European Commission

Study on hydrogen quality in dedicated infrastructure and standardisation

Final Report

LBST | DNV | DBI GUT | Trinomics

October – 2025

EUROPEAN COMMISSION

Directorate-General for Energy
Directorate C — Green Transition and Energy System Integration
Unit C.2 — Decarbonisation and Sustainability of Energy Sources

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European Commission
B-1049 Brussels

EUROPEAN COMMISSION

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Manuscript completed in March 2025

1st edition

Luxembourg: Publications Office of the European Union, 2025

PDF ISBN 978-92-68-33238-2 doi:10.2833/8623209 MJ-01-25-136-EN-N

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FINAL REPORT

31-03-2025

Contract details

European Commission – Directorate-General for Energy
Study on hydrogen quality in dedicated infrastructure and standardisation
Reference Number: ENER/C2/2023-397

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Ottobrunn, Germany, 31/03/2025

Disclaimer:

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Ottobrunn, 31/03/2025

Study on hydrogen quality in dedicated infrastructure and standardisation

Final Report

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Table of Contents

Abstract

English

The study provides a technical analysis as support for further standardization activities on the gas quality in Europe's future hydrogen infrastructure. It synthesizes key literature on the influence of different supply chain elements on hydrogen gas composition and assesses the implications of varying purity levels for end-users. Existing hydrogen quality standards are reviewed, and a wide set of stakeholder positions, gathered through a survey among key actors of the future hydrogen supply chain, are analyzed. From that, three hydrogen quality specifications (98 mol%, 99.5 mol%, and 99.97 mol%) along with different limits for key contaminants are derived. Finally, the respective costs of purification efforts are assessed for the case, these specifications were applied as a grid standard. The analysis covers different elements across the supply chain, including transport pipelines, underground storage, and different end user groups. The modular cost assessment enables scenario-based evaluations aligned with projected market developments and different grid configurations. The results can support upcoming discussions among key stakeholders on the identification of a common grid specification but also the underlying questions of who should bear the responsibility (and the costs) of ensuring this quality.

French

L'étude fournit une analyse technique à l'appui de nouvelles activités de standardisation sur la qualité du gaz dans la future infrastructure européenne de l'hydrogène. Elle synthétise les principales publications sur l'influence des différents éléments de la chaîne d'approvisionnement sur la composition de l'hydrogène gazeux et évalue les implications des différents niveaux de pureté pour les utilisateurs finaux. Les normes de qualité de l'hydrogène existantes sont passées en revue et un large éventail de positions des parties prenantes, recueillies par le biais d'une enquête auprès des principaux acteurs de la chaîne d'approvisionnement de l'hydrogène, est analysé. À partir d'ici, trois spécifications de qualité de l'hydrogène (98 mol%, 99,5 mol% et 99,97 mol%) ainsi que différentes limites pour les principaux contaminants sont dérivées. Enfin, les coûts respectifs des efforts de purification sont évalués dans le cas où ces spécifications sont appliquées comme norme de réseau. L'analyse couvre différents éléments de la chaîne d'approvisionnement, y compris les pipelines de transport, le stockage souterrain et différents groupes d'utilisateurs finaux. L'évaluation modulaire des coûts permet des évaluations basées sur des scénarios alignés sur les développements prévus du marché et les différentes configurations du réseau. Les résultats peuvent étayer les discussions à venir entre les principales parties prenantes sur l'identification d'une spécification de réseau commune, mais aussi sur les questions sous-jacentes de savoir qui devrait assumer la responsabilité (et les coûts) de la garantie de cette qualité.

Executive Summary

The transition of the European gas infrastructure from natural gas to hydrogen and other renewable gases is a fundamental pillar of the European strategy to reach climate neutrality and to achieve a higher energy independency via diversification and domestic production. Coordination among the interests of different actors and Member States will be needed to enable and ensure a successful pathway towards decarbonisation. Harmonisation of the gas quality within a dedicated gaseous hydrogen grid on European level is considered one crucial element for building a strongly-interconnected and transparent European hydrogen market. Examples from the existing natural system show that differences between countries in gas quality specifications or contaminants' limits pose limitations and challenges on cross-border trade resulting in the need for additional quality adjustment measures at interconnection points.

