On the basis of the QRA in Section 6, this project recommends burying the ammonia pipeline at a depth of 2 metres so there is less risk of it being hit during excavations or ploughing. For reference, chemical pipelines are typically buried at 1.2 metres and natural gas (NG) transport pipelines are usually at a depth of 1.5 metres. The corridor could also be fenced off to limit access, however this is not always feasible due to agricultural use. In these instances, the project recommends providing protective plates instead to reduce the risk of failure due to accidental damage. Automated leak detection (e.g. fibre optics), cathodic protection and a coating for external corrosion protection are best practices and should be in place. In addition, an acoustic soil movement warning system is recommended for sensitive areas. Stipulations pertaining to distances to existing (registered) pipeline (chemical) services, structures and other cables and pipelines should be adhered to.

External Coating

Ammonia pipelines can suffer from external corrosion caused by a combination of water, oxygen and bacteria in the soil. To prevent this, the ammonia pipeline should be coated externally. A three-layer polypropylene (3LPP) coating is specified, composed of a high-performance, fusion bonded epoxy (FBE) primer, a copolymer adhesive (mid-layer) and an outer polypropylene layer. A total thickness of 3 mm would be sufficient for this application.

Cathodic Protection

Over time, coatings can suffer from external damage during construction and operation. To mitigate any corrosion at the damaged sites, a cathodic protection (CP) system should be used to supress external corrosion at coating defects. An impressed current cathodic protection (ICCP) system is used for long, large-diameter onshore pipelines. The ICCP system includes an external power supply, often a transformer rectifier, which converts AC power from the grid into DC power. The power supply could be located at the valve stations.

Leak Detection

A leak detection system should be implemented as per local regulations pertaining to pipeline safety. The design should include a recommended leak detection systems in line with the following:

- Distributed leak detection, for instance, using fibre optic cable trenched together with pipeline, which could provide immediate detection of a full range of leaks, provides the option to localise a leak and can also be used to safeguard pipeline integrity
- Pressure alarm in the pipeline for the immediate detection of larger leaks and catastrophic failures due to rupture, followed by operator action or automatic ESD
- Permanent, above ground, gas detectors at valve and pumping stations for the detection of small to medium leaks
- Regular monitoring by means of frequent patrols, for example, using drones and on foot to detect signs of pipeline leaks and to confirm suspected deviations.

Key finding

A safe design was proposed based on hazard identification, credible scenarios, preventive reduction measures, mitigating measures, and emergency response and control. The design comprises an emergency shutdown system (ESD), segmentation through ESD valves, flow assurance modelling for pipeline sizing, materials selection and external coating addressing corrosion, a booster pumping station with collection systems, pig launchers and receivers, leak detection, burial depth and trench design.

6 QRA Results

Introduction

The main objective of the QRAs was to calculate the hazards addressed in Section 5 i.e. external safety risks to society associated with operating an ammonia pipeline transporting 222 kg/s liquid ammonia at 50 or 100 barg. The two scenarios with pipeline rupture and leaks for the three pipeline designs (Table X) were used as the basis for the QRA calculations. QRAs were prepared using SAFETI.NL software for the pipeline and pumping stations to determine the risk contours to an individual civilian present at specific location (LSIR) of an accident with a probability of 1 in 1 million years and a fatality effect. In addition, maximum effect distances, defined as focus areas protecting groups of people, were determined on the basis of a worst-case release scenario, which is a pipeline rupture. Several sensitivity analyses were performed to assess the impacts of various parameters such as segmentation using variable distances between ESD valves. This section presents the main results from the study conducted by DNV.[55]

Risk Reduction Measures

The presence of certain risk reducing[56] measures can be used to justify a lower failure frequency for a pipeline. Module V of the Dutch calculation method specifies a number of risk reducing measures and factors that can be applied as part of a permit issuing procedure.[23] If these measures are present in the design and implemented, they can be used in the QRA to grant a permit. The risk reducing measures are split up into seven clusters. Only one from each cluster may be selected and used in the QRA to lower the failure frequency. In addition to the measures listed in Module V, the explanation of the calculation method contains additional measures that – in consultation with the competent authorities – can be used in a QRA. These additional risk reduction measures must be incorporated into the permit for the safe design and operation of the ammonia pipeline.

Selection for Basic and Proposed Designs

The clustered measures and the additional measures are presented in Table 4. The last column represents a selection of risk reducing measures as proposed for this project based on the design in Section 5. Next to this, a basic selection of reduction measures, without additional measures was used to represent common practices. This allows an overall failure frequency to be obtained for the selected reduction measures for both the proposed and the basic design case in the QRAs to assess the respective risk contours. The latter assessment was conducted for the three pipeline diameters considered, known as the base, alternative and reference case.

55 24-1700 DNV Report Ammonia Pipeline QRA 2.0, DNV, 2025 (confidential)

56 The Calculation module refers to risk reduction as preventive/ control barriers, reducing the failure rate or likelihood of events.

Table 4: Risk Reduction Measures

Category	Reduction measures	Risk reduction measures for a basic design case	Risk reduction measures for proposed design case
Depth	Burial depth below ground to reduce failure rate due to damage	1.2 metres	2 metres
Cluster 1	Active Reminders, comprising information exchange	Included	Included
Cluster 2	Covering, including underground protective plates and warning ribbons	Protective plates (partly)	Underground protective plates, if fences are impossible and warning ribbons
Cluster 3	Controls, imposing rules and regulations for prohibiting digging/drilling to various degrees	Limited restrictions	Digging/drilling prohibited
Cluster 4	Physical barriers such as fences, etc. as long as these do not hamper agriculture or other land use	No measures, usually part of an existing corridor	Fences, if possible
Cluster 5	Other provisions, e.g. supervision of works	No measures	Surveying and supervision of work
Cluster 6	Additional ground cover (m), increasing elevation and burial depth	No measures	No measures
Cluster 7	Minimum wall thickness (WT) 15 mm	A WT of 15 mm was assumed	In this study the minimum WT is in accordance with the required mechanical design pressure: 15 mm for 32" diameter, 15 mm for 20" diameter and 19 mm for 18" diameter
Additional	Mechanical failure	Not considered	Mechanical failure can be controlled using materials selection and by reducing the operating pressure to below a mechanical parameter <30% SMYS
Additional	Internal corrosion	Medium is non-corrosive to selected material, also 0.2% water is present	Medium is non-corrosive to selected material, also 0.2% water is present
Additional	External corrosion	External coating is applied	In addition, external corrosion of pipeline can be controlled using cathodic protection
Additional	Natural causes	Not considered	Natural causes can be ruled out due to routing and design
Additional	Operational and other causes	Not considered	Calculated SIL+1

The main differences between the reduction measures and factors (see Annex 4) and between the proposed design and the basic design lie in the burial depth, procedural measures (Clusters 3 and 5) and the additional measures. For instance, the normalised failure rate for damage by 3rd party can be reduced by a factor of 16 if a 2 metre burial depth is used, whereas for 1.2 meter this factor is 2.3. Another example is the operation reduction measure SIL+1, which was discussed in Section 5, which adds a factor of 10. The WT 15 mm is assumed to be the same due to the same pipe diameter and design pressure rating. Geotechnical surveys, provisions and the route are the pre-conditions for stating that natural causes can be ruled out.

Total Pipeline Failure Frequency

Based on a selection of reduction measures, a total failure frequency or rate can be obtained using the aggregate of prescribed failure rates and respective reduction factors as listed in Annex 4. Figure 14 shows for the proposed design with 20" pipeline how a lower total pipeline failure frequency, due to increasing the number of reduction measures leads to a lower risk contour. The 10^{-6} per year risk contour (LSIR) due to a loss of containment corresponds to a distance along a pipeline. This failure rate is calculated for a suggested combination of scenarios with a ratio of 3:1 for leak to rupture, as prescribed by the QRA software. The dotted line indicates the cut-off failure rate as result of the selected risk reduction measures. The dotted line should be left to the intersection with a horizontal line representing the imposed 5 meter distance (see Table 2), which is approximately the x-axe.

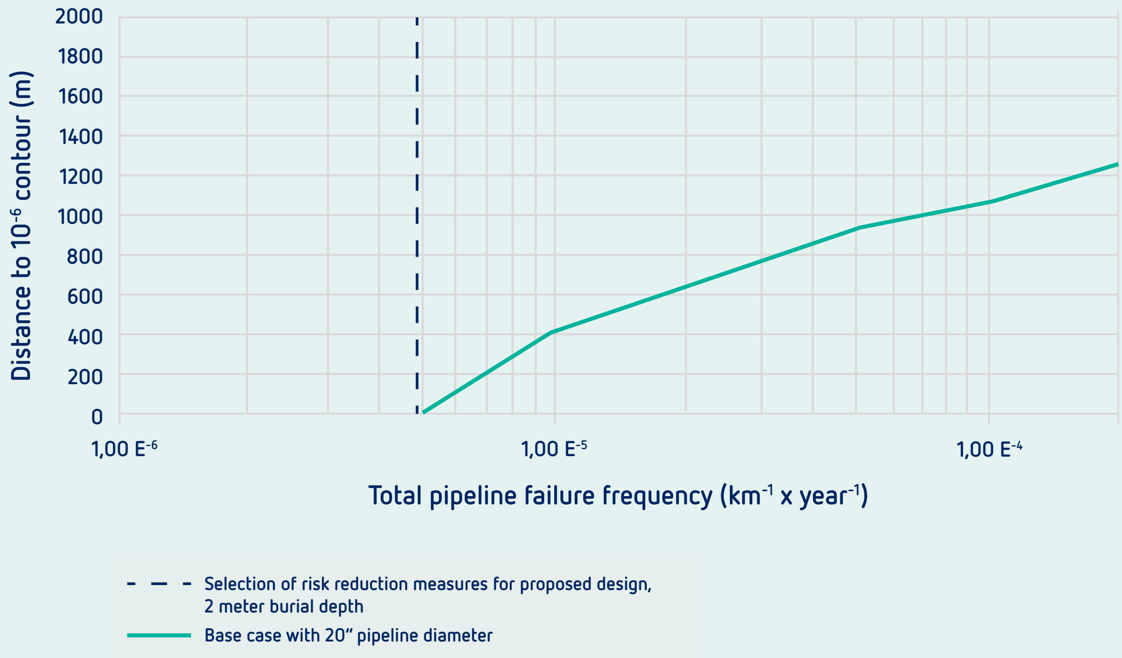


Figure 14: Impact Failure Frequency (20" pipeline) with Regard to Risk Distance and Maximum Failure Frequency [55]

Sensitivity analysis conducted on the failure rates reveals that for lines with a 20" diameter, the 10^{-6} per year risk contour distance can be reduced to below 5 metres using the proposed selection of measures from Table 4. The inverse of the total failure rate is the mean time between failures (MTBF), the number of estimated years of operation without failures based on the 3:1 leak to rupture scenario. This means that no failures could statistically happen for 300 years across the entire pipeline's length, which is much longer than its technical lifespan of 50 years.

Figure 15 indicates the other pipeline diameters and also the impact of reduction measures without implementing additional measures or implementing no measures at all from the Dutch guidelines. The 18" pipe diameter shows similar results as the 20"pipeline meeting the required 5 meter distance. The distance representing the 10^{-6} per year risk contour is slightly lower for the 18"pipeline at the same failure frequency having the same set of reduction measures, due to the smaller effect of a gas cloud. Regarding the 32" pipeline, even if all the (additional) measures are implemented to lower the failure frequencies, the distance still exceeds the 5 metres by the 10^{-6} per year risk contour, due to the release of a larger gas cloud.

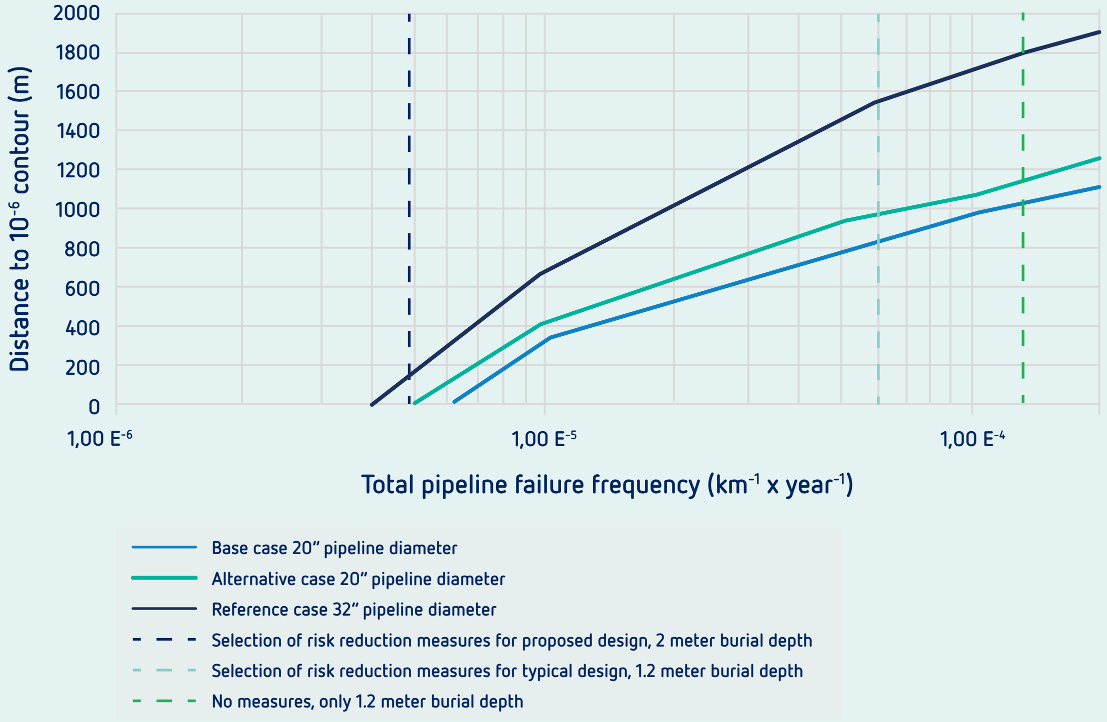


Figure 15: Sensitivity Analysis for Three Pipe Diameters Regarding Failure Frequency on Risk Distance [55]

The dotted blue line represents the total pipeline failure frequency for the basic case having fewer reduction measures (basically only Module V). In this case, the failure frequency would be roughly 10 times higher than needed to achieve the required 5 meter resulting in a 10^{-6} contour of more than 800 meter. This is not allowed in the Netherlands. The estimated MTBF would be 30 years for the basic case, which is indeed not tolerable were an accident to happen during the lifetime of the pipeline. The dotted green line represents the total pipeline failure frequency for a pipeline, having no reduction measures in place (other than designed WT≥15mm with proper material selection at 1.2 meter dept). The calculated distance is more than 1000 meter equivalent to a MTBF of 13 years.

Additional measures that are not included in the Dutch guideline will have to be implemented to further reduce this. New measures, such as a double walled pipe design (PiP) might be approved for use to further reduce the failure frequency of the pipeline, in consultation with and justified to the relevant authorities. The PiP design could be promising, but requires extensive substantiation of proven state-of-the-art technology and failure rates. For now, the 32" diameter pipeline for ammonia presented by this project remains non-compliant.

Key finding

The proposed design and selection of risk reduction measures enables the risk contour of a 20" pipeline to be reduced to below the legally required 5 metres. The large-scale clean ammonia pipeline from Rotterdam to Germany can be made to comply with Dutch standards as well as utilising German state-of-the-art techniques.

QRA Pumping Stations

Pumping stations will be subject to SEVESOIII requirements and should therefore be equipped with process safety management systems as well as have a planned out emergency response which the company is prepared to implement, see Section 5. It is envisioned that such pumping stations would be at a location of on existing industrial site along the route as long as this is in line with the hydraulic calculations. A permit application should also include a QRA for the 2 pumping stations for the 20" or the 3 pumping stations for the 18" pipelines.

The failure scenarios for the pumps are expected to dominate the risk profiles for the intermediate pumping stations. A QRA should therefore be performed assuming that the pumping station consists of 3 pumps that are in continuous use with one back-up. The design of the pumps, pipes, valves, process automation and buildings needs further engineering before a more accurate QRA can be drawn up. The proposed failure scenarios for the pumps are as follows:

- Catastrophic rupture of the pump (modelled as a rupture of the feed line to the pump): $1*10^{-4}$ per year
- Leak (10% of the diameter): $4.4*10^{-3}$ per year

The QRA (LSIR) results in a 10^{-6} per year risk contour of 1,800 metres from the intermediate pumping station. The preliminary maximum effect distance or focus area extends to about 4,000 metres from the pump station.

Key finding

The risk contour of a pumping station is around 1,800 meters. The design and operation should follow the SEVESO III requirements. The pumping station should preferably be situated at an industry site.

Focus Areas and Maximum Effect Distances

Focus areas as defined in the Dutch Environmental Act are interpreted as maximum effect distances, see Section 4. This is based on a worst case scenario leading to the release of an ammonia cloud after a pipeline rupture or a pipe rupture (above ground) at a pumping station. The consequences could be potential fatalities among people living at a certain distance from the site. The maximum effect distance was therefore calculated regardless of the preventive measures (Table 4) reducing a rupture's failure rates.

The focus area refers to an applicable intervention value: a lethality threat value (LBW) of 780 mg/m^3 (1,100 ppm under atmospheric conditions) with an exposure of 1 hour (3,600 seconds). The dispersion of a wind-borne gas cloud was modelled using SAFETY.NL software. Figure 16 for example shows the simulation of a toxic gas cloud present at 1,300 to a maximum of 2,300 m at ground level, downwind from the accident, 3,600 seconds after the accident happened.

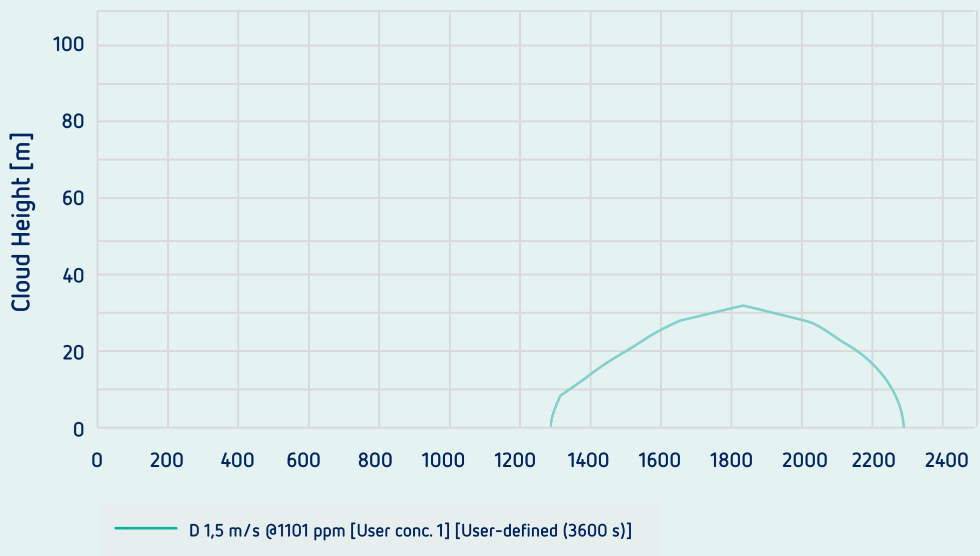


Figure 16: Dispersion of an Ammonia Gas Cloud at 780 mg/m^3 (1,100 ppm) due to the Rupture of a 20" Pipeline [55]

Segmentation Distances

The maximum effect distances (focus areas) have been simulated for a number of cases with different segment lengths and pipeline diameters. Varying the distance between two ESD valve stations between 5, 12, 16 km was employed during modelling to simulate the effect of larger inventories in order to ultimately optimise the design. Table 5 shows for a pipeline with a 20" diameter a maximum distance corresponding to LBW of about 2km. The simulation shows a duration for the ammonia gas cloud concentration to fall below 780 mg/m^3 due to dilution effects from the wind between 2300 and 2900 seconds. The other pipe diameters 18" and 32" were also modelled to show the effect of pipe dimensioning on distances, see Tabel 6 and 7. The distances for the larger, 32" pipeline are about 3 km due to the larger inventory. Also the time for dispersion of an ammonia gas cloud to reach this intervention value takes longer. As expected, the distances and duration for an 18" pipe are a little lower than for the 20" pipe.

Table 5: Focus Areas for 20''/50barg, Full Bore Rupture

ESD valve distances	Max. distance (at LBW)	Duration for cloud conc. <780g/m3 (s)	NH3 left (x106 kg) >1800s (% of total inventory)
5 km	1.9 km	2,300	0
12 km	2.0 km	2,800	0.72 (47%)
16 km	2.0 km	2,900	1.2 (60%)

Table 6: 18"/100 barg, Full Bore Rupture

ESD valve distances	Max. distance (at LBW)	Duration for cloud conc. <780g/m3 (s)	NH3 left (x106 kg) >1800s (% of total inventory)
5 km	1.6 km	2,200	0
12 km	1.7 km	2,700	0.60 (49%)
16 km	1.7 km	2,700	1.0 (62%)

Table 7: 32''/50barg, Full Bore Rupture

ESD valve distances	Max. distance (at LBW)	Duration for cloud conc. <780g/m3 (s)	NH3 left (x106 kg) >1800s (% of total inventory)
5 km	3.0 km	3,000	0
12 km	3.2 km	3,800	1.4 (37%)
16 km	3.2 km	3,800	2.7 (52%)

The findings as discussed are regardless of the segments lengths based on the QRA software simulating releases for up to 1,800 seconds (see Section 2), however the actual release would continue after that. The amount of ammonia left in the segment after 1,800 seconds to 3,600 seconds was therefore calculated by researchers. In 5 km segments, the full inventory will already have been released during the first 1,800 seconds, whereas for 12 and 16 km segments there will be approximately 37 - 62% ammonia left in the pipeline. This volume will also be released into the atmosphere, but at a slower rate due to the reduced pressure in the pipeline. With ESDs every 5 km and using 18" diameter pipes, the focus areas for adhering to the LBW of 780 mg/m3 are limited to a maximum effect distance of 1.6 km from the rupture location. For 20" diameter pipes, this distance increases to 1.9 km and for 32" diameter pipes this increases to 3.2 km. The conclusion is that smaller inventories have a positive effect on protecting the civilian population.

Key finding

For the large scale ammonia service in this project it is suggested that protecting the population from a toxic ammonia cloud resulting from a pipeline rupture can best be achieved by reducing pipeline inventory. This can be achieved by reducing pipe diameters, in this study from 32" to 20", and utilising shorter, for example 5 km, segments between ESD valve stations combined with pumping stations.

Crater Model

This study's findings were based on simulations using the SAFETI model. As is always the case with models, this is a simplification of reality and therefore requires validation. Dispersion is illustrated in Figure 17. Two regimes were introduced to better understand the processes taking place:

- A fast and dynamic process immediately after the accident: liquid ammonia evaporation forms a gas cloud which can travel over great distances depending on the ammonia concentration (in red)
- A slow, more steady state process, starting later and continuing for a longer period of time: liquid ammonia forms a pool of evaporation and a subsequent gas cloud that travels a shorter distance at the same concentration (in green).

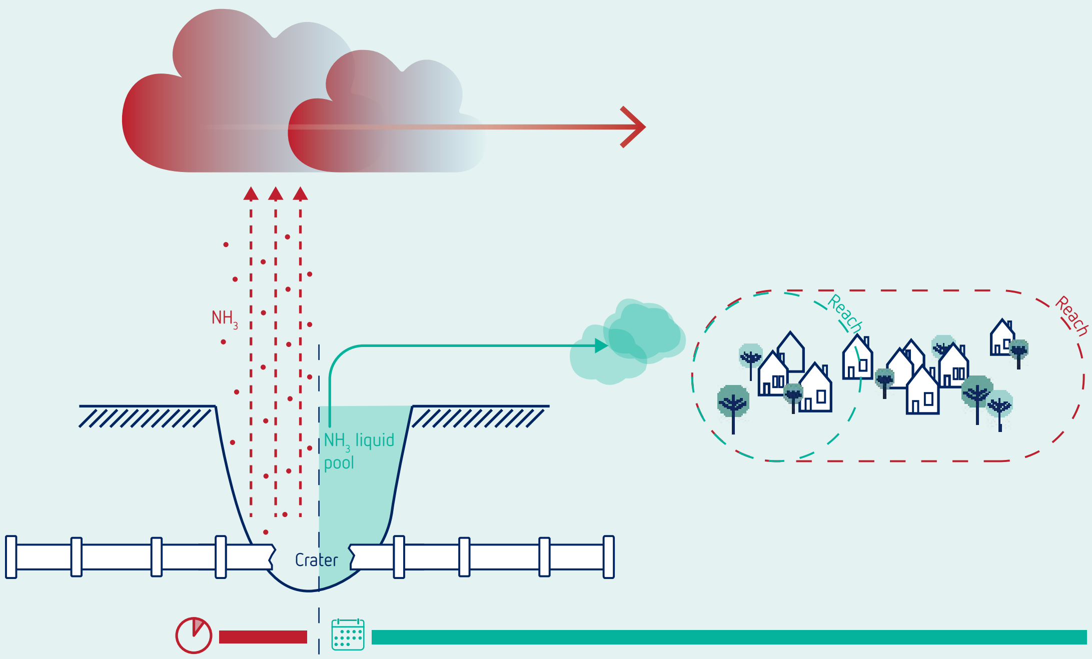


Figure 17: Visualisation of Ammonia Dispersion from a Crater [57]

After some time, the first regime will transfer into the second regime. At first, immediate evaporation (flashing) of the pressurised ammonia flowing from the pipeline occurs due to the drop in pressure of the liquid flow as it emerges from the open pipeline into the atmosphere. After a while, the pipeline pressure of the remaining liquid ammonia is expected to reach the temperature of the (frozen) soil and, as a result, flashing stops.[58] This results in purely liquid ammonia flowing from the pipeline resulting in a pool which evaporates slowly at ambient temperature.

57 Communication with Victor van der Pas, Ministry of Infrastructure and Waterways, 2024

58 The boiling point of ammonia is -33°C at 1 bara; 0°C at 4 bara; 10°C at 10 bara

The simplified crater model described above has a few limitations:

- It assumes that the amount of energy released by the ammonia flow from both sides of a ruptured buried pipeline results in an open crater, exposing the ruptured pipeline and its inventory to the atmosphere. This needs to be validated.
- The heat causing evaporation arises from the soil and subsequently from the air in the immediate vicinity of the crater. It is thermodynamically limited and moreover subject to heat and mass transfer kinetics. This limitation is not fully considered by the SAFETI.NL software, theoretically leading to an overestimation of the initial distance.
- The ammonia cloud would be heavy in the event of aerosols or high humidity and dispersion could also be severely impacted by the terrain. This should be mentioned as an uncertainty, unless it can be argued that the terrain is mostly flat.
- As indicated, the model limits the release of ammonia to 30 minutes (1,800 seconds) whereas in reality the release could continue depending on the inventory. As a result, the dispersion of a significant part of the flashing and pool evaporation might not be modelled. As a result, the distances might also be underestimated.
- In general, the models used require validation for the above processes and assumptions and the dispersion of a toxic gas cloud.

Discussion

This and other referenced projects seem to suggest that the software model is not validated for scenarios with rupture and leaks concerning large-scale ammonia pipelines. Clearly, some work still needs to be done to improve and validate the QRA models. As explained, the industry and authorities are obliged to use SAFETI.NL dispersion modelling, which as demonstrated above still entails certain uncertainties with regard to the fundamentals of the crater model. Model validation for the scenarios in a similar ammonia service is crucial, but yet to be carried out. The model also limits the release of ammonia to 30 minutes (1,800 seconds) whereas in reality the release could continue for longer depending on the pipeline's inventory. These reservations influence the interpretation of the QRA results for justifying maximum effect distances (focus areas) and risk contours. Challenges exist concerning the harmonisation of NL-DE-(BE) regulatory aspects for cross-border pipelines, for motivating state of the art (best) practices and capping focus areas at 1,500 m when it comes to spatial planning.

Key finding

The modelling results concerning risk contours and maximum effect distances have been determined, but should be taken with care. It is crucial that the model is validated for large ammonia releases due to pipeline ruptures. The QRA and dispersion model have limitations and uncertainties, which need to be addressed. Simultaneously, the approach to and emphasis on the design's safety aspects is paramount to ensure the safe operation and maintenance of a long-distance, large-volume ammonia pipeline.

7 Economics

This section outlines the investment costs (CAPEX) for the creation of the entire pipeline project as well as the annual costs for operation and maintenance (OPEX. The purpose is to determine the costs for the safe, compliant design and operation of the pipeline based on the design proposed in Section 5 and the accompanying reduction measures and ESD valve distances as discussed in Section 6. The costs of a basic design based on common practices will also be presented as a comparison, even though it is viewed as non-compliant in Section 6. The difference provides an indication of the additional CAPEX and OPEX costs required to make such a clean ammonia service safe and compliant.

CAPEX and OPEX

Budgetary OPEX and CAPEX estimates have been prepared, see Table 8.[59] The costs are presented for the 18" and 20" pipelines specified concerning the proposed and the basic design as well as the risk reduction measures concerned, see Table 4. The proposed design includes all the reduction measures, a 2 metre burial depth and 5 km segments between ESD valve stations. The basic design has fewer reduction measures, is buried at 1.2 metres and has 16 km between ESD valve stations as it reflects common practices.

The differences are summarised in Table 8 and show the extra expenditure required to become compliant. The CAPEX estimate for the 18" and 20" pipelines is 2,100 Mio EUR. The cost estimate for the basic design is 1,600 Mio EUR. The costs for the 18" and 20" pipelines are in the same order of magnitude, given the high level of inaccuracy. The costs for the 32" pipeline are not relevant as this appears non-compliant. Similarly, the annual costs, comprising OPEX and annualised capital costs, amounts to 310 and 240 Mio EUR/a for the proposed and the basic design, respectively.

Table 8: Total CAPEX and OPEX [5]

Costs in Mio Euro (+100/-50% accuracy) for 18"/20" pipeline	Basic design, only standard measures, 1.2 m depth, 16 km distance ESD valve stations	Proposed design with all reduction measures (incl. additional) and 5 km distance ESD valve stations	Difference
Total CAPEX	1,600	2,100	500
Total annual costs	240	310	70

The difference between the proposed and the basic design reveals a difference in CAPEX of 500 Mio EUR, which is roughly 31% higher. The annual costs increase is estimated at 70 Mio EUR/a or 29% higher. An approximately 22 - 32% increase can be observed based on the sensitivity analyses and a more differentiated combination of reduction measures. The estimated transport costs equal 0.078 EUR/ton NH3/km or 0.5 EUR/ton H2 equivalent/km.

Table 9 provides a cost breakdown for this project's CAPEX estimate. This reveals that the pipeline's material and installation costs, followed by the building of 110 valve stations are the dominant scope items.

59 ISPT - Phase D Ammonia Pipeline CAPEX OPEX Estimate 25-0128 Rev. 1

Table 9: Indicative Cost Breakdown [59]

Costs in Mio Euro	This project, proposed design and risk reduction measures
Pipeline	71%
Valve stations	21%
Pumping stations	2%
Protective plates	3%
Other	3%

One of the points for discussion is the initial filling of the pipeline with ammonia and the associated (high) costs this represents. This has not been included in the CAPEX yet. This needs to be further examined in future planning stages as there are different ways of conducting the first fill.

Benchmarking

The costs could be benchmarked with respect to hydrogen pipelines. Investment costs for the Dutch hydrogen backbone are now estimated at roughly CAPEX 3,800 Mio EUR. This was based on updated figures (excl. capital costs), which were previously estimated to be 1,500 Mio EUR, 1,200 km of combined refurbishment of NG pipelines and new pipelines.[60] The cost increase is due to the need for more new vs refurbished pipelines, inflation and increased labour and material costs.

In this study, transport costs were estimated to be 0.50 EUR/ton H_2 equivalent/km. According to a 2021 European hydrogen backbone study, the transport costs would amount to 0.27 EUR/ton H_2/km. Using the same assumptions for OPEX and inflation and escalation correction this would lead to 0.5 EUR /ton H_2/km. This is similar to what the current study determined.

Decision Making

In conclusion, the findings can be used for decision-making regarding the development and operation of ammonia pipelines, emphasizing the importance of safety and cost efficiency. More accurate cost estimates and informed decisions can be made in the front-end engineering design to move forward with this or similar projects at specific locations. The ongoing discussions at a national level, as part of cross-border cooperations and in the EU are expected to have a major impact on the justification of the investments needed for the energy transition, reaching energy independence and making Europe more competitive.

60 Kostenraming voor waterstoftransport geactualiseerd › Gasunie

Key finding

The CAPEX estimate for the 20" pipeline case study is 2,100 Mio EUR based on the proposed safe and compliant design. The cost estimate for the basic design which reflects common practices and does not appear compliant amounts to 1,600 Mio EUR. The 500 Mio EUR difference provides an indication of the additional CAPEX required to make such a clean ammonia service safe and compliant. This would be a 31% CAPEX increase. The annual costs, comprising OPEX and annualised capital costs, amount to 310 and 240 Mio EUR/a respectively for the proposed and the basic design. The annual costs increase are estimated at 70 Mio EUR/a or 29% higher. The pipeline materials and installation costs followed by creation of 110 valve stations are the dominant scope items. Based on these figures, the transport costs are estimated at 0.50 EUR /ton H_2 equivalent/km. According to a European hydrogen backbone study (2021), and corrected for inflation and escalation, the transport costs for hydrogen today would also be around this figure of 0.5 EUR/ton H_2/km.

8 Key Findings and Recommendations

Key Findings

The Ammonia Pipeline Safety study assessed the necessary design and risk reduction measures for the long-distance pipeline transport of large volumes of liquid anhydrous ammonia through rural and densely populated areas. A pipeline design has been proposed for a 7mtpa pressurised ammonia service from Rotterdam to Germany. Safety studies with HAZIDs and QRAs have been conducted to optimise the design. The impact of accidents with pressurised ammonia transfer through pipelines on society is evaluated in terms of risk contours and maximum effect distances defined as focus areas. It has been determined that all risk reduction measures should be in place in line with the applicable regulations, codes and standards.

The Netherlands and Germany's legal frameworks were also screened and compared. At first sight, the approaches look different between the two countries, as the former applies a risk-based approach whereas in Germany an adverse effects to people and nature (and also risks) is used. The principles employing focus areas as in the recently implemented Environmental Act in the Netherlands and in the avoidance criteria in Germany could both be considered as effect oriented, although they approach the issues from different angles, reducing/respectively avoiding effects. The incorporation into state-of-the-art techniques in design, practices and methods in Germany has also been adopted in the risk-reduction measures and factors incorporated in the Dutch Calculation modules.

The proposed design comprises hydraulic calculations, intermediate pumping stations, materials selection, process safety measures, pipeline trench design and emergency response. Three cases with different pipeline diameters were compared: 18" and 20" diameters with booster pump stations and, for reference purposes, a 32" diameter with a single pumping station at the import terminal. To meet the legally required maximum 5 metre risk contour, a deeper burial depth of 2 metres and additional reduction measures have to be incorporated in the permit to safely design and operate the ammonia pipeline.

Focus areas can be simulated using dispersion models to assess maximum effect distances that meet the LBW value of 780 mg/m3 after 1 hour of exposure. It can be concluded that smaller inventories have a positive effect on the protection of the population. At 5 km distances between ESD valve stations and an 18" pipe diameter, the maximum effect distance is 1.6 km to the location of the pipeline rupture. For a 20" pipe diameter, this distance is 1.9km and for a 32" pipe this is 3.2 km. For the ammonia pipeline considered by this project, it is suggested that safe design, peration and maintenance of a long-distance, large-volume ammonia pipeline. can be achieved by reducing pipe diameters from 32" to 18" or 20", installing intermediate pumping stations and shortening segment lengths between ESD valve stations to, for example, 5 km.

The pumping station will be subject to SEVESOIII requirements and a process safety management system should therefore be installed and the emergency response and preparedness should also be taken care of. Such pumping stations should preferably be built at existing industrial sites along the route.

Industry and the authorities are obliged to use QRA dispersion modelling software (SAFETI.NL), which still has uncertainties concerning its fundamentals and is not validated for ammonia pipelines. The findings of this QRA study therefore should be taken with care. At the same time, the approach to and emphasis on including safety aspects in the design is paramount to ensuring the safe operation and maintenance of long-distance, large-volume ammonia pipelines. The acceptance and inclusion of all the risk reduction measures discussed is therefore necessary to meet legal requirements.

The CAPEX and OPEX were estimated at budgetary level (-50%/+100%), including 50% contingency. The CAPEX estimate for the case study with a 20" pipeline is 2,100 Mio EUR based on the proposed safe and compliant design. This would mean a 31% CAPEX increase. The annual costs, comprising OPEX and annualised capital costs, are 310 and 240 Mio EUR/a respectively for the proposed and the basic design. The annual costs increase is estimated to be 70 Mio EUR/a or 29% higher. An approximately 22 - 32% increase can be observed in the model to if the ammonia service is made safe and compliant. The cost of ammonia transport in terms of EUR/ton H_2 equivalent /km is similar to that reported in literature for a hydrogen backbone in Europe.

Recommendations

A front-end engineering and design study is necessary to improve the project definition and increase the accuracy level of the cost estimate for each dedicated project. The proposed design and key findings can be used as guidance. Some limitations can be observed in the modelling, which require follow-up.

- The (crater)model assumes that the amount of energy released by the ammonia flow from both sides of a ruptured buried pipeline results in an open crater, exposing the ruptured pipeline and its inventory to the atmosphere. This needs to be validated.
- The heat causing evaporation arises from the soil and subsequently from the air in the immediate vicinity of the crater. It is thermodynamically limited and moreover subject to heat and mass transfer kinetics. This limitation is not fully considered in the SAFETI.NL software, theoretically leading to an overestimation of the first distance.
- The ammonia cloud would be heavy in the event of aerosols or high humidity and dispersion could also be severely impacted by the terrain. This could be mentioned as an uncertainty, unless it can be argued that the terrain is mostly flat.
- As indicated above, the model limits the release of ammonia to 30 minutes (1,800 seconds) whereas, in reality, the release could continue for longer depending on the pipeline's inventory. As a result, the dispersion of a significant part of the flashing and pool evaporation might not be modelled. It could also be argued that as a result the distances would be underestimated.
- In general, the models used need validation for the above mechanism and dispersion of a toxic gas cloud.

It seems recommendable to agree with the authorities that the requirements in the Calculation Module need to be reconsidered in terms of legally including the additional ('explanation') risk reduction measures. Meanwhile, these additional risk reduction measures must be incorporated into the permit for safely designing and operating an ammonia pipeline.

This project suggests defining state-of-the-art techniques on the basis of the Netherlands' risk-based approach with required reduction measures. As such this could be applicable to German state-of-the-art techniques in accordance with the Pipeline Ordinance (RohrFltgV) and the Technical Regulations (TRFL). A more design oriented approach, following developments in state-of-the-art design practices, as implicitly intended in Germany, is recommended.

A common approach for the EU including the Netherlands and Germany is advocated for long-distance ammonia pipelines as well as hydrogen and other energy carriers to help meet energy transition challenges in Western Europe.

Annex 1 List of abbreviations, definitions and clarifications

Table 10: List of Abbreviations, Definitions and Clarifications

Reference	Definitions and clarifications
ALARP/ALARA	As Low As Reasonably Practical, used in risk assessment to determine which risks are (in) tolerable. As Low As Reasonably Achievable, is used in risk assessment as a synonym. Whether the risks are tolerable depends on whether the efforts to reduce risks should be continued until the incremental sacrifice is grossly disproportionate to the incremental risk reduction achieved.
Ammonia	Ammonia (NH_3) is an important nutrient for agriculture, as well as for humans for proteins. It contains 83% nitrogen. It is also known in diluted form (5 - 10 vol%) as a household cleaning agent. Anhydrous ammonia (containing no water) is a well-known building block for fertilisers, explosives and is used by the chemical industry. It is also used as refrigerant in, for example, heat pumps. Trade-quality anhydrous ammonia is at least 99.5 vol% NH3. Anhydrous ammonia is labelled T-toxic. Its toxicity depends on exposure and concentration (expressed as LBW). Liquid ammonia evaporates rapidly under atmospheric conditions and is very water-soluble.
Bal	Activity Environmental Decree *(Besluit Activiteiten Leefomgeving)* is part of the Environmental Act (NL)
Bkl	Quality Environmental Decree *(Besluit Kwaliteit Leefomgeving)* pertains to spatial planning *(inpassingsplannen)* and is part of the Environmental Act (NL).
BEVB	External Pipeline Safety Decree *(Besluit Externe Veiligheid Buisleidingen)* for pipelines transporting dangerous substances including chlorine, ethylene, propylene, ammonia, ethylene oxide, hydrogen, carbon monoxide and carbon dioxide, regulates the pipeline operator's tasks and responsibilities. The BEVB refers to Calculation Module V for pipelines to determine the external safety distances using a QRA. This Degree expired on 1 January 2024. Its scope is now covered by the Environmental Act, which also refers to the Calculation Modules.
Bow tie	A risk assessment method focusing on activity risks considered Major Accident Hazards (MAH), where there is a potential for fatalities, significant damage to assets as well as environmental impact. Threats, Event, Consequences and Barriers illustrated together look somewhat like a bowtie.
BW	German State Baden-Würtenberg. A relevant stakeholder due to the route to Karlsruhe.
Calculation Module V	RIVM makes the use of prescribed calculation modules *(Rekenvoorschriften)* of which Module V applies to pipelines. These calculation modules are in line with the Bkl in the Environmental Act and aim to calculate the individual risks (LSIR) and effects in terms of focus areas of activities impacting the environment and society. Modules I and II apply to (SEVESO) sites' equipment and relevant to pumping stations. Calculation package SAFETI-NL Version 8 (2021 edition) or higher should be used. An Addendum to calculation Module V (Section 15) elaborates on the conditions for the application of improved (lower) failure frequencies relative to more general failure frequences for pipelines. Important conditions are requiring state-of-the-art pipelines including safety management system and more elaborate risk reduction measures.
CAPEX	Capital Expenditures or investment costs (Euro) for the design, construction and starting up of the pipeline, excluding depreciation.
Clean ammonia	Similar to hydrogen, ammonia (NH_3) can also be described using the colours 'green', 'blue' and 'grey'. Both blue and green types are often referred to as 'clean' ammonia and are viewed as a part of the energy mix required for the energy transition and the decarbonisation of the industry which, in turn, contribute to achieving climate goals. 'Grey' ammonia is produced from natural gas and steam methane reforming (SMR) is used to produce (grey) hydrogen followed by the Haber-Bosch process to yield ammonia from hydrogen and atmospheric nitrogen. Global annual CO_2 emissions from grey ammonia production amount to 2% of total global annual CO_2 emissions.'Blue' ammonia is low carbon ammonia deÞned by using hydrogen based on Autothermal Reforming (ATR) or SMR with natural gas as feedstock combined with Carbon Capture and Storage (CCS). It is suggested as an attainable energy transition carrier and can pave the way for green ammonia.

DCS	Distributed Control System
DN500	Diameter Nominal, internationally standardised internal diameter according to ISO/ANSI/DIN. In this case DN500 refers to approximately 500 mm. Depending on the design pressure, the wall thickness should be added to calculate the external diameter.
DRC	The Delta Rhine Corridor consists of proposed hydrogen and carbon dioxide pipelines from Rotterdam to Venlo which are to be operational in 2032 and the potential addition of an ammonia pipeline at a later stage. This corridor is part of the Structural Vision Pipelines 2012 - 2035 (October 2012), by the Ministry of Climate and Economic Growth in a letter to parliament (5 December 2024). In addition, a HVDC power cable was rejected because of space limitations and therefore another route will be required. An ammonia pipeline is an option, but was not included in the approved DRC procedure. Sufficient space has been reserved to accommodate ammonia pipelines and possibly other commodities in the future. The ammonia pipeline would then continue as a separate project.
Dunkelflaute	The German term Dunkelflaute describes the simultaneous occurrence of darkness and a lull in wind activity. As a result, solar and wind energy yields go down, while electricity demand is seasonally high. A Dunkelflaute can last for several days. The central question remains: how can such periods be effectively accommodated?
EIA	Environment Impact Assessment maps the effects of hazardous activities including large and long-distance pipelines on the environment. According to the Environmental Act, pipelines with a diameter >0.8 m or a length >40 km are subject to the EIA.
ESD	Emergency ShutDown is part of the safeguarding philosophy for (petro)chemical plants or activities and leads to the immediate cessation of operations and moving the plant into safety mod[e.]
Event	An (initiating) event or cause of an accident involving chemical processes and/or human or external factors. Several initiating events can lead to a so-called top event, such as a release, resulting in potentially different consequences. An event is usually part of a scenario.
External safety	The Dutch government has the responsibility to ensure the population’s external safety. Here, external safety is applied in terms of offering protection to people living near routes down which hazardous substances are transported and near to companies that produce, process or store these substances.
FID	Financial investment decision
Focus areas	The 2024 Environmental Act introduces a new approach (aandachtsgebieden). Bal, Article 4.1115 and Bkl, Section D2 of Annex VII mention the requirement to calculate focus areas replacing the External Safety Acts (BEVI, BEVB). Focus areas show where and at which distance people are insufficiently protected from the consequences of accidents involving hazardous substances, in the absence of additional measures and during existing and new activities involving hazardous substances. This means that, in the event of an accident involving hazardous substances, life-threatening hazards may occur to people inside buildings. Extra attention is needed to protect people from possible accidents involving fire, explosions and toxic clouds. This dose-based approach provides insight into the possible effects of an accident with a toxic gas cloud, to what extent this would be life-threatening to the population in the vicinity, expressed by a life threatening or lethality threat value (LBW). The application of focus areas should ensure that local and regional authorities take the external safety of populated areas into account at an earlier stage in spatial planning and incorporate it into emergency response and crisis management plans. The distance is capped at 1.5 km for toxic clouds. Authorities may therefore also issue requirements for the operator during the approval process.
ICCP	Impressed current cathodic protection system
Inventory	Inventory of one or more pipeline segments indicating the applicable volume, representing a monetary value. In this context the inventory relates to the volume which could be released in case of a rupture.
HAZID	A Hazard Identification Study (workshop) is used to systematically identify relevant hazards are in order to evaluate alternative designs, for the direction and resourcing of projects or work safety.
HAZOP	A Hazard and Operability study is used to identify process hazards, deviations, causes and consequences as well as potential operating problems.

Hazard	A hazard is the potential of a substance to cause damage to people, property or the environment.
HDD	Horizontal Directional Drilling of pipelines, e.g. for river crossings
HNS	Netherlands Hydrogen Network Services, developing a backbone owner-operator for hydrogen transport pipelines in the Netherlands and part of Gasunie, the natural gas grid operator. Hydrogen converted from ammonia could also potentially be transported by these networks.
Accident	An event resulting in a release of toxic substance or fire/explosion.
Inherent safer design	A way of thinking about the design of chemical processes that focusses on the elimination or reduction of hazards rather than on management and control. There are four principles: Intensification/minimisation: reducing the volume of hazardous substances potentially released Substitution of hazardous substances Attenuation/moderation: less hazardous conditions or facilities Simplification: eliminating complexity and errors
KGG	Ministry of Climate and Green Growth (Klimaat en Groene Groei)
LOPA	Level of Protection Assessment to determine the independence and reliability of risk reduction measures pertaining to fire, explosions and toxic emissions.
KAS	Committee for safety of installations (Kommission für Anlagensicherheit) part of the German Ministry of the Environment, nature protection and reactor safety (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit). KAS-18 recommends, as a starting point, a green field ammonia site distance of 500 meters or a credible accident release area of 490 mm^2 with an assumed end point of ERPG-2 (150 ppm).
Lethality (contour)	Lethality is calculated on the basis of the dose and duration in a toxic cloud, meaning the time the gas cloud is present at a specific concentration. The dispersion of this cloud leads to a contour or distance from an accident. The assumptions for this contour are: • The maximum effect is considered i.e. no control and reduction measures are in place which would lower the probability of an accident occurring • a person does not leave the area after exposure • no mitigations and emergency response are in place. Usually a 1% lethality rate is referred to as a 1% probability of fatality. This should not be confused with LBW.
LBW	Lethality threat value (Levens Bedreigende Waarde) is a Dutch intervention value and is used by the authorities to determine focus areas for toxic clouds. The LBW refers to an exposure with a duration of 30 minutes, 1 hour or 8 hours. This report considered an ammonia cloud: 780 mg/m^3 (1,100 ppm) with a duration of 1 hour (3,600sec)). The Public Threshold Value (VRW) is 21.3 mg/m^3 (30 ppm) whereas the Level for Odour Awareness (LOA) is much lower at 1.7 mg/m^3 (2 ppm).
LHV	Lower Heating Value which is 18.6 MJ/kg for ammonia.
LOC	Loss Of Containment or the release of hazardous substances into the environment from a closed component, equipment or system, which is the result of an accident scenario or a fire/explosion or a leakage/rupture.
LOPA	Level of Protection Analysis
LSIR	Location-specific Individual Risk (Plaats Risico-PR) is used in external safety and QRA. LSIR in the context of a topographical risk contour or area with a calculated probability of $1*10^{-6}$ or 1 in 1,000,000, leading to at least one fatality per year as consequence to an accident. The located-based individual or personal risk (PR or LSIR) 10^{-6} contour may not extend further than 5 metres from the centre of the pipeline.
MAOP	Maximum Allowable Operating Pressure
MTBF	Mean Time Between Failures, representing the inverse of the total (aggregated) failure frequency.
mtpa	Million Tonnes (1 Tonne is 1,000 kg) Per Annum (year)
MW	Mega Watt (1,000,000 Watt)
NG	Natural gas
NRW	German State North Rhine-Westphalia, a relevant stakeholder due to proposed pipeline route to Duisburg and Cologne.

OPEX	Operational expenditures or annual operational and maintenance costs (Euro).
Permitting	The development and construction of (underground) infrastructure projects such as the DRC will require an extensive spatial planning procedure and environmental impact assessment (EIA). The Ministry of KGG will coordinate this process according to a Government Coordination Scheme (RCR). The latter also ensures that all procedures, spatial planning decisions and the required permits are aligned, so communication and participation is clearly organised.
PFD	Process Flow Diagram
PGS12	PGS 12 Ammonia - Storage and Loading Guidelines for the safe storing and loading of ammonia. These guidelines were completely reviewed and updated to safely accommodate very large volumes of ammonia in double walled concrete storage tanks with vertical shaft pumps.
PLR	Pig Launcher Receiver to clean, inspect, test and check the condition of new or existing pipelines using a pigging device.
PR	see LSIR (Plaats Risico)
PFD	Process Flow Diagram
Process safety	See Risk assessment
QRA	Quantitative Risk Assessment is a method for assessing the risks of the usage, transport and storage of hazardous substances that enables the project team to identify major risk contributors and take action to mitigate those risks. QRA software like SAFETI is based on properties, failure rates, effects, flow dynamics, evaporation/condensation kinetics and dispersion models for hazardous substances based on a loss of containment. The QRA model calculates location-specific individual risk contours for vulnerable and very vulnerable buildings as well as vulnerable locations (LSIR). Focus areas were introduced for societal/group risk metrics in line with the Environmental Act. Risk points allow the determination of risk at any location on a map.
RCR	The Government Coordination Scheme (Rijks Coördinatie Regeling) ensures that large infrastructure projects are carefully incorporated into spatial planning terms and procedures aimed at acquiring project consent.
Risk assessment	A process using risk-based approach that assesses the probability of events, consequences and scenarios to make decisions concerning risk reduction divided into: • process safety hazards: an assessment of (petro)chemical processes to prevent and safeguard against fire, explosion, environmental and toxic emission hazards based on the HAZID-HAZOP-SIL-LOPA methodology, a risk matrix and risk criteria such as ALARP/ALARA. • Environmental Safety Assessment or external safety, largely based on Quantitative Risk Analysis (QRA) • And other risk assessments not elaborated on here such as occupational health, workplace safety (i.e. ATEX) and product safety assessments.
RFNBO	Renewable Fuels of Non-Biological Origin (RFNBO) are gaseous or liquid synthetic fuels derived from renewable electricity and carbon dioxide.
RIVM	Dutch National Institute for Public Health and the Environment (Rijksinstituut voor Volksgezondheid en Milieu)
RohrFLtgV	Pipeline ordinance (Rohrfernleitungsverordnung) establishes technical regulations for pipeline systems (TRFL), for hazardous substances, that reference the state of the art of technology according to German law (Stand der Technik nach Deutscher Rechtsauffassung). It specifies requirements, in particular regarding the TRFL, to avoid any impairment of the welfare of the general public and in particular to avoid any harmful effects on people and the environment. As a result, there is a notification obligation and the operator must ensure that inspections of the pipeline systems are carried out by the notified bodies, especially before commissioning.
SAFETI	SAFETI is a dispersion-model based QRA software solution. SAFETI includes PHAST software to calculate consequence analysis. The latest version, Version 9.0 was released in December 2023. This tool is an internationally recognised method of performing QRA in the Netherlands. For the Netherland, the model SAFETI.NL is applied.

SEVESO III	The SEVESO guideline implemented as BRZO in the Netherlands (Besluit Risico's Zware Ongevallen) concerns the control of major accident hazards involving dangerous substances relevant for industrial sites.
SIL	The Safety Integrity Level is a classification for the availability and reliability-on-demand of an (often) electronic safety device, based on the IEC 61508 or IEC 61511 standards.
SIS	Safety Integrity System
SMYS	Specified Minimum Yield Strength specifies a mechanical parameter (tensile strength) that indicates the amount of stress that has to be applied to steel before it begins to deform permanently.
SRA	Safety relevant plant inventory (Sicherheitrelevante Anlageteile -SRA) as part of SEVESOIII.
State of the art	State of the art is often used in industry to refer to the latest technology. This applied technology level can differ per industrial sector (e.g. nuclear) in part due to requirements imposed such as safety. The pipeline ordinance RohrFLtgV refers to the state of the art as an undefined legal term. In order to avoid the legal system lagging behind advancing technological developments using the generally recognised rules of technology (Allgemein anerkannte Regeln der Technik) as a benchmark, the state of the art (Stand der Technik) is taken as the basis instead.
Reduction factors	According to Calculation Module V, reduction measures categorised into clusters are applicable. Depending on the legal requirements, conditions and economics, all or a selection of these reduction factors can be applied. A reduction factor is used for each reduction measure which, aggregated, leads to a decrease in the probability of a hazardous event. The addendum to Calculation Module V (Section 15) lists additional reduction measures, based on the same clusters, that can be applied to reach the required failure frequencies for pipeline designs if so required.
Safeguarding	Methodology for interrupting a chain of events leading to a loss of containment or that mitigates the consequences of potential harm to people or the environment. There are active and passive safeguards. Active safeguards can be mechanical (e.g. relief valves), instrumental (e.g. ESD valves). Passive safeguards are, for example, procedures. The standard for functional safety using instrumental safeguards is IEC61511.
SCC	Stress Corrosion Cracking is the formation of cracks, owing to the combined action of applied stresses, material properties and aggressive environmental effects, for example from ammonia as a caustic.
TRV	Thermal relief valves
TRFL	Technical regulations for pipeline system (Technische Regeln für Rohrfernleitungsanlagen) § 3 of the RohrFLtgV establishes the basic requirements. Section 2 references the state of the art (Stand der Technik nach Deutscher Rechtsauffassung) as well as the technical regulations. The TRFL as a concretisation of the state of the art, should therefore be viewed as compulsory.
UPS	Uninterrupted power supply or battery for back-up power to ESD functions in the event of a power cut.
UVPG	According to the Environmental Impact Assessment Act (UVPG: Umweltverträglichkeitsprüfungsgesetz) pipeline systems for transporting substances hazardous to water including ammonia over 40 km in length require an EIA. UVPG NRW (Environmental impact assessment act in the state of North Rhine-Westphalia)
Wasserstoff-Kernnetzes	In Germany a hydrogen core network (Wasserstoff-Kernnetzes) will be developed. This will be connected to the HNS backbone.
WT	Wall thickness, internal diameter of a pipe(line), usually in mm or inches.
Weather type D.1.5	In QRA dispersion modelling, Weather Type D.1.5 refers to a specific set of atmospheric conditions used to simulate how pollutants disperse in the atmosphere. Weather Type D indicates neutral stability, which typically occurs during overcast conditions, both day and night or during the hour before and after sunset. 1.5 refers to the wind speed in metres per second (m/s) at 10 metres above ground. This combination of neutral stability and low wind speed is used to model scenarios where pollutants are moderately dispersed, neither rapidly diluted nor remaining concentrated near the source.

Annex 2 Results of HAZID

Table 11: Consequences, Threats and Barriers in a Pipeline Rupture Event

Potential Catastrophic consequences of a Rupture Event	Consequence mitigating or moderating barriers
(Cons.) Domino effect or escalation to other H_2, CH_4 or CO_2 pipelines or critical infrastructure	Physical barriers to domino effect
	Route selection (distance)
(Cons.) Environmental pollution	Enclosures and containments
	Route selection (avoidance or moderation)
(Cons.) Nature reserves, impacting flora and fauna	Route selection (avoidance)
(Cons.) Toxic cloud, fatal in nearby municipalities	Automated leak detection, shutdown and isolation
	Water curtains to capture vapourised NH_3
	Route selection (moderation)
	Frequent patrols to detect and respond to leaks
	Isolation valves close to each other
	Municipality crisis response

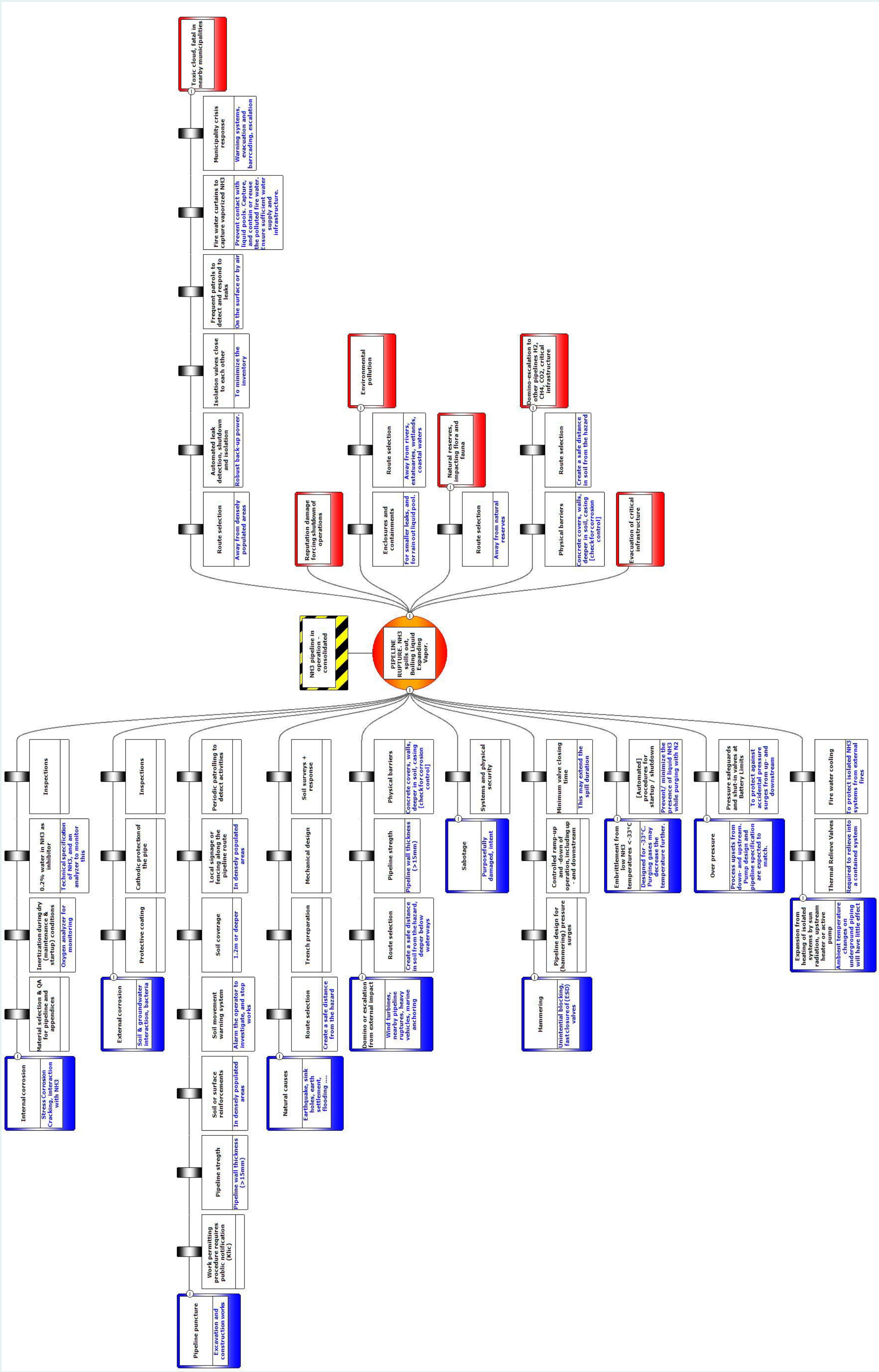
Potential threat for a rupture event	preventing and likelihood-reducing barriers
Domino effect or escalation from external impact	Pipeline strength
	Physical barriers to domino effect
	Route selection (distance)
Expansion from heating of isolated systems by solar radiation, an upstream heater or an active pump	Water cooling
	Thermal Relieve Valves (to process or for recovery)
Embrittlement from low NH_3 temperatures <-33° C	[Automated] procedures for startup/shutdown
External corrosion	Protective coating
	Cathodic protection of the pipe
	Inspections
Liquid Hammering	Controlled ramp-up and down of operations, including up and downstream
	Pipeline design against (liquid hammering) pressure surges
	Minimum valve closing time
Internal corrosion	Material selection & QA for pipeline and appendices
	0.2% water in NH_3 as inhibitor
	Intertisation during dry (maintenance & startup) conditions
	Inspections
Natural causes (earthquake, flood, landslide)	Mechanical design
	Route selection (avoidance, moderation)
	Soil surveys + response

Table 12: Selection of Safety Requirements Related to the Highest Consequence Hazards

#	Technical safety requirement (where relevant, Dutch and German are leading)
1	Do not use copper and zinc for pipes, pipelines and related equipment. Such alloys deteriorate in ammonia
6	Earthquake risk to be evaluated in the design. The pipeline route goes through regions with a (low) risk of earthquake such as Northern Limburg and downstream of Duisburg.
11	Apply interlock pressure safeguard at the interface between the upstream terminal and the pipeline that shuts sections if upstream pressure is lost.
13	As inherently safer design: limit the maximum temperature of the upstream terminal heater or heating medium, to prevent boiling & excess pressure thereby preventing the need for safeguards. Consider using seawater.
14	Engineer the pumps and apply pipeline design in such a manner that there will be no pressure exceedance above design limits. Pressure relief valves as safeguard should be avoided as protection against a pressure loss control loop.
16	Apply sprinklers to protect the aboveground installation against external fire. Although the ammonia flow cools the equipment, any isolated sections will suffer excess pressure and burst.
18	To protect against accidental impacts from excavation, construction work or nearby operations, apply soil or surface reinforcements in high risk areas
19	Increased pipeline depth to protect against accidental impacts from excavation, construction work or nearby operations.
20	Fibre optic/acoustic soil movement warning systems to respond in a timely manner before an accidental impact from excavation, construction work or a nearby operation occurs.
21	Additional pipeline thickness beyond 15 mm in high risk areas. To protect against accidental impacts from excavation, construction work or a nearby operation.
38	Develop a proper start-up procedure (after pre-commissioning) which considers the following: - the pre-startup conditions (emergency shutdown, after inline inspections, Phase B report conditions Paragraph 4.9.4) - oxygen (SCC) - 2 phased ammonia - nitrogen/ammonia treatment if ammonia replaces the inventory - temperature control, with ammonia boiling at -33°C and lower under atmospheric pressure - economic viability - passing of valves between sections and pumps between segments - consumer specifics - depressurisation - isolating and emptying a segment - removing ammonia vapour, not to the air - temperature control - passing of valves between segments - number of pigging stations
43	Research inherently safer design to reduce the need for maintenance, particularly those that required depressurization: - repair corrosion (SCC, external, internal, CUI, ...) - valve replacement - impacts - natural perils

60	Consider cyber-attacks in the design
62	Recommendation concerning ignition/explosion hazards: • in non-confined [open] spaces the ignition of NH_3 vapour leading to a jet fire or explosion is improbable. • areas should be classified (ATEX) within enclosed or confined spaces
65	Although pipeline standards allow for brief (10%) instances of pressure exceeding the design limitations, the inherently safer preference is to design for maximum liquid hammering pressure as caused by the emergency shut-in valve. Estimated at approx. 18 bar. Also take the inertia of the volume of ammonia flowing down the pipeline into account.

Annex 3 Bow tie



Annex 4 Failure Frequencies and Risk Reduction Factors

The failure frequencies for a pipeline in a Dutch QRA consist of two parts: base frequency, which depends on the type of pipeline; and final frequency, which takes into account certain preventative risk reducing measures.

Base frequency

The Dutch Risk calculation method environmental safety specifies two sets of failure frequency data for a chemical pipeline. One for a “state of technology” (stand-der-techniek) chemical pipeline and one for a pipeline that is not “state of technology”. For a pipeline to be considered “state of technology” the following conditions must be met.

General	The use of an effective safety management system, article 4.1111 of the Bal and 0/NEN3655.
Third party damage	• Clear above ground marking of the pipeline that is visible from each viewing angle. This rule can be deviated from in case of practical limitations such as corners, foliage and obstacles. • Periodical communication with landowners to make and keep them aware of the presence of the pipeline. • Implemented KLIC/WIBON system with active reminder.
Mechanical	• For pipelines built before 1980: availability of the mechanical assessment of the pipeline. • For pipelines built after 1980: None, this is covered by greatly improved quality checks and quality control (QA/QC) during the building stage of the pipeline.
Internal corrosion	Corrosion management system containing: • Determining the corrosive properties of the product. • Implementing design measures based on the corrosive properties; (e.g. corrosion allowance in wall thickness, using of corrosion inhibition, using of corrosion resistant steel alloys for the pipe wall and potentially using internal coating / liner). • Effective monitoring program (e.g. safeguarding product quality via sampling, chemical injection, sampling for metal deposits).
External corrosion	Usage of appropriate coating and cathodic protection in accordance with NEN 3654. Effective monitoring program for cathodic protection and coating.
Natural causes	The structural design in relation to settlements and stresses is known, documented and appropriate provisions have been made.
Operational and other failure causes	• Specified working envelope with regard to flow rate, pressure, temperature, trip settings. • Automated process monitoring and process safeguards. • Monitoring relevant DCS or SCADA data to continue operating within this working envelope. • Changes in working envelope are only permitted through established procedures, such as Management of Change (MoC).

The base failure frequencies for a state-of-the-art pipeline and for a pipeline that is not state of technology are provided in the table below.

Failure cause	Failure rate chemical pipeline ($km^{-1}year^{-1}$)		Failure rate state of technology chemical pipeline ($km^{-1}year^{-1}$)	
	Rupture	**Leak**	**Rupture**	**Leak**
Damage by 3rd party	7.19E-05	9.86E-05	1.77E-05	2.63E-05
Mechanical	3.23E-05	1.45E-04	7.96E-06	3.86E-05
Internal corrosion	5.71E-06	4.40E-05	1.41E-06	1.17E-05
External corrosion	1.72E-05	1.32E-04	4.25E-06	3.52E-05
Natural causes	9.15E-06	1.35E-05	2.26E-06	3.60E-06
Operational/other	1.38E-05	1.71E-05	3.40E-06	4.56E-06
Total	**1.50E-04**	**4.50E-04**	**3.70E-05**	**1.20E-04**

The failure rate for damage by 3rd party can be reduced by a factor of $e^{-2.4\,x\,(0.84-z)}$, where z is equal to the depth of the pipeline in meters.

Risk reducing measures

The presence of certain risk reducing measures can be used to justify a lower failure frequency for the pipeline. Module V of the Dutch calculation method specifies a number of risk reducing measures that can be applied. If these measures are present, then they can be used in the QRA.

In addition to the measures listed in module V, the explanation of the calculation method (*toelichting*) contains additional measures that can be used in a QRA in consultation with the relevant authorities.

The risk reducing measures are split up into "clusters", for each cluster of measures, only one can be selected and used in the QRA to lower the failure frequency. The table below shows all the risk reducing measures that are contained in the Dutch calculation method. Additional information on the requirements for each risk reducing measure are provided in the Calculation method.

Measures not included in the calculation method (such as a double walled pipe design) might still be allowed to be used to further reduce the failure frequency of the pipeline, but this requires extensive substantiation and consultation with relevant authorities.

Failure cause	Cluster	Measure	Reduction factor	Reference
Third party damage	Cluster 1	No measures	1	Module V
		Active reminders	1.2	
	Cluster 2	No measures	1	
		Warning tape	1.67	
		Protective plates	5	
		Warning tape + protective plates	30	
	Cluster 3	No measures	1	
		Far reaching restrictions	100	
		Digging/drilling prohibited	10	
		Limited restrictions	1.6	
	Cluster 4	No measures	1	
		Fence	Infinite	
		Dike	10	
		Barriere at ground level	8	
	Cluster 5	No measures	1	
		Supervised work	2.5	
		Camera supervision	2.4	
	Cluster 6	0.1 m additional ground coverage	1.3	
		0.2 m additional ground coverage	1.6	
		0.3 m additional ground coverage	2.1	
		0.4 m additional ground coverage	2.6	
		0.5 m additional ground coverage	3.3	
		0.6 m additional ground coverage	4.2	
		0.7 m additional ground coverage	5.4	
		0.8 m additional ground coverage	6.8	
		0.9 m additional ground coverage	8.7	
		1.0 m additional ground coverage	11.0	
	Cluster 7	Additional wall thickness (on top of corrosion allowance) > 15 mm	10	
		Additional wall thickness (on top of corrosion allowance) < 15 mm	1	
Internal corrosion	-	No measures	1	Module V
		Product sufficiently not corrosive towards to material of the pipeline, but measures still required	10	Toelichting
		In-Line inspection with defect analysis and reparation	10	Toelichting
		Product not corrosive towards the material of the pipeline	Infinite	Module V
External corrosion	-	No measures	1	Module V
		In-Line inspection with defect analysis and reparation	10	Toelichting
		Environment not corrosive towards the material of the pipeline	Infinite	Module V
Mechanical	-	No measures	1	Module V
		Operational pressure reduced to <30% of SMYS	10	Toelichting
		In-Line inspection with defect analysis and reparation	10	Toelichting
Natural causes	-	No measures	1	Module V
		Impermissible settlements or tensions can be largely excluded by evaluation	10	Toelichting
		Natural causes can be excluded	100	Toelichting
Operational and other causes	-	No measures	1	Module V
		Applied SIL = Calculated SIL + 1	10	Toelichting
		Applied SIL = Calculated SIL + 2	100	Toelichting

The failure frequency of the pipeline is calculated by dividing the failure frequency for a specific cause by the product of all the reduction factors that have been implemented for that cause.

Consortium partners:

Colophon

Title: Design and safety aspects for large-scale clean ammonia pipelines

Publication date: 20 May 2025

Authors: Hans van 't Noordende (ISPT), Victoria Monsma et al. (DNV)

Editor and graphic design: Franka Wijnbergen, Hella Good Design and Li-Shi Works

Text editor: Titus Verheijen (Titus Translations)

Published by Institute for Sustainable Process Technology (ISPT)

About this report: This public report was prepared by ISPT and based on the internal reports performed by DNV. DNV was assigned by ISPT and partners to conduct the feasibility study. The project was initiated and managed by the Institute for Sustainable Process Technology (ISPT) and is part of the Clean Ammonia Innovation Platform. The study has been done in close cooperation with consortium partners.

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