HyDelta 3

Compendium of research

HyDelta

Consortium

TKI NIEUW GAS Topsector Energie

Gasunie

Netbeheer Nederland

New Energy Coalition

TNO innovation for life

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DNV

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Foreword

Groningen, The Netherlands, June 2025

Dear reader,
Welcome to the results of the third phase of the HyDelta research program. HyDelta 3 aimed to make further progress towards the introduction of clean hydrogen as an energy carrier in The Netherlands. Between November 2023 and December 2024 our consortium of New Energy Coalition (coordinator), DNV, TNO, Kiwa, Gasunie and Netbeheer Nederland (NBNL) has worked together to answer the most urgent technical, environmental, societal and economic questions with regards to hydrogen transport and distribution.

The work has resulted in no less than 25 deliverables, which are publicly available on the hydelta.nl website. This compendium containing summaries of the 5 main work packages in the project, provides you with a way to explore the various results more efficiently. Readers interested in a deeper understanding of the results, methods, precise working instructions, quantified risks etcetera are invited to visit the website or our results tool on https://reports.hydelta.nl

Over the course of the full HyDelta program, which started late 2020, the expectations for clean hydrogen have risen, fallen, shifted focus and seen a number of breakthroughs. In our eyes, one thing has remained: the need for an infrastructure that allows renewable gases to connect producers and users across the country. Doing so in an affordable and safe way, for humans and for the planet, has always been at the heart of the HyDelta activities. We considered many of the prerequisites to achieve this: designs for regional hydrogen hubs, best practices for asset management and repurposing offshore pipelines, measures that reduce emissions and various operational risks, but also needs for a working supply chain, space and digital infrastructure.

We are not finished yet: at the time of writing we only have small parts of the transport and distribution network completed and we can still develop cheaper and faster ways to roll out the system, while remaining safe and compliant with our sustainability goals. Integral planning and innovative tools to optimise expansion of the network nation-wide are therefore considered in the fourth phase of the project.

Finally, we want to thank TKI Nieuw Gas for sponsoring this program and all the stakeholders we interviewed or contributed in any way to the results.

On behalf of the HyDelta 3 consortium,
Dr. Pim W.J.M. Frederix
Coordinator of the HyDelta program

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Introduction

Summary

The HyDelta Derde Tranche (HyDelta 3) project was a research project carried out between November 2023 and December 2024. It is a direct follow-up of the HyDelta Eerste Tranche en HyDelta Tweede Tranche (HyDelta 1 en HyDelta 2) projects. Like its predecessors, HyDelta 3 focused on researching the topics deemed the most urgent and relevant with regard to hydrogen transmission and distribution in this phase: best practices for asset management (WP1), deploying societally optimal hydrogen distribution in standalone areas (WP2), emissions from hydrogen infrastructure and the role of ammonia (WP3), value chain development (WP4) and quantifying and mitigating risks for with regards to various technical aspects of the future hydrogen network (WP5).

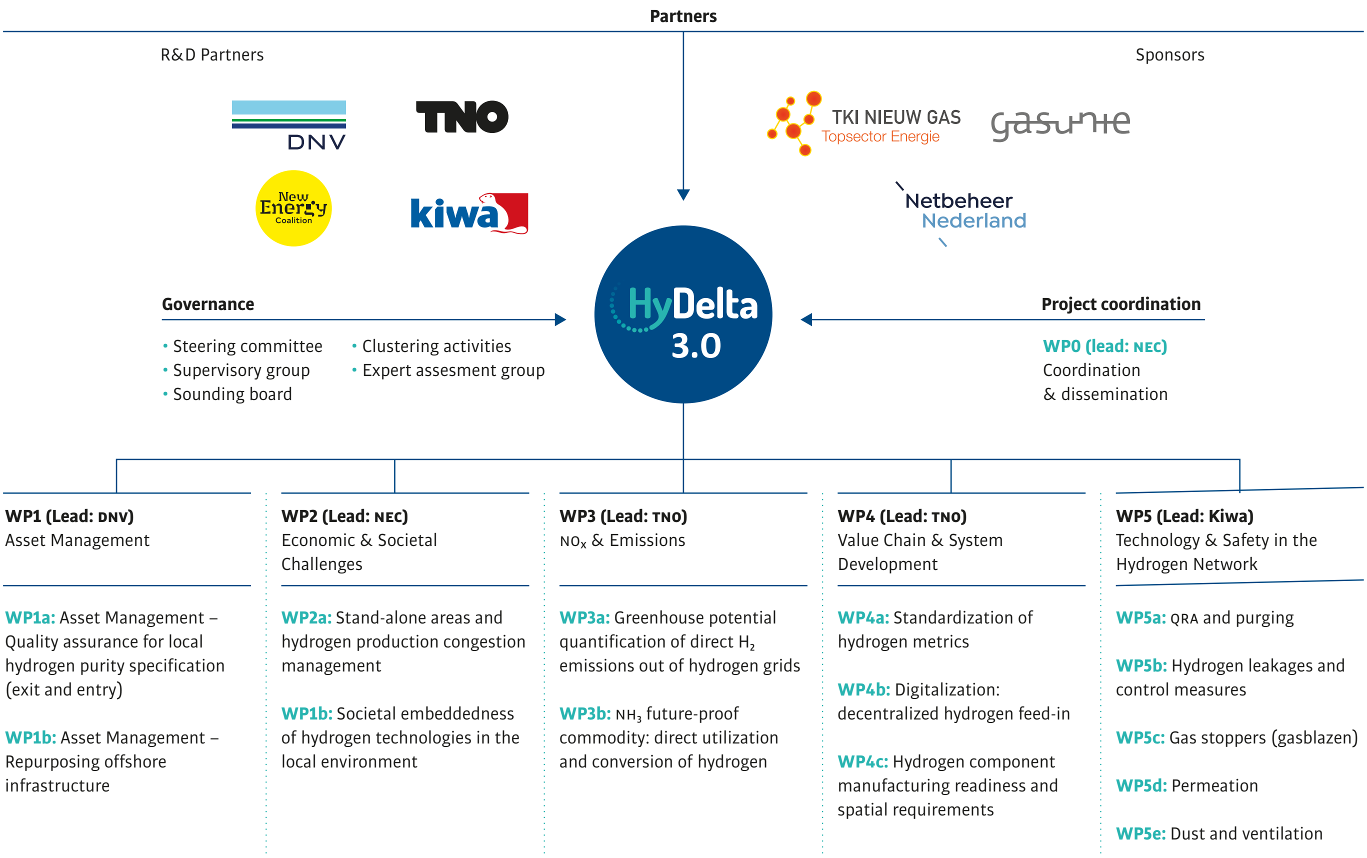


Figure 1. Overview of the HyDelta 3 project: project partners, governance and the division into work packages

The HyDelta 3 project is a collaboration between the natural gas transport and distribution operators in the Netherlands, and key research institutions in the Netherlands. With the 25 publicly available reports resulting from the project, we support decision-making towards investments (for pilots, projects and large-scale infrastructure) in the Netherlands and beyond. In this compendium, you will find HyDelta 3's main results, summarized into 2-3 pages per topic.

Research themes

Research themes

There are five main research themes addressed in HyDelta 3, each subdivided in work packages that addressed a concrete set of research questions:

Table 1

Research theme	Work packages	Description
Asset management	1a: Quality assurance for local hydrogen purity	Development of entry and exit specification for hydrogen quality in a Dutch distribution network including monitor and control
	1b: Repurposing offshore infrastructure	Gain insights into contaminants and available cleaning technologies, as well as which re-qualification criteria for offshore hydrogen pipelines
Economic and Societal challenges	2a: Standalone hydrogen areas in the Netherlands	Provide answers on if, and how standalone hydrogen areas can have a role in the roll-out of decentral hydrogen infrastructure in the Netherlands
	2b: Risk governance and societal embeddedness	Analysis of the cross-cutting aspects (communication, stakeholder engagement and context) of risk governance in the hydrogen value chain (ranging from hydrogen transport via high- and low pressure networks and storage in salt caverns and porous media)
NO_x and emissions	3a: Greenhouse potential of direct H_2 emissions out of grids	Define Dutch DSOs and TSOs' position on hydrogen emission reduction in transport and distribution grids by identifying potential hydrogen emission sources, quantities and recommendations for hydrogen emissions reduction measures
	3b: NH_3 direct utilization and conversion to hydrogen	Investigate into the 'how' of NH_3 as a means for direct utilization and conversion to hydrogen by breaking down the practical implementation of renewable NH_3 a s fuel source for ship fleets, identifying industrials that could benefit, assesses capacity requirements, and exploring NH_3 cracking technology.
Value Chain and System Development	4a: Standardization of Hydrogen Metrics	Mapping and comparing metrics across the hydrogen value chain, identifying the most suitable metric/units options and how process of standardization should be put into practice
	4b: Digitalisation: Decentralized hydrogen feed-in	Development of a controlling protocol for decentralized renewable gas feed-in for networks managed by the DSOs, including an ATO (Aansluit- en Transport overeenkomst) with feeders and system requirements.
	4c: Hydrogen component manufacturing readiness and spatial requirements	Clarifying the component manufacturing supply chain readiness and the spatial requirements of hydrogen related technologies that may be deployed in the Netherlands.
Technology and Safety in the H_2 network	5a: QRA and Purging	Following up on the QRA modeling of Hydelta 2 by making specific calculations on the effect of risk mitigating actions, and assessing the effectiveness versus potentials risks of purging.
	5b: Hydrogen leakages and control measures	Provide an overview of potential risks and practical implications that a mechanic might faces in case of a leakage in the distribution grid, including preventive and corrective safety measures
	5c: Gas stoppers	Investigating into the practical implications of using IPCO-type gas stoppers and giving insights into the effectiveness of double-block and bleed method in combination with flushing nitrogen
	5d: Permeation	Gain insight into the potential safety risks and changes in hydrogen purity due to permeation over time at specific asset components in the distribution grid
	5e: Dust and ventilation	Investigating into the risk of self-ignition due to dust in a hydrogen gas flow, and possible ventilation hardware improvements to current gas stations operated with hydrogen

Section 1

Asset management

1 Asset management

Sources for this section

DELIVERABLE:

D1a.1 Overview of basic elements for hydrogen purity standards

Link to deliverable

DELIVERABLE:

D1a.2 Strategies/Scenarios on how to deliver hydrogen purity in distribution networks

Link to deliverable

D1b.1 Pipeline Contamination

Link to deliverable

D1b.2 Repurposing protocol offshore pipelines for hydrogen transport

Link to deliverable

Asset management – infrastructure repurposing

Repurposing offshore and onshore natural gas infrastructure for hydrogen is economically attractive but comes with challenges such as contamination, material compatibility, and varying end-user hydrogen quality requirements. This research developed a dedicated cleaning process and a 10-step re-qualification protocol for offshore pipelines. For regional distribution grids, it provides a framework for defining technically and economically viable hydrogen quality specifications. Together, these efforts support a safe, cost-effective rollout of a robust hydrogen network.

Developing hydrogen networks in the Netherlands

The Netherlands is actively advancing its hydrogen infrastructure as part of its broader energy transition strategy. A key milestone is the rollout of the HyNetwork grid, a national hydrogen transmission backbone. This network will connect major industrial clusters, import terminals, and storage facilities, enabling large-scale onshore hydrogen transport across the country. The rollout has already begun and is set to expand significantly – towards 1200 km, largely converting hydrogen-ready natural gas pipelines- in the coming years.

In parallel, plans are underway for a dedicated offshore hydrogen network in the North Sea. This infrastructure will support the production of green hydrogen at sea, leveraging the vast offshore wind potential in the North Sea. The hydrogen produced offshore will be transported to shore via repurposed or new pipelines and connected to the HyNetwork system. At the local level, distribution system operators (DSOs) are preparing their networks to accommodate hydrogen. This includes technical assessments, pilot projects, and safety analyses to ensure that regional and municipal grids can safely and cost-effectively distribute hydrogen to end-users in the built environment.

However, repurposing existing natural gas infrastructure – both offshore and onshore – presents significant challenges. These include contamination risks, material compatibility, and connecting customer with diverse needs on hydrogen purity level. The aims of this research is to support a safe, cost-effective roll-out of hydrogen infrastructure across offshore and regional networks, helping to build a robust, integrated system that advances the Netherlands' climate goals and strengthens its leadership in the European hydrogen economy.

Adapting distribution grids to safely handle hydrogen

Clear and transparent hydrogen quality specifications are crucial for pipeline integrity and safe performance of end-use equipment. While national standards for the Dutch high-pressure transmission grids are in development, none exist yet for distribution networks (30 mbar - 1 bar). Specifications must balance end-user protection, network cost-effectiveness and production cost.

European level stakeholders are discussing hydrogen purity between >98% and >99,5%. For the Netherlands the proposed specifications includes a hydrogen purity level ≥99.5%, ≤0.5% inerts, and strict limits on impurities like sulfur, CO, and halogens.

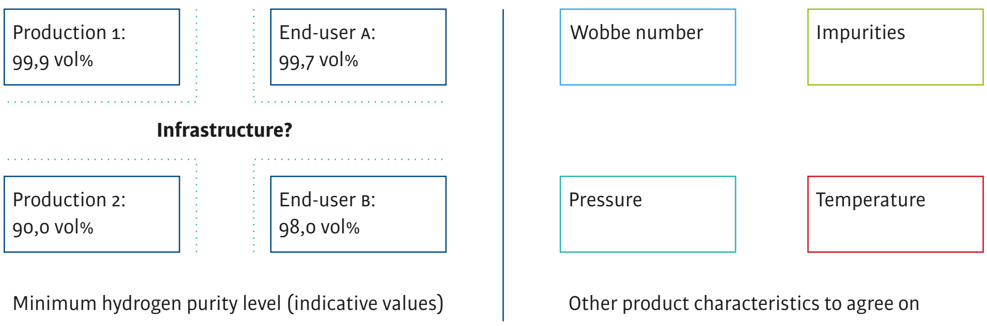
Hydrogen Quality Requirements for End-Users

The Dutch hydrogen distribution network will serve a wide range of end-users – industrial, residential, mobility, and power generation – each with different sensitivity to purity level and impurities. Report D1a.2 delivers a comprehensive picture of the requirements of all end-user categories. While fuel cell solutions for e.g. mobility need a minimum purity of 99,95%, boilers for heating built environment only need purity levels of 98%.

Hydrogen quality from production methods

Hydrogen production methods vary in output purity. Electrolysers typically deliver high-purity hydrogen (≥99.9%), while other technologies like Steam Methane Reforming (SMR), Autothermal Reforming (ATR) and Partial Oxidation (POX) have rather low level of output hydrogen purity and therefore will require further purification to bring the output purity level on 95% or higher. The same is true for gasification technology after: CO_2 capture the when hydrogen purity output is ~88%.

Figure 2: The complexity of connecting production and end-user with different hydrogen purity needs



Purification technology

When production purity doesn't meet network or end-user specs or trace components are at too high level purification or filtering is needed. A range of purification technologies to purify hydrogen-rich gas mixtures have been analysed, from mature industrial methods like pressure swing adsorption (PSA) and cryogenic distillation to emerging options like electrochemical separation. The most mature technologies are:

- Pressure Swing Adsorption (PSA) – preferred for high flow rates, offering up to 99.9999% output purity.
- Polymer membranes – used for low flow situations, up to 99.7% output purity and
- Cryogenic Distillation for mid-range flows that that achieves lower purity at a level of 90-98% purity.

Market-based techno-economic analyses

The above describe production, end-user and purification insights served as input for a hydrogen purity cost model to assess optimal hydrogen purity levels in regional gas distribution networks (1-16 bar). The model analyses two network types (harbour and rural) and includes seven production/consumption scenarios for 2035 and 2050. All producers and users are linked to the network with their respective purity levels. Pressure Swing Adsorption (PSA), which produces high-purity hydrogen and a tail gas containing impurities has been used where purification was needed.

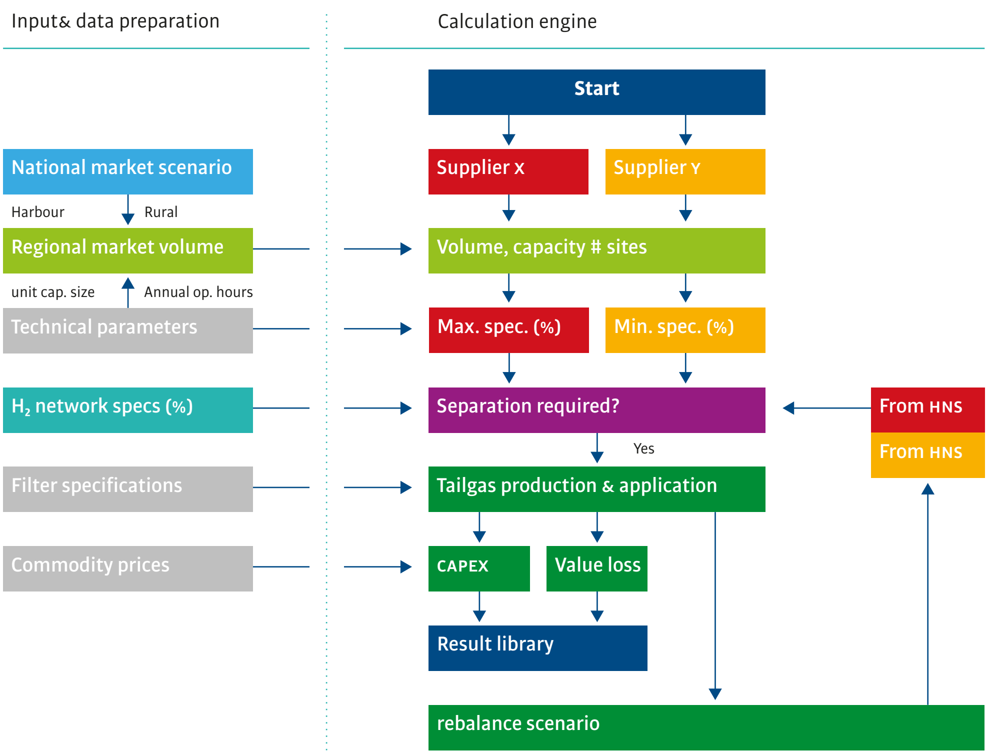
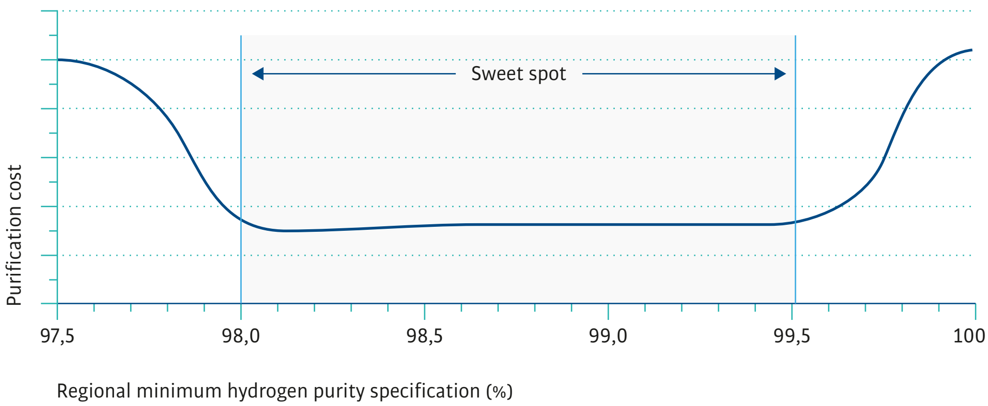


Figure 3: the data flow through the main hydrogen purity cost model

- User macro interaction
- Input case
- Prepared input
- “What if” input
- Network in
- Network out
- Yes / no
- Calculation
- Fixed input

Report D1a.2 describes the main results. It has been concluded that the optimal (cost-effective) exit hydrogen purity range is 98-99.5%. Within this range, purification costs are ~ €0.10/kg H_2. Outside this range costs rise 2-3×. From the model results it can be concluded that aligning regional network purity with the Hynetwork specification will maximize flexibility and compatibility for hydrogen exchange.

Figure 4: Overarching result of techno-economic analysis (all scenarios, both network types)



Impact of Permeation and Desorption on Hydrogen Purity

A technical model was developed to assess how Dutch distribution grids (steel, PE, PVC material) affect hydrogen purity through permeation and desorption. The focus is on environmental gases (O_2, N_2, H_2O) entering pipelines, not solids or accidental contaminants.

For higher pressures (>1 bar) networks the impact of permeation on hydrogen purity is limited as there is less incoming contamination (due to the greater wall thickness) and more gas inside the pipeline (due to the higher pressure) in which it mixes. It should be noted that for repurposed pipelines on 1-8 bar) level there are some challenges related to existing contaminations. Further research is needed on this. The largest effects of permeation are in the low-pressure networks (30-200 mbar). Especially when there is (almost) no flow (comparable with the current natural gas offtake in summer), permeation can lead to a significant amount of impurities which affects the hydrogen purity.

Additionally, it was concluded that the effect of desorption is limited to the initial pipeline, which can be managed by operational agreements with customers or technical measures. THT, used for odorization of natural gas, could pose a challenge when using repurposed pipelines, especially if the end-user utilizes a fuel cells. If this use-case presents itself, it should be further investigated

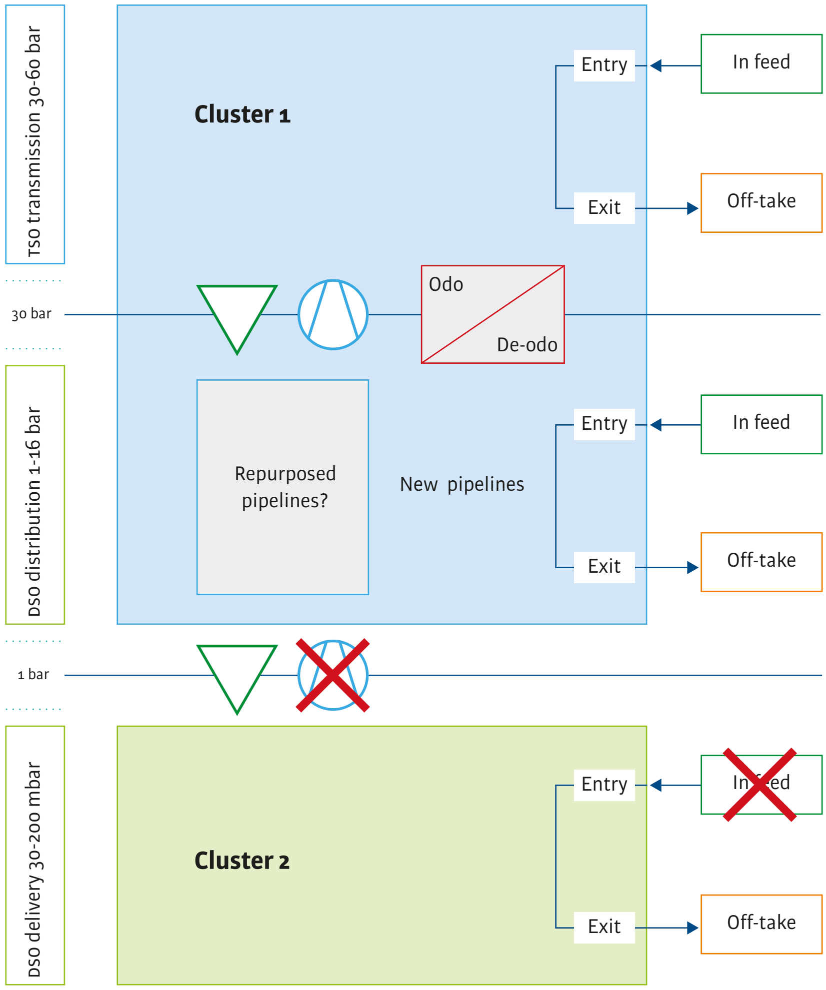


Figure 5: Two-cluster approach proposed for managing hydrogen purity in regional distribution networks

Managing hydrogen purity in future distribution networks:
Combining the above described market-based techno-economic analysis with the infrastructure-focused technical analysis, a two-cluster approach is proposed for managing hydrogen purity in regional distribution networks:

- **Cluster 1: Aligned with Hynetwork:** For high-pressure distribution networks (1-16 bar), it is optimal to match the HN purity level (98-99.5%) to allow seamless hydrogen exchange with the HN system. This range suits most producers and end-users. For repurposed pipelines (1-8 bar), uncertainty remains due to potential residual contaminants – further investigation is needed. Reverse flow from distribution to transmission networks will likely require de-odorization, as odorants like THT (used in distribution) are not allowed in transport networks. The cost and readiness of de-odorization technologies need further study.
- **Cluster 2: Lower exit purity for Low-Pressure Networks:** Low-pressure networks (30-200 mbar) are more susceptible to impurity ingress, especially during low-flow periods. These networks should allow for a lower exit purity level and be isolated from high-pressure distribution systems to prevent reverse flow. Due to limited capacity, local hydrogen injection into these networks will also be restricted.

To support this structure, a robust infeed protocol is needed to monitor hydrogen quality from local producers. This study laid the groundwork for such a protocol, drawing from existing Dutch biomethane standards.

Repurposing offshore natural gas pipelines for hydrogen transport

In 2022, the Esbjerg Declaration marked a joint pledge by Belgium, Denmark, Germany, and the Netherlands to transform the North Sea into a major hub for renewable energy. This ambition expanded in 2024 with the Ostend Declaration, where nine countries committed to accelerating offshore wind development and cross-border energy integration – targeting 120 GW of offshore wind by 2030 and 300 GW by 2050.

As oil and gas activities decline, existing North Sea infrastructure offers a promising opportunity for hydrogen transport. Offshore wind energy can be converted into hydrogen via electrolysis and delivered to shore using repurposed natural gas pipelines. However, adapting these pipelines requires clear technical standards and robust safety protocols, as offshore systems face unique environmental stresses and potential failure modes not present in onshore networks.

While onshore pipelines are generally considered hydrogen-ready, offshore applications demand further investigation. This research addresses that gap by delivering a dedicated cleaning process and a 10-step requalification protocol to help offshore operators assess and prepare existing pipelines for safe hydrogen transport.

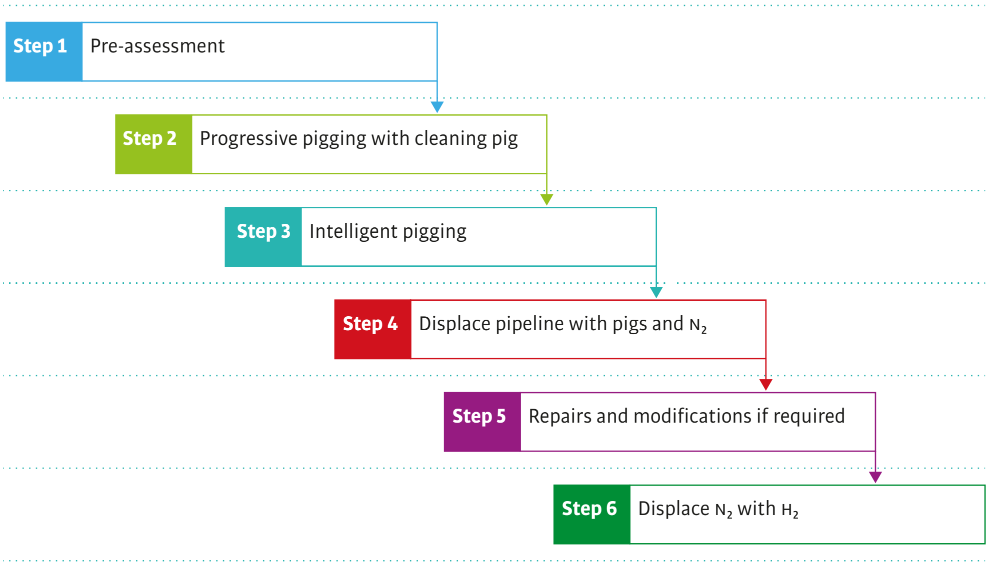
Cleaning protocol for offshore pipelines

Repurposed upstream natural gas pipelines may contain significant residual impurities – solids, liquids, and volatile components – accumulated over decades of operation.

Most common contaminants that can be found in upstream offshore natural gas pipelines include sulphur and H_2S, oxygen, mercury, siloxanes, amines, glycols, oil and grease, upstream production chemicals, solids and fines. Each of these contaminants poses different challenges and risks for the pipeline integrity and safety A thorough investigation has been delivered on the contaminant sources, effects, and mitigation methods.

Consequently a cleaning methodology – based on industry best practices – has been developed for offshore natural gas pipelines to ensure natural gas pipelines are sufficiently cleaned in order to re-qualify them for hydrogen service.

Figure 6: Offshore pipeline cleaning process (report D1b.1)



Re-qualification protocol for Offshore pipelines

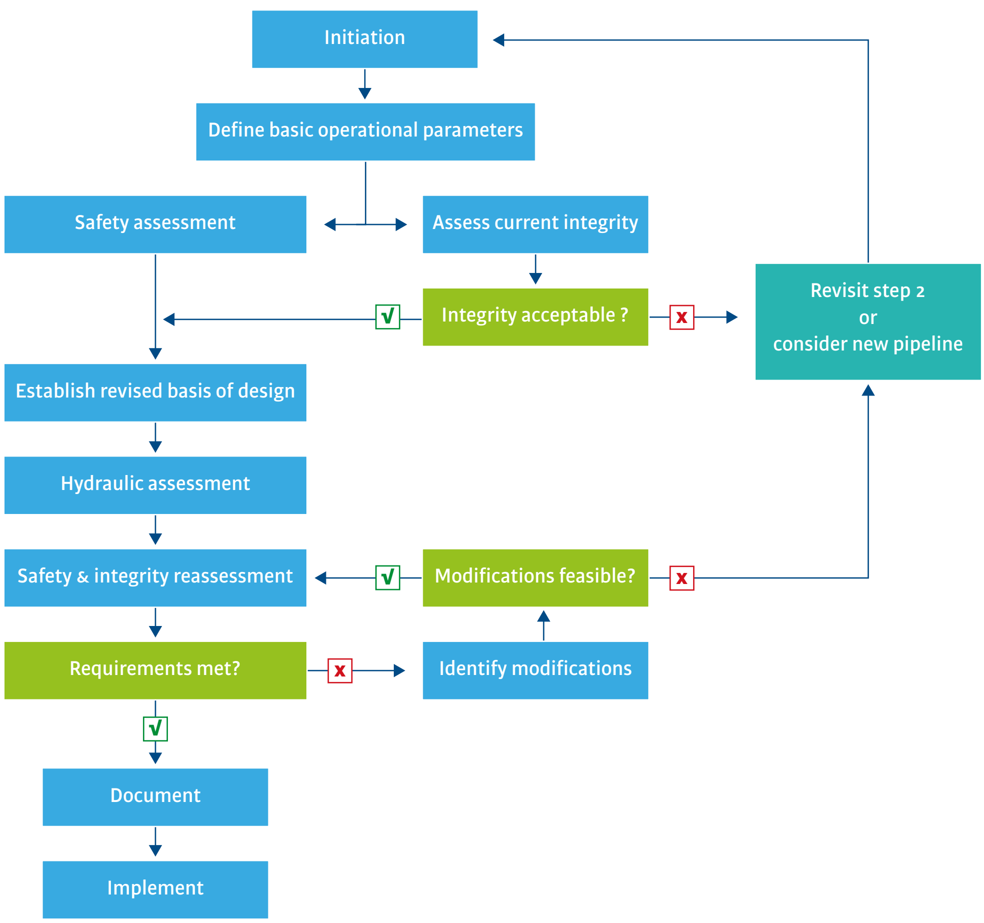
Repurposing existing pipelines for hydrogen transport offers a cost-effective alternative to new infrastructure but requires thorough evaluation of pipeline condition, material compatibility, and hydrogen-specific risks. Ensuring safety and compliance demands extensive integrity assessments and structured requalification processes.

Most offshore pipelines in the Dutch North Sea were built between the 1970s and 1990s for natural gas transport, typically using carbon steel (grades X42-X70) and designed to older standards like NEN 3656. Many have exceeded their original design life, raising concerns about fatigue, corrosion, coating degradation, and limited inspection capabilities.

A clear governance structure is needed to support the safe transition to hydrogen infrastructure. Subsea pipeline safety in the Netherlands is governed by national laws, EU directives, and international standards. These must be reviewed when repurposing pipelines for hydrogen. For offshore hydrogen pipelines, the regulatory framework is still evolving, with oversight expected to shift from the State Supervision of Mines (SODM) to Rijkswaterstaat (RWS), pending formal designation by the Ministry of Climate and Energy Policy.

Repurposing these pipelines for hydrogen is technically complex. Offshore conditions differ significantly from onshore, and existing hydrogen standards (e.g., ASME B31.12, NEN 3650) are not fully applicable. To address this, DNV is leading the H2Pipe initiative and developing DNV RP-F123 to provide clear guidance for hydrogen pipeline design and requalification. Building on this, report D1b.2 introduces a 10-step re-qualification protocol, guiding offshore operators systematically and comprehensively through compliance checks and assessments to ensure repurposed pipelines meet modern safety, regulatory, and operational standards. Key factors when evaluating the repurposing of pipelines for hydrogen transportation are categorized into environmental (hydrogen pressure, impurities, and temperature), material (grade, microstructure, and chemical composition), operations (pressure, loading variations, and residual stresses), and current state (weld quality, defects, and installation strain). Re-qualification must be based on comprehensive information from the original design, construction, and operational phases. Once a pipeline is re-qualified for a new fluid, it can be re-commissioned under revised design specifications and operational parameters.

Figure 7: Ten-step process for the re-qualification of pipeline systems



Section 2

Economy and Society

2 Economy and Society

Sources for this section

DELIVERABLE:

D2a.1 – The role of standalone hydrogen areas in decentral hydrogen infrastructure development

Link to deliverable

DELIVERABLE:

D2a.2 – Societal optimal hydrogen distribution

Link to deliverable

DELIVERABLE:

D2a.3 – Electrolyzer business case in a standalone hydrogen area and the effect of adding firm/non-firm grid tariffs

Link to deliverable

DELIVERABLE:

D2b1+2 – Risk governance and societal embeddedness for hydrogen infrastructure

Link to deliverable

Summary: Standalone hydrogen areas, disconnected from a central backbone, are feasible when a set of conditions is met. For such cases, the research output contains enablers and barriers, practical guidelines for developing the standalone area with suitable stakeholder engagement, societally optimal grid planning tools and ways to stimulate green hydrogen production.

Standalone hydrogen areas

The role of hydrogen in the Dutch energy transition is vital. Still, the roll-out plan for decentral hydrogen infrastructure remains rather uncertain. There is a good picture on how decentral industries can be launching customers for creating branches from the backbone and how areas in the regional gas grid can be converted from natural gas into hydrogen. However, there are also regional hydrogen initiatives developing that aim to start without a pipeline connection to the central transmission system. D2a.1 defines those initiatives as 'standalone hydrogen areas', although the term "hydrogen hub" is also becoming popular, and describes under what conditions such areas can contribute to the successful roll-out of hydrogen infrastructure in the Netherlands and how to practically approach them.

Figure 8: Selected case study locations and other standalone hydrogen projects considered.

Based on semi-structured interviews with stakeholders from projects of varying maturity and across the Netherlands, main drivers and barriers for successful standalone initiatives were drawn up (*Table 2*). Standalone hydrogen areas were then characterized into topologies, the potential role of the DSO was determined, and the various stakeholder roles in developing and operating a standalone area that the initiatives have in common were identified. The goal of supplying area developers with these results is to optimally prepare them with learnings from other projects, all of which can help determine the key actions to take in the development of the area.

As an overall conclusion, standalone hydrogen areas could be feasible in areas with motivated industrial off-takers that can accept blended grey hydrogen or natural gas for security of supply, but in most cases, they plan to connect to HNS once available. However, not all standalone H_2 areas are reliant on a future HNS connection: regional demand in the mobility sector could be served by high-purity local H_2 from standalone electrolysis due to the avoided purification step. Some areas develop to serve other purposes (e.g., reduce curtailment, oxygen off-take, backup power). The key actions and learnings from the study have been used as input to a separate practical guideline document, that can be retrieved via RVO (https://www.rvo.nl/onderwerpen/energiehubs/wat-een-energiehub/waterstofhubs).

Table 2: Criteria and barriers with respect to standalone hydrogen areas

Must-have criteria for standalone areas	**Common barriers to standalone hydrogen areas**
Favourable off-take conditions	Decentral areas have many stakeholders involved and difficult to get them all in line
Coordination	Newness of standalone areas results in many unforeseen obstacles during project development
Availability of hydrogen through import or local production. For local production, availability of green electricity (either via sufficient grid connection or direct integration of renewables) is an additional must-have.	Subsidy funding is limited but critical for standalone area development before hydrogen market reaches maturity
Subsidy funding	Challenges facing standalone areas are diverse and unique (technical, regulatory, financial, etc.)
Government support (particularly for permitting but nice for other aspects)	Newness of hydrogen can lead to concerns about its feasibility and safety
Nice-to-have criteria: Synergies (waste heat / O_2); Scale-up phase; Backbone timeline clarity; DSO involvement; geographic concentration of demand	Standalone hydrogen areas require continued long-term support from a wide range of stakeholders in the face of repeated hurdles

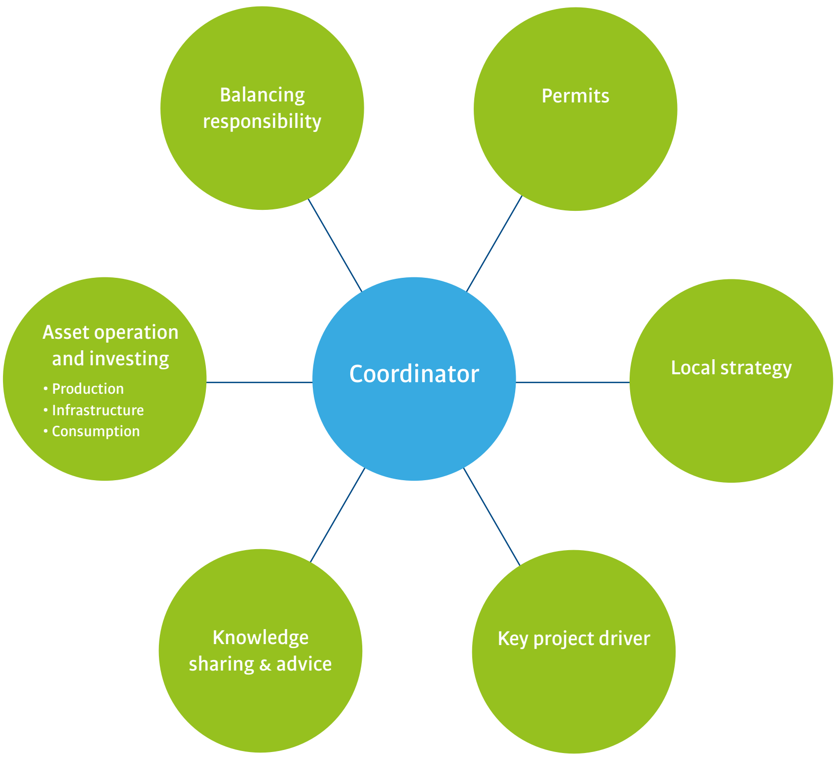


Figure 9: Overview of 7 key roles in standalone hydrogen areas.

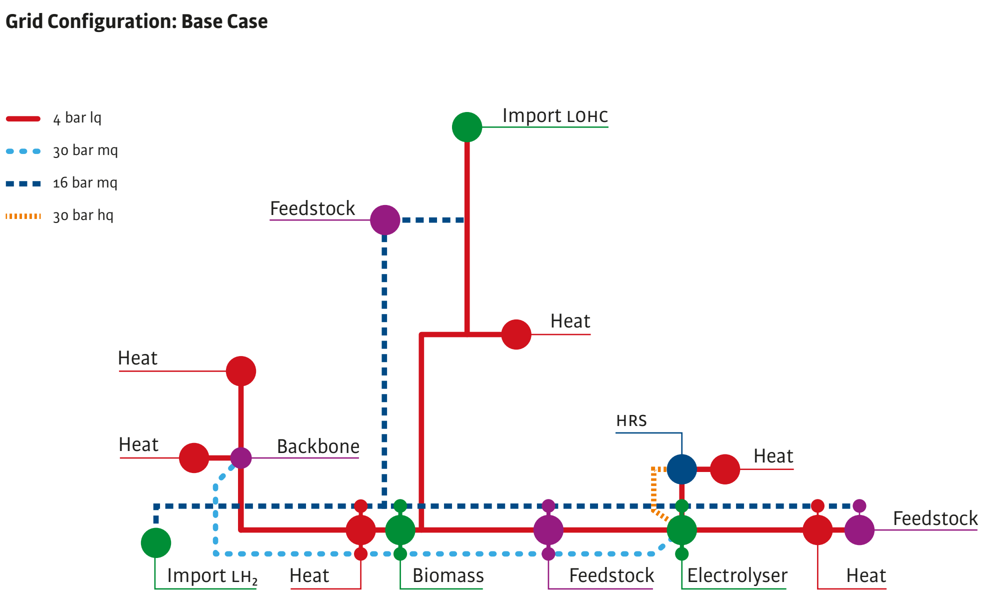


Figure 10: Optimized grid configuration for the base case.
*lq= low quality (98%),
mq= medium quality (99.5%),
hq = high quality (99.999%).

Optimising the hydrogen distribution in standalone hydrogen areas

With regional hydrogen supply and demand in standalone hydrogen areas, hydrogen distribution grids will need to be developed to connect the region to the HNS backbone and to interconnect supply and demand nodes locally. Since distribution grids not only serve a large number of clients with different hydrogen pressure, purity, and volume requirements, but also can have numerous sources of hydrogen supply, the optimal grid configuration and characteristics need to be (to an extent) determined on a case-by-case basis. D2a.2 describes how the end use for various energy-intensive industries (food, chemical, paper, domestic transport, etc.) can translate into future demand characteristics for hydrogen. The resulting expected volume, pressure and gas quality demands were transferred into a grid optimization model in the Calliope energy modelling framework that can be applied to diverse use cases. The model's main goal is to minimize the total system costs by making decisions on the following: optimal pipeline pressure and purity level on each transmission arc; optimal placement and capacity of purification and compression technologies; and optimal H_2 source at a given timestep. The optimized grid layout for a base case, loosely based on the Port of Amsterdam H2avennet, is given in *Figure 10*.

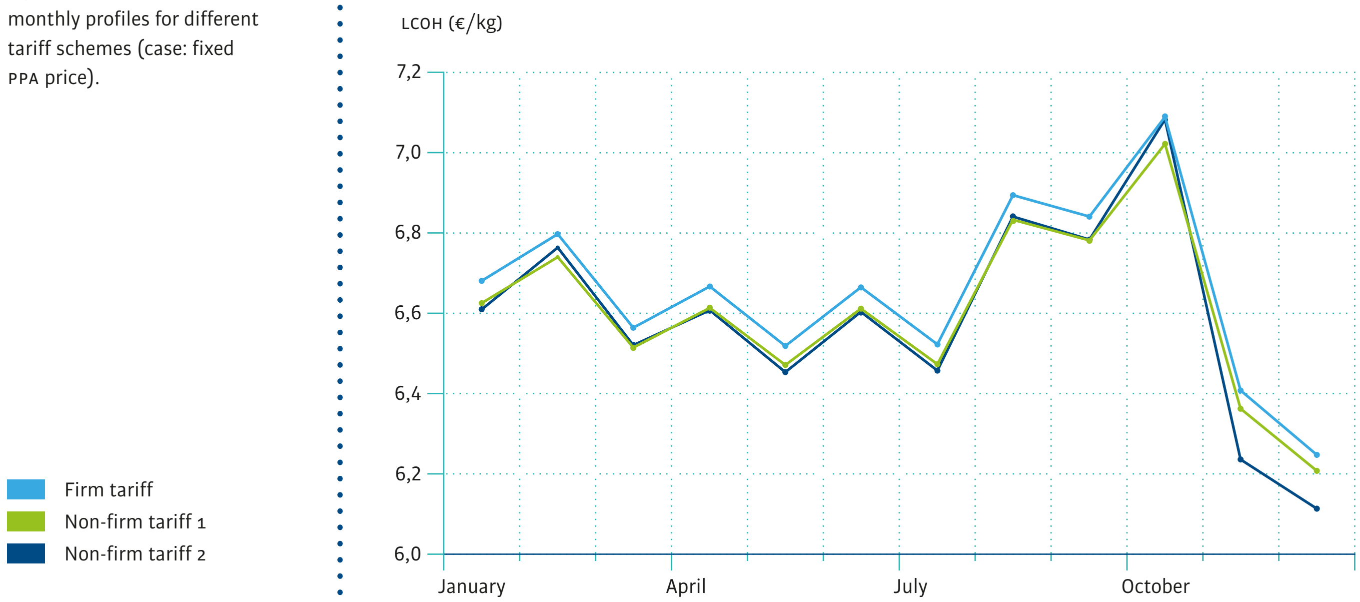
As an example, the model may indicate multiple pressure and quality layers, resulting in multiple pipelines connecting the same trajectory, if the entry and exit points are geographically close. In general, it is concluded that pressure and purity requirements of end-users have a significant impact on optimal grid configurations and lower total system costs in the base case are driven by lower marginal costs of hydrogen supply from avoiding hydrogen recovery losses due to purification. The model is available on demand.

Incentivizing hydrogen production in standalone initiatives

With increasingly higher amounts of renewable, fluctuating power expected by 2040 and 2050, electricity grid congestion is a difficult challenge to be faced by the grid operators in The Netherlands, both at transmission and distribution levels. The limitations in power availability due to current and future grid congestion are relevant when considering the business case of new assets that consume power, such as electrolyzers.

D2a.3 describes the effect in the business case of an electrolyzer of contract-based strategies at the Distribution System Operator (DSO) level, when combining a multi-energy asset of power generation (solar) and consumption (electrolyzer) within the same asset owner. The case study chosen was inspired by the H_2 Hollandia pilot in Drenthe, with 115 MW of solar power and a 5 MW electrolyzer, but the report covers the sensitivity of the results to other relative sizing. Following the spirit of the ATR85 proposal for transmission rights, a similar set of tariffs is studied here: 15% power can be restricted at selected time slots, providing in exchange a reduction in the grid tariff (non-firm tariffs). In addition, subcases restricting consumption and generation and the grid availability for a fixed solar park and firm/non-firm tariffs have been studied, using green electricity with and without a dedicated wind farm with a fixed Power Purchase Agreement (PPA) price.

Figure 11: Example of LCOH monthly profiles for different tariff schemes (case: fixed PPA price).



The results of the study indicate that, if the infrastructure and other conditions (e.g., off-taker agreements) are present, grid tariffs could be one of the relevant incentives (in combination with others) to bring hydrogen production to certain areas. A reduction of 0.3 €/kg in the LCOH could be achieved for some of the cases. This work highlights that non-firm tariffs could potentially present an opportunity to encourage the placement of electrolyzers in certain areas and/or to improve the business case of a system composed of renewable energy assets and an electrolyzer. However, their specific implementation may require significant tailoring to each asset/value chain.

Points of attention in collaboration and communication for risk governance in hydrogen infrastructure

When standalone hydrogen area infrastructure, or any hydrogen infrastructure for that matter, is to be developed, communication and collaboration are essential cross cutting components for the entire process. The work presented in D2b.1+2 describes how these are relevant specifically to managing technical risks in the hydrogen transport and distribution sector in the Netherlands. Involving and collaborating with stakeholders during the risk governance process can improve the quality of the (risk-related) decision-making process. Effective stakeholder engagement is important for the success of the risk governance process, and open, transparent, and inclusive communication helps to foster trust in risk governance and the involved parties. The results of the research were obtained through interviews with stakeholders in the sector and a document study, and are divided into five focus points:

1. For good collaboration and (risk) communication, it is desirable to use common terms or at least be aware of each other's terms and principles. For common terms in hydrogen units, see section 4 of this compendium.
2. It is important to make a joint, future-proof value assessment. Here, safety should be weighed against other relevant values as elaborated in the NPE (national energy system plan).
3. For stable long-term collaboration, a clear and logical division of roles is essential. Since the hydrogen distribution sector through pipelines is not yet regulated under established policy, the roles that stakeholders assume are also not yet fixed. For small initiatives such as regional hydrogen hubs, roles are suggested in D2a.1.
4. Knowledge development in the sector is still ongoing and not accessible to everyone. There is a need for an efficient and structured system for both bringing and acquiring knowledge.
5. Interaction with other spatial developments requires more coordination. Developing multiple spatial projects, such as a hydrogen and electricity grid, requires coordination in communication between projects and towards residents. A spatial analysis of the hydrogen system can be found in D4c.2

Figure 12: (Dutch). Five points of attention for future collaboration and communication

Although the five focus points for communication and collaboration in this report are tailored to hydrogen distribution and transport through pipelines, they cannot be seen in isolation from the broader context of the energy transition. To make the five focus points broadly applicable, they are linked in a reflection to the principles of “Responsible handling of safety and health in the energy transition.” A more extensive theoretical background of applied concepts is also given in the report itself.

Section 3

NO_X and emissions

3 NO$_X$ and emissions

Sources for this section

DELIVERABLE:

D3a.1 & D3a.2 – Greenhouse potential of hydrogen emissions from the grid – Emission amounts and Priority of reduction

Link to deliverable

DELIVERABLE:

D3b.1 – Factsheet Ammonia Cracking Technologies

Link to deliverable

DELIVERABLE:

D3b.2 – Ammonia utilization in the power sector

Link to deliverable

DELIVERABLE:

D3b.3 – Ammonia Tanker Fleet Analysis

Link to deliverable

DELIVERABLE:

D3b.4 – Scenario analysis of emissions associated with supply of hydrogen in the form of ammonia

Link to deliverable

Summary: An important and urgent social issue concerns the emissions of greenhouse gases and, especially important for the economic development of our country, nitrogen. The development of the hydrogen value chain can contribute to this insofar as hydrogen can escape and thus function as a greenhouse gas or insofar as the splitting of ammonia into hydrogen and nitrogen creates the risk of nitrogen oxide emissions. This work package investigates to what extent these risks are real and what can be optimally fed in in terms of hydrogen volumes in national but especially decentralised gas pipelines: how can the emissions be measured exactly; which ICT is required for this; and what bottlenecks can be expected in this feed-in due to the emissions?

Greenhouse potential of direct H_2 emissions out of grids

It was addressed that hydrogen is a greenhouse gas itself, and the implications were researched. This might be counterintuitive, as dipole molecules (such as hydrogen) normally do not absorb radiation from the sun. However, the presence of hydrogen in the atmosphere extends the lifetime of other greenhouse gases (mainly methane). A GWP value was chosen based on a literature review, and this value was then combined with the methane emission data from the grid operators. This provided a CO_2 equivalent number if the current natural gas grid were repurposed to transport and distribute hydrogen. The main result was that when this number was combined with the most hydrogen-intensive II3050 scenario, a decrease of 92% in CO_2 equivalent emissions from the grid is achieved by switching from natural gas to hydrogen.

(a) GWP based equivalent emissions (%)

Leakage rate (%) \ Time horizon (yr)	1	10	20	40	80	100	200
15.0	167	93	63	40	24	20	12
10.0	106	59	40	25	15	13	7.7
7.0	72	40	28	17	10	8.8	8.2
5.0	51	28	19	12	73	6.1	3.7
3.0	30	17	11	7.7	4.3	3.6	2.1
1.0	9,8	5.5	3.7	2.3	1.4	1.2	0.7
0.1	1.0	0.5	0.4	0.2	0.1	0.1	0.07

Figure 13: The GWP based equivalent emissions for hydrogen. [Didier Hauglustaine et al., "Climate benefit of a future hydrogen economy," Earth & environment , 2022].

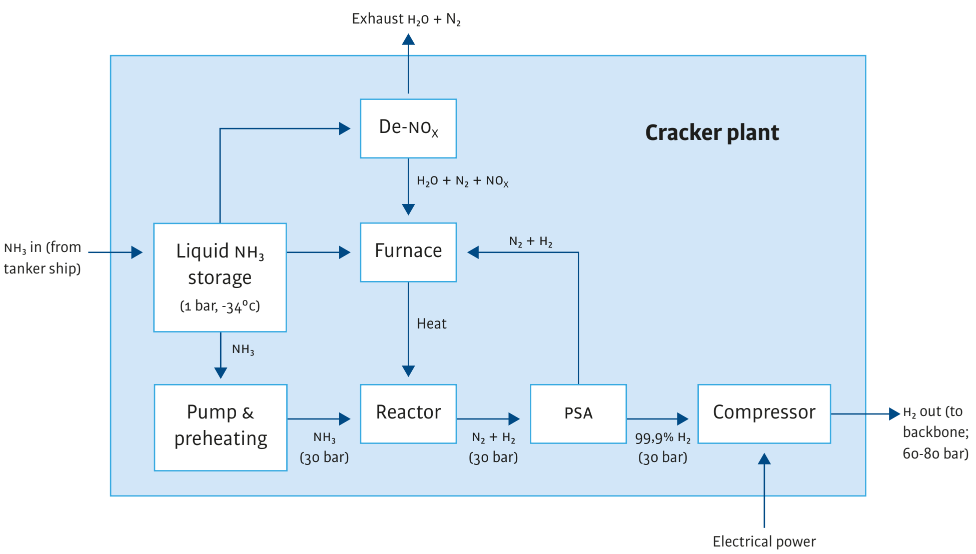
NH_3 direct utilization and conversion to hydrogen Large scale cracking

A key method for large-scale hydrogen import is through ammonia, which must be reconverted in cracker plants before use or further transport in a gas grid. These cracker plants can be operated dynamically to match fluctuating hydrogen demand, potentially enhancing overall energy system stability. Studies show that cracker plants can adjust their production rates without technological barriers, with projected ramp rates of 3% per minute and stable operation down to 10-20% of peak capacity.

Direct combustion

In the Netherlands, hydrogen-fired powerplants retrofitted from gas-fired plants are planned by 2035, fuelled through a hydrogen backbone supplied partly by imported ammonia. However, direct ammonia combustion in powerplants remains a challenge due to NO_x emissions, and 100% ammonia-fired turbines are unlikely to reach maturity by 2035. Integrating hydrogen-fired turbines with ammonia crackers using turbine exhaust heat could improve efficiency.

Figure 14: System overview of a NH_3 or H_2 fired SMR-type cracker plant.



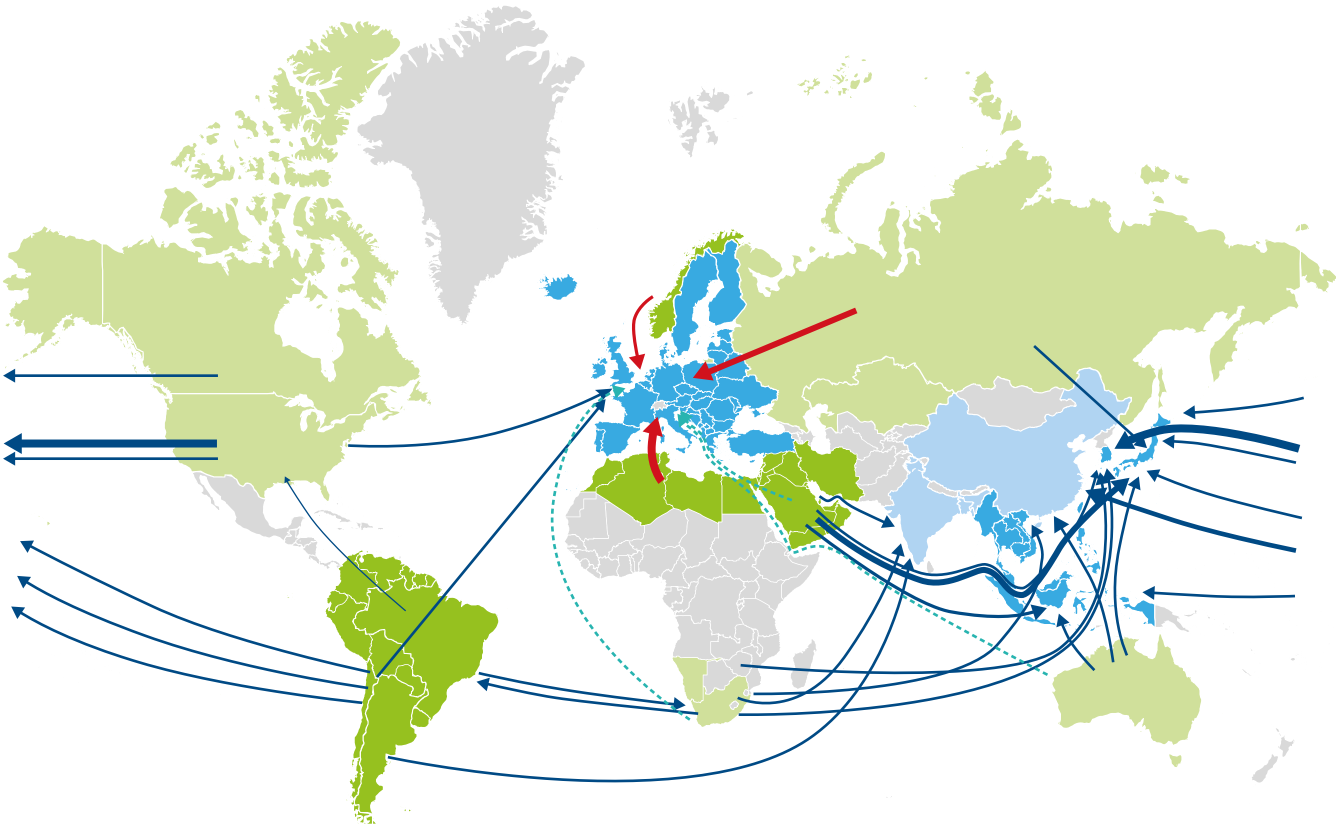


Figure 15: Scenario for the future of the internation hydrogen trade [Hydrogen Council and McKinsey & Company, "Global Hydrogen Flows: Hydrogen trade as a key enabler for efficient decarbonization," 2022].

Region consumes more than it produces

Region produces more than it consumes

Neutral

Net trade flows, million tons hydrogen per annum

> 20

10–20

5–10

1–5

Mostly shipped

Mostly piped

Alternative potential flows if optimal sources constrained

Shipping

A key factor in this transition is ammonia shipping, which is crucial for hydrogen import. The global ammonia shipping market is growing moderately, but existing LPG carriers can be repurposed to meet demand, making a shipping shortage unlikely. If ammonia adoption rises significantly, maritime trade could surge from 17 million to 320 million tons by 2050, requiring an expanded shipping fleet.

Emission

Life Cycle Assessments (LCA) of ammonia-based hydrogen imports highlight the importance of minimizing greenhouse gas emissions in the supply chain. Using grid electricity in ammonia synthesis significantly increases emissions, with major differences observed between countries like Australia and Canada due to their electricity mixes. Companies aiming to lead in green hydrogen should prioritize sourcing from regions with low-carbon grids and strong renewable energy integration.

Section 4

Value chain

4 Value chain

Sources for this section

DELIVERABLE:

D4a.1 – Roadmap to Hydrogen Metrics Standardization

Link to deliverable

DELIVERABLE:

D4a.2 – Which unit is best to use for hydrogen?

Link to deliverable

DELIVERABLE:

D4b.1 – Controlling protocols and strategies for decentralized hydrogen feed-in

Link to deliverable

DELIVERABLE:

D4b.2 – Optimal sensor placement strategies for monitoring the dynamic pressure of gas networks

Link to deliverable

DELIVERABLE:

D4c.1 – Supply chain risk management approach for hydrogen infrastructure components

Link to deliverable

DELIVERABLE:

D4c.2 – Spatial requirement contours of hydrogen projects

Link to deliverable

Value chain and system development

Summary: There are still many questions regarding the first applications of hydrogen for industrial high-temperature processes or power generation. The most critical of these relate to 1) standardizing hydrogen units (e.g. MJ, kg, ton), such that a common nomenclature in this field will develop that contributes to the drafting of stakeholder-supported protocols and the like; 2) developing a digital environment for the feeding of hydrogen into decentralized applications such that such feeding can also proceed smoothly and without problems in multi-gas cases; and inventorying the availability of the various components required for the development and application of hydrogen technology such that it is known in time when possible bottlenecks may arise. The total hydrogen value chain can only be closed once these questions and uncertainties in particular have been sufficiently investigated.

Standardization of hydrogen metrics

Hydrogen is expected to play a crucial role in the future energy mix, but its value chain currently relies on multiple metrics such as kg, MWh, and m^3, leading to inefficiencies. D4a.1 explores the benefits of adopting a single unified metric across the hydrogen industry. A literature review and stakeholder interviews indicate that the existing mass-based, volume-based, and energy-based metrics have various purposes. The study recommends exclusively using energy-based metrics, particularly watt-hour (Wh), to simplify transactions, reduce confusion, and align with other energy markets like electricity. However, challenges such as the lack of direct energy flow metering and implementation complexities must be addressed. The industry prefers using the Higher Heating Value (HHV) to measure hydrogen energy content accurately. While sectors like mobility recognize the benefits of kWh, they face practical barriers, making a hybrid approach – combining energy-based and mass-based metrics – an alternative. Government support and standardized regulations are essential for ensuring industry-wide adoption. Delays in establishing a single metric could make convergence more difficult over time. This study provides key insights, but future research should focus on practical implementation and standardization efforts.

Value Chain and System Development – Digitalization: decentralized hydrogen feed-in

Controlling the outlet pressure of a decentralized hydrogen feeder can increase the feed-in capacity of this feeder. To do this, the pressures in the network need to be measured with a certain accuracy. A combination of a gas network simulator and sensors provides more insight into the pressures in the network than using a simulator or sensors alone. It has been demonstrated that the pressure uncertainty from the gas network model (due to uncertainty in the demand data) can be simulated and reduced by using sensors. The application of practical rules combined with an optimizing algorithm can find the optimal pressure sensor locations to achieve acceptable pressure uncertainty levels. This allows the pressures of the feeders to be actively controlled, increasing the total feed-in capacity and reducing the need for shutdowns or boosters to manage surplus production.

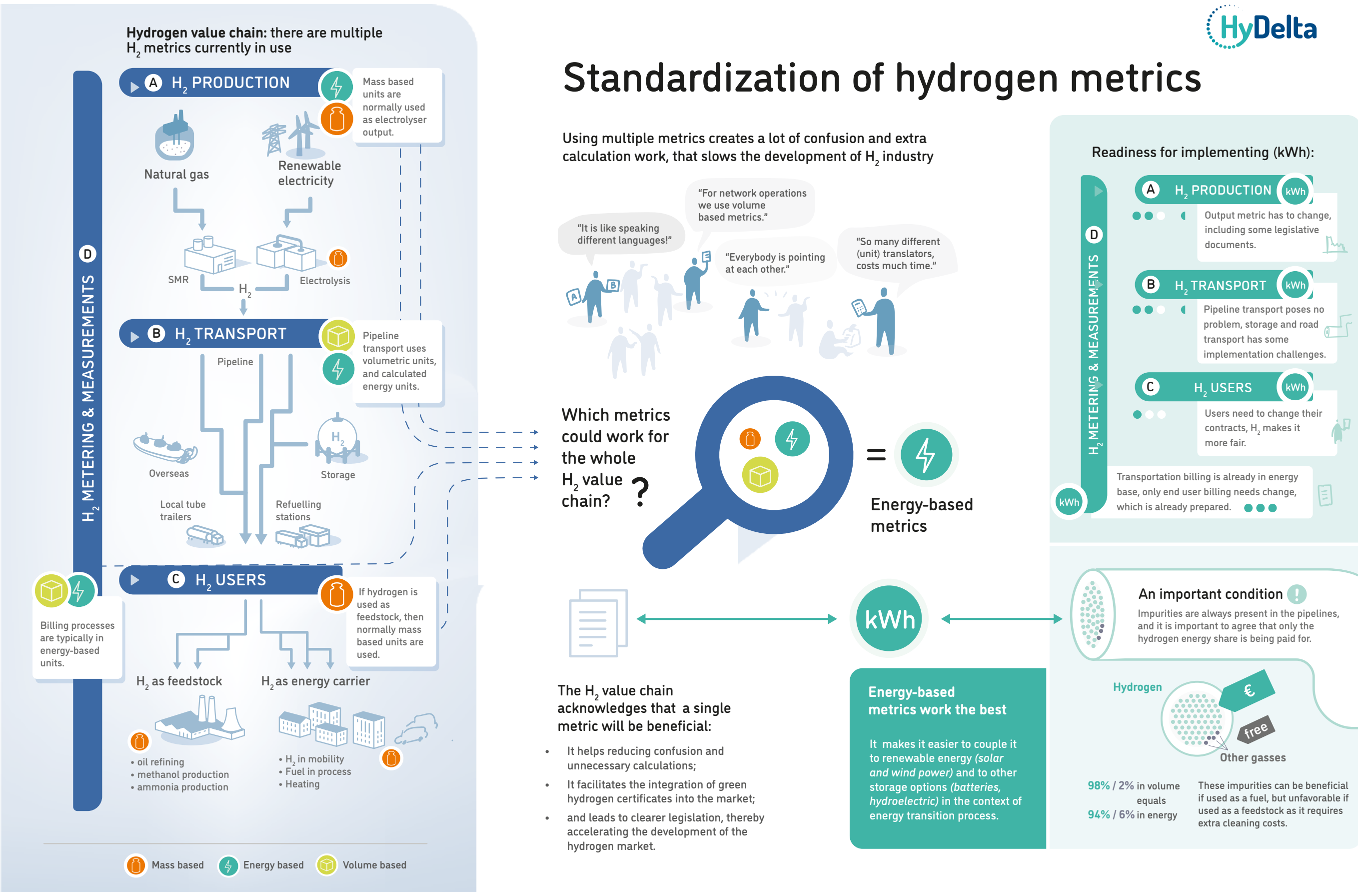


Figure 16: Infographic on hydrogen metrics.

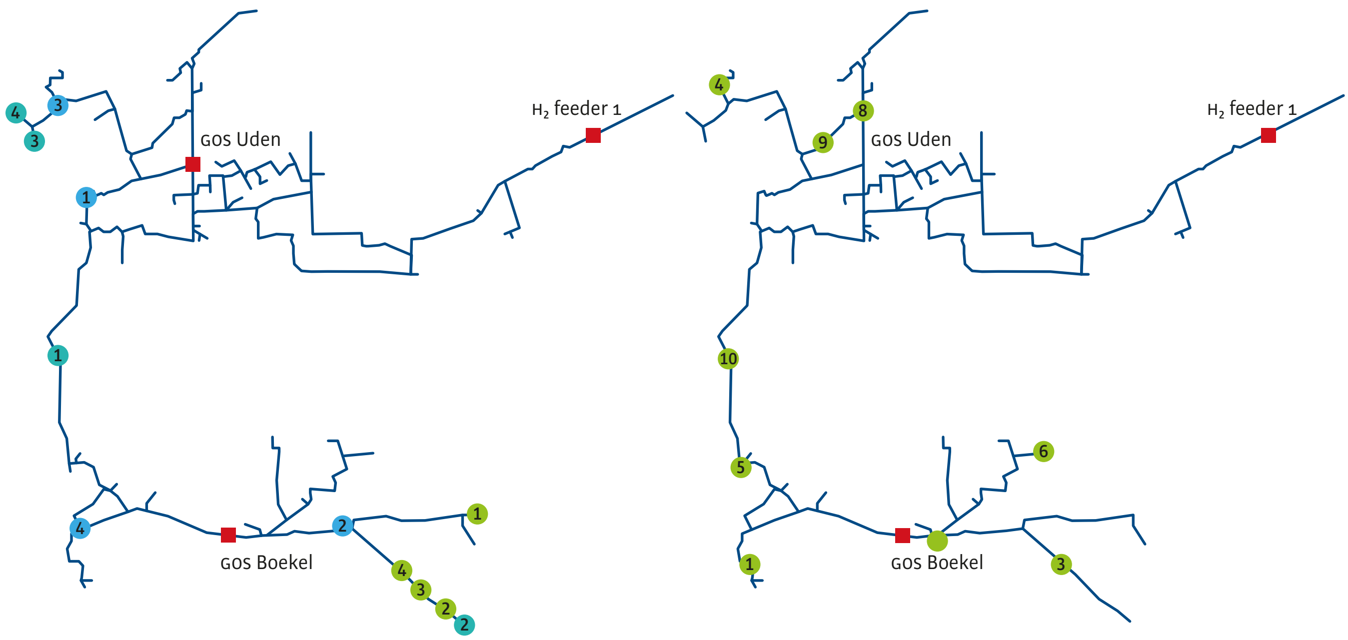


Figure 17: Comparison of pressure sensors placed by the practical rules (left) with the pressure sensors placed by the smart sensor placement algorithm Astraia (right).

Highest flow
Highest pressure drop
Longest distance GOS/feeder

From a legislative perspective the role of the DSOs is still not fully defined in the current situation, and therefore it is not clear who is responsible for the future feed in of hydrogen in the distribution grid and balancing demand and supply. Almost all important matters that still need to be arranged have to do with the role and responsibilities of the DSOs.

Hydrogen component manufacturing readiness and spatial requirements Components

The result of this study is a supply chain risk management (SCRM) approach that can be used by many different stakeholders in the hydrogen system.

The key finding from this study therefore is the importance of early-stage and continuous supply chain risk management to prevent component supply issues from hindering project timelines. Throughout the execution of these five steps, four methods or tools are applied: scenario planning, stakeholder consultation, risk assessment and critical path planning. In addition, generative AI software is applied to gather manufacturing industry characteristics. The SCRM approach is tested by means of two component case study deep-dives from an infrastructure point of view and one end-use component case: hydrogen gas compressors, hydrogen flow meter and hydrogen burner system.

The selected case study supply chains for compressor, flow meter and burner system demonstrate that these existing supply chains are ready to scale up further and have little vulnerabilities regarding sourcing, routing and flow volume. The flow destination and value density (i.e., compliancy to quality demands) does require mitigation actions to reduce the supply chain risk levels from those perspectives.

Figure 18: The five-step approach to assess supply chain risk in project planning

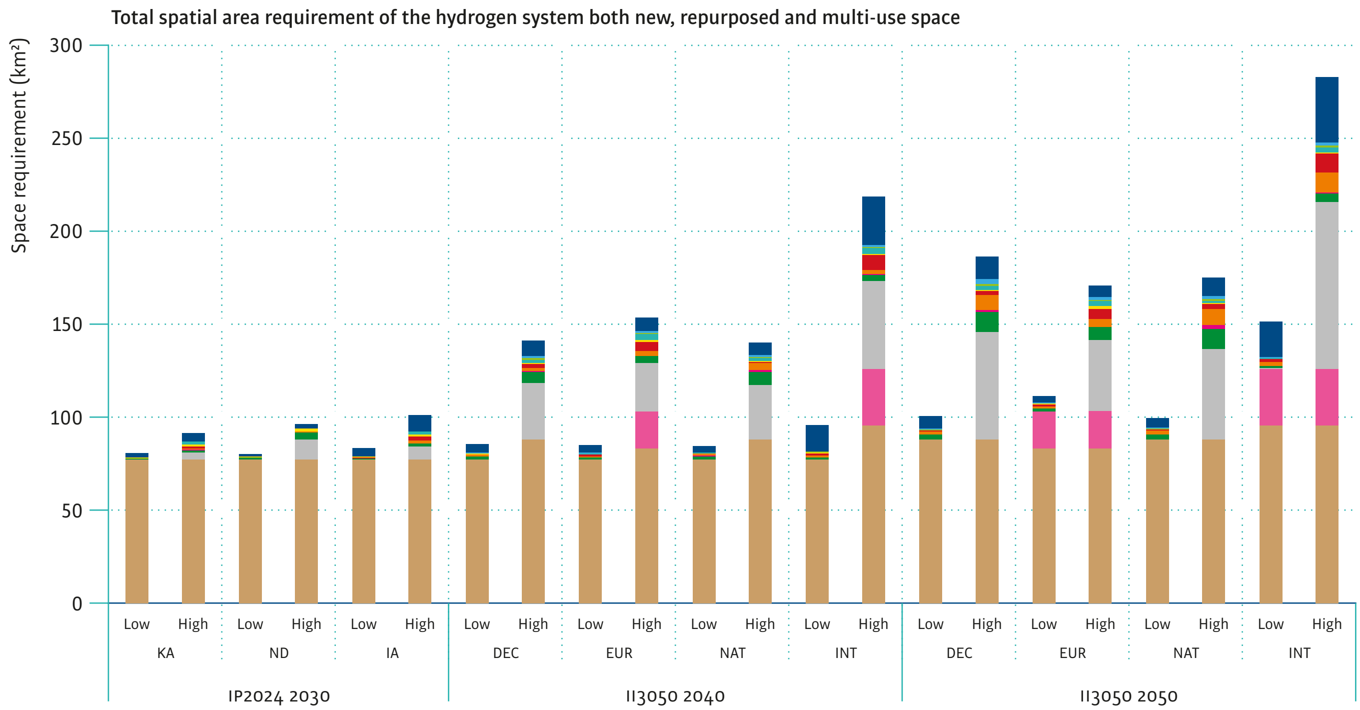


Figure 19: Bandwidth estimates of the total spatial requirement for the hydrogen subsystems included in the analysis

- HTL pipelines
- Electrolysis
- Hydrogen import terminals (baseload)
- Hydrogen CCGT
- RTL pipelines
- Offshore electrolysis
- SMR + CCS
- Hydrogen GT
- Hydrogen storage
- Hydrogen import terminals (peak)
- Biomass gasification
- Hydrogen tank stations

Footprint

The spatial footprint of the hydrogen system varies significantly due to uncertainties in assumptions and scenario choices. By 2050, the total area required ranges from 99 to 280 km², with the International Trade scenario needing the most space. The pipeline network is a major contributor, requiring 88-125 km², though repurposing existing natural gas pipelines can reduce new land use. Underground hydrogen storage needs 0.1-89 km², depending on inclusion criteria, while hydrogen refueling stations could take 3-35 km², though space-efficient designs may mitigate this. Hydrogen import terminals require 2-21 km², varying by import chain, with methanol storage needing less space than liquid hydrogen. Peak hydrogen import facilities add to the footprint despite contributing little to total imports. Hydrogen production needs up to 15 km², with onshore electrolysers occupying 11 km² and biomass gasification requiring relatively large space. Overall, reuse and efficiency measures can help minimize the system's land impact.

Section 5

Technology and Safety

5 Technology and Safety

Sources for this section

DELIVERABLE:

D5a.1 Quantitative risk assessment of hydrogen in the built environment - effect of mitigating measures

Link to deliverable

DELIVERABLE:

D5a.2 Purging of gas grids: alternatives for purging with nitrogen

Link to deliverable

DELIVERABLE:

D5b.1+2 Risks of hydrogen leakages // Preventive and corrective measures

Link to deliverable

DELIVERABLE:

D5c.1+2 Behaviour IPCO and Kleiss inflatable gas stoppers during ignition in pipes / Effectiveness double inflatable gas stoppers

Link to deliverable

DELIVERABLE:

D5d.1+2 Safety impact of permeation in gas distribution grids

Link to deliverable

DELIVERABLE:

D5e.2 Improving ventilation in hydrogen pressure regulation stations

Link to deliverable

Summary: The transition from natural gas to hydrogen in gas distribution networks presents new technological challenges and opportunities. In the HyDelta 3 work package on Technology and Safety various lab and field test were conducted to understand the risks, their mitigating measures, and safety considerations associated with using hydrogen in these networks.
The overall conclusion from the reports is that while hydrogen presents unique risks compared to natural gas, these risks can be effectively managed through various mitigating measures.

Quantifying risks of hydrogen in the built environment – the effect of mitigating measures

Any energy carrier comes with risks when handled, also in the built environment (homes, offices, shops etc.), where the impact of incidents could lead to personal injury. Avoiding all risks completely is often impossible or very costly, which is why any implementation needs to consider various risk mitigation measures in relation to their cost. HyDelta 2.0 (WP6) and new HyDelta 3 (WP5a) work has evaluated the risks of using hydrogen in distribution and transport networks compared to natural gas. A quantitative risk assessment (QRA) was conducted for a typical neighbourhood use case, revealing that the individual risk for hydrogen is higher than for natural gas due to the effects of a potential risk , but lower when considering the risk of carbon monoxide poisoning, which is not a factor with hydrogen. The total individual risk for hydrogen, without additional measures, is lower than for natural gas and lower than the generally accepted $1x10^{-6}$ contour. Nonetheless, the risk could be decreased further by additional measures and several such mitigating measures were assessed for their effectiveness in reducing risks associated with hydrogen leaks.

Doubling ventilation can give a risk reduction of 54% compared to the reference value, regular inspections can reduce it by up to 51%, excess flow valves can reduce it by 22.5%, and gas sensors can reduce it by 31% or up to 77% if coupled with an automatic shut-off valve. The study emphasizes the importance of implementing these measures cautiously, considering practical challenges and uncertainties in their effectiveness.

Purging gas grids with nitrogen, or with alternatives to nitrogen

Risks can be present in the built environment, but also during maintenance (and construction) in the gas distribution system itself. Typical maintenance may involve purging of assets with nitrogen to remove all flammable gases, but this comes at the cost of valuable hydrogen being flared or vented. It is therefore necessary to understand whether nitrogen purging is necessary for subsystems like gas stations, main/service lines, and gas meter installations prior to switching to or from hydrogen, and during maintenance. The findings described in D5a.2 suggest nitrogen purging isn't always needed for main lines without connections (up to 8 bar), but is recommended for low-pressure main lines with connections, service lines, and inhouse installations. Alternatives such as pressure swing, vacuum swing, and slug purging are reviewed. Slug purging is considered as an alternative, but further research is recommended.

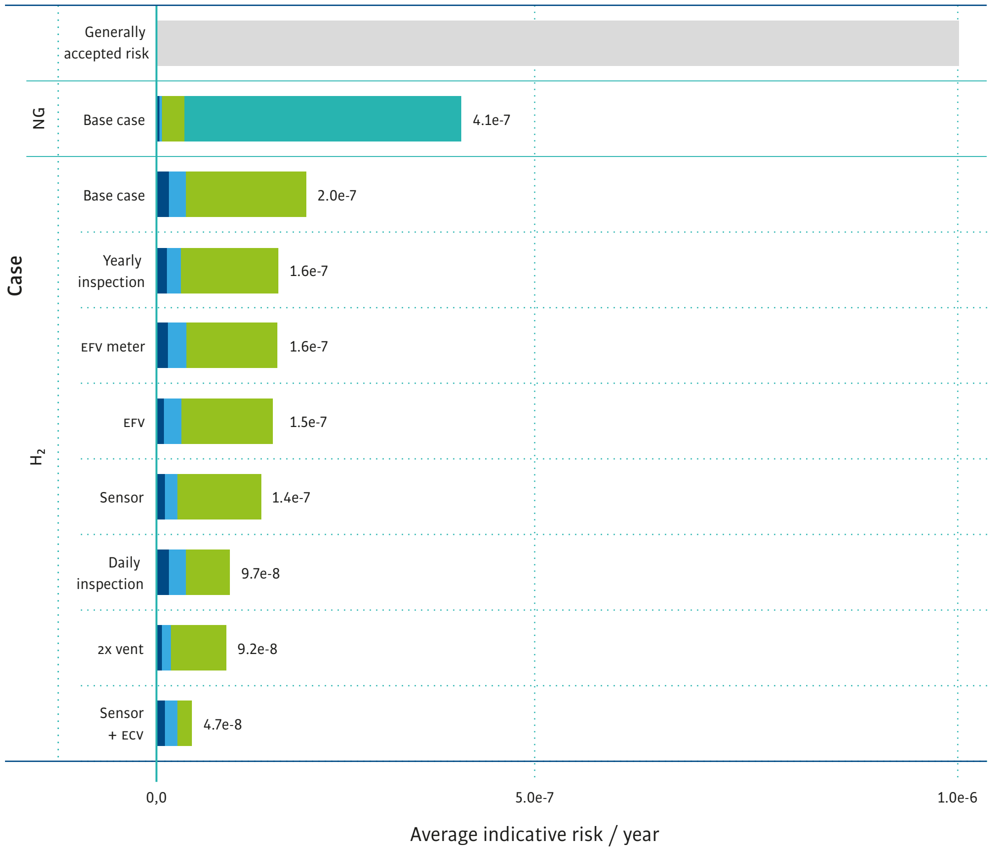


Figure 20: Quantified risk of hydrogen (and natural gas) in the built environment: base case and the effect of risk mitigation measures

Leakages and how to approach them

In general, most risks related to hydrogen distribution grids only occur when hydrogen starts leaking from the assets. Therefore, a review of the risks of hydrogen leaks was conducted and outlines for preventive and corrective measures are presented. The work presented in D5b.1+2 identifies causes such as corrosion, excavation damage, installation errors, ground movement, and point loads. Due to hydrogen's properties – lower ignition energy, wider flammability limits, higher outflow rate, and faster flame speed – leaks pose greater risks than for natural gas in comparable situations. Recommended measures include using thermal imaging cameras for leak detection, maintaining greater safety distances, flushing sectioned pipe sections with nitrogen, and ensuring repairs are not done under gas pressure. The importance of proper technician training is also emphasized.
Determining safety distances based on explosion consequences of smaller leak rates and further research into excavation work in hydrogen-saturated soil are suggested.

Behaviour of Inflatable Gas Stoppers

The results of WP5C evaluate the functionality of the IPCO and Kleiss inflatable gas stoppers (Dutch: "gasblazen") during ignition in pipes. The study finds that single inflatable gas stoppers are not always safe for hydrogen distribution networks. However, IPCO and Kleiss inflatable gas stoppers can be used temporarily with specific guidelines based on pipe size. Double inflatable gas stoppers enhance safety, especially for pipes over 110 mm in diameter. Recommendations include using nitrogen purging and simultaneous inflation of both stoppers to minimize risks. The report emphasizes proper preparation and application to avoid unsafe situations.

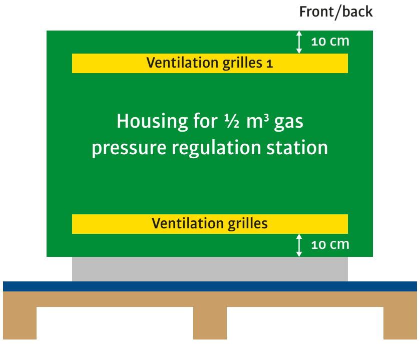


Figure 21: Schematic and photo of the pressure regulation station used for the ventilation experiments.

Ventilation in Hydrogen Pressure Regulation Stations

An asset in a hydrogen distribution chain where leakages may lead to risks is the pressure regulation station (PRS). As the properties of natural gas and hydrogen differ, a different build-up of hydrogen in the existing stations could be anticipated, which can be mitigated by changing the ventilation in the PRS. The work in WP5e explored solutions to improve ventilation in hydrogen gas pressure regulating stations. It emphasizes that enhancing ventilation, particularly by increasing the surface area with ventilation grilles, can lower hydrogen concentrations and mitigate risks at low additional cost. Various ventilation methods were tested, such as top and cross ventilation, showing that larger openings are effective for managing leaks. The report recommends additional ventilation grilles for future station designs to ensure better ventilation efficiency.

Safety surrounding hydrogen permeation

Permeation is a natural and unavoidable process where oxygen from the surrounding environment will permeate through the pipe wall into the gas network. Conversely, hydrogen from the gas network can permeate through the pipe wall to the environment. While it is typically a slow process, at least much slower than leakage where there is no barrier for the gas to permeate through, it could result in a hydrogen-oxygen at various locations in the distribution network.

Permeation (into the pipe) reduces gas quality, which can be detrimental to users and combustion appliances, as discussed in WP1a. Additionally, permeation may lead to the formation of a flammable mixture, potentially impacting safety during normal operations or maintenance work on the network. However, how the hydrogen-oxygen ratio evolves over time and in which situations a flammable mixture may form was not yet well understood. Deliverable 5d.1+2 describes 10 different scenarios where permeation may have an effect. These were evaluated for their realistic chance of occurrence and how fast flammable mixtures may arise.

Annex I

List of publications

Annex I List of publications

List of publications of the HyDelta 3 project

The HyDelta 3 project led to a total of 25 separate reports, and a public summary

All publications from the HyDelta 3 project are publicly available and can be found in the hydelta.nl/research-programme website (as for HyDelta 1 & 2). To increase the traceability and findability of all publications e.g., to be cited or included in further research down within and without the HyDelta programme of projects, each publication was given a Digital Object Identifier (DOI) i.e., a persistent identifier that uniquely points at each publication. Below is a list of all publications and their URLs in the Zenodo database.

Deliverable & publication date	URL
D1a.1: – Overview of basic elements for hydrogen purity standards – 21-8-2024	https://zenodo.org/records/13347786
D1a.2: – Strategies/Scenarios on how to deliver hydrogen purity in distribution networks – 26-3-2025	https://zenodo.org/records/15023897
D1b.1 – Pipeline Contamination – 2-9-2024	https://zenodo.org/records/13627543
D1b.2 – Repurposing protocol offshore pipelines for hydrogen transport – 6-2-2025	https://zenodo.org/records/14825905
D2a.1 – The role of standalone hydrogen areas in decentral hydrogen infrastructure development – 25-3-2024	https://zenodo.org/records/13255231
D2a.2 – Societal optimal hydrogen distribution – 6-8-2024	https://zenodo.org/records/13238281
D2a.3 – Electrolyzer business case in a standalone hydrogen area and the effect of adding firm/non-firm grid tariffs – 16-12-2024	https://zenodo.org/records/14399317
D2b.1+2 – Risk governance and societal embeddedness for hydrogen infrastructure – 18-12-2024	https://zenodo.org/records/14515047
D3a.1 & D3a.2 – Greenhouse potential of hydrogen emissions from the grid - Emission amounts and Priority of reduction – 6-10-2024	https://zenodo.org/records/13895376
D3b.1 – Factsheet Ammonia Cracking Technologies – 5-4-2024	https://zenodo.org/records/14134308
D3b.2 – Ammonia utilization in the power sector – 20-8-2024	https://zenodo.org/records/13347756
D3b.3 – Ammonia Tanker Fleet Analysis – 6-10-2024	https://zenodo.org/records/13895458
D3b.4 – Scenario analysis of emissions associated with supply of hydrogen in the form of ammonia – 22-11-2024	https://zenodo.org/records/14204393
D4a.1 – Roadmap to Hydrogen Metrics Standardization – 6-10-2024	https://zenodo.org/records/14016452
D4a.2 – Which unit is best to use for hydrogen? – 6-11-2024	https://hydelta.nl/welke-eenheid-gebruik-je-het-beste-voor-waterstof
D4b.1 – Controlling protocols and strategies for decentralized hydrogen feed-in – 10-7-2024	https://zenodo.org/records/12705978
D4b.2 – Optimal sensor placement strategies for monitoring the dynamic pressure of gas networks – 29-11-2024	https://zenodo.org/records/14242942

D4c.1 – Supply chain risk management approach for hydrogen infrastructure components – 4-12-2024	https://zenodo.org/records/14272947
D4c.2 – Spatial requirement contours of hydrogen projects – 25-11-2024	https://zenodo.org/records/14216178
D5a.1 – Quantitative risk assessment of hydrogen in the built environment - effect of mitigating measures – 6-1-2025	https://zenodo.org/records/14552778
D5a.2 – Purging of gas grids: alternatives for purging with nitrogen – 12-03-2025	https://zenodo.org/records/15011297
D5b.1+2 – Risks of hydrogen leakages / Preventive and corrective measures – 15-04-2025	https://zenodo.org/records/15023952
D5c.1 – Behaviour IPCO and Kleiss inflatable gas stoppers during ignition in pipes / D5c.2 – Effectiveness double inflatable gas stoppers – 16-12-2024	https://zenodo.org/records/14399445
D5d.1 – Safety impact of permeation in hydrogen distribution grids – 16-05-2025	https://zenodo.org/records/15437198
D5e.2 Improving ventilation in hydrogen pressure regulation stations – 6-1-2025	https://zenodo.org/records/14698032