In contrast to natural gas, an interconnected European hydrogen infrastructure is still at the very beginning. As there are no binding national hydrogen quality specifications in place yet, there is a window of opportunity for all market actors in creating a common quality standard applied for the transport of hydrogen via pipelines in Europe. Regulators can provide guidance during that process by considering technical and economic issues of a wide range of involved stakeholders to develop widely accepted standards. This is supplemented by the Hydrogen and Decarbonised Gas Market Package: with the Directive (EU) 2024/1788 (e.g. Art. 44 and 50) and the Regulation (EU) 2024/1789 (e.g. Art. 69 and 72), the EU Member States as well as the European Parliament enforces the European Commission to support further international standardisation activities on hydrogen quality. Therefore, a standardisation request to the relevant standardisation organisation CEN/CENELEC is planned with the aim to achieve a consensus among different stakeholders that supports the development of hydrogen markets and future legislation in Europe.

The present study provides technical background and assistance for this task, presenting key elements of the technical and economic discussions in the context of hydrogen quality. In a first step, key literature findings on the impact of different supply chain elements on the hydrogen quality as well as the potential effect of different hydrogen qualities on end-users are summarized. This is followed by an overview and comparison of existing quality standards for gaseous hydrogen. A summary of a wide set of stakeholder positions, expectations and opinions was collected via an intensive stakeholder interaction process and are presented in this study. Based on that, three different quality specifications with hydrogen concentrations of 98 mol%, 99.5 mol% and 99.97 mol% as well as contaminants' limits are derived. The study includes an intensive analysis of the purification efforts and costs that are related with applying these specifications as a grid standard for the European hydrogen grid – both, the purification costs for individual supply chain elements as well as along the overall supply chain (i.e. transport pipelines, underground storage and different end-user groups with deviating quality requirements). By taking not only the hydrogen content but also a wide set of relevant contaminants into account, the study provides profound insights and guidance for further development of gas quality regulation and standardisation. In addition, the modular set-up of the purification cost analysis allows an individual analysis for each EU Member State and their expectations on a future hydrogen gas system. The results will support further discussions among key stakeholders on the identification of a common grid specification but also the underlying questions of who should bear the responsibility (and the costs) of ensuring this quality.

State-of-the-art – Interplay of gas quality with hydrogen supply chain elements

In order to enable a fact-based analysis and discussion, this study provides an overview of existing knowledge and experience on these quality-related aspects. In a first step, the impact of different key infrastructure elements along the hydrogen supply chain on hydrogen gas quality and possible contaminations are summarised based on the available literature. Depending on the technology for production, transport and storage, different sources of impurities and contaminants are described

(see Table 1-1). Based on the analysis, repurposed natural gas pipelines and certain types of underground storage sites (e.g. repurposed salt caverns and porous media reservoirs) can be considered as key bottlenecks along the supply chain as they may introduce additional contaminants into the hydrogen gas stream via transport and storage leading to significant purification efforts.

Table 1-1: Overview of main contaminants along key elements of the hydrogen supply chain

Supply chain elements	Potential sources	Potential Impurities / contaminants (in brackets: indication of probability[1])
Production	Electrolysis - AEL	Nitrogen (+), water (o), oxygen (o), cations (o), argon (-)
	Electrolysis – PEMEL	Nitrogen (o), water (o), oxygen (o), carbon dioxide (-)
	Steam reformation (SMR) + (PSA)	Carbon monoxide (++), nitrogen (+), methane (o), water (o), argon (o), formaldehyde (-)
Conversion	Ammonia cracking	Ammonia (+), nitrogen (+)
Transmission and Distribution	Converted natural gas pipelines	Typical associated gas components, trace odorants (sulphur), condensate components (+) (decreasing over time)
	Operations and maintenance (new and repurposed pipes)	Nitrogen (purging) (o), Lubricants / compressor oils (piston compressors) (o)
Underground storage	Salt caverns (new)	Water (+), methane (o), sulphur compounds (o), higher hydrocarbons (o)
	Porous media storage	Water (+), methane (++), sulphur compounds (+), higher hydrocarbons (+)
	Operations and maintenance	Lubricants / compressor oils (piston compressors) (o) Glycol (dehydration processes) (o)

[1] Assumed probability: (++) frequent, (+) possible, (o) rare, (-) very rare (based on terminology used in Bacquart 2018[1], adapted for transmission and storage elements based on qualitative analysis performed in this study). Note: probability indicative only.

In a second step, the study discusses the **purity requirements and the effect of different contaminants on end-use applications.** Table 1-2 summarises key learnings on the tolerance of different end-user sectors and applications for low, medium and high hydrogen quality levels.

Table 1-2: Quality requirements of different application without further on-site purification

Quality requirements by sector / application		≥ 98 mol% H_2 = "low" quality	≥ 99 mol% H_2 = "medium" quality	≥ 99.97 mol% H_2 = "high" quality
Building (low temperature heat)		(✓)	(✓)	✓
Energy / power generation		(✓)**	(✓)**	✓
Mobility	ICE	✓	✓	✓
	PEM FC	Not suitable	Not suitable	✓
PtX		Not suitable	✓	✓
Industry (examples)	Construction aggregates (Stones and soils)	✓	✓	✓
	Paper	✓	✓	✓
	Glass and ceramic	✓**	✓**	✓
	Iron and steel	✓*	✓*	✓
	(Petro-) chemistry (feedstock / non-energy use)	Not suitable	✓*	✓

Source: Adapted based on DBI GUT & Frontier (2022)[2]. Low- and high-quality specifications referring to DVGW G260 Group A & D.
Please note: parathesis ( ) indicate that suitability depends on type of use or specific contaminant / trace component
*Dependent on the composition of trace components. **Dependent on stability of the Wobbe index over time.

[1] *Bacquart, T. (2018): Probability of occurrence of ISO 14687-2 contaminants in hydrogen: Principles and examples from steam methane reforming and electrolysis (water and chlor-alkali) production processes model. International Journal of Hydrogen Energy, Volume 43, Issue 26, Pages 11872-11883, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2018.03.084.*

[2] *DBI GUT & Frontier Economics (2022): H2 Rein - H_2 short study: Hydrogen quality in an all-German hydrogen network, https://www.dvgw.de/medien/dvgw/forschung/berichte/g202140-finalreport-h2shortstudy-engl.pdf*

Due to high technological readiness, there is a good understanding of the impact of different contaminants on **fuel cell mobility applications**: Purity level ≥ 99.97 mol%[3] is considered as the minimum hydrogen concentration as described in international standards (e.g. ISO 14687 or EN 17124). CO, H_2S and NH_3 impurities are typically seen as the critical contaminants with the largest negative effect on fuel cell performance. Differently, **combustion processes** for heat or energy use are mostly not considered being sensitive regarding the composition of the gas. Instead, burning properties (Wobbe index and heating value) of the fuel gas must not fluctuate too much. Certain types of industries, where end-product properties are directly influenced by flame properties (e.g. temperature and flame speed) can, however, show stricter quality requirements, e.g. the glass industry. Sectors, where hydrogen is used as a **feedstock** show very case-specific quality requirements, both regarding gas purity and the tolerated level and type of contaminants. To limit poisoning of process catalysts, very high qualities (sometimes even above 99.97 mol%) are desired in some processes, requiring on-site purification.

All these elements show the complexity of setting a harmonised network standard for hydrogen quality.

Existing standardization landscape and developments in selected Member States

A comprehensive set of different hydrogen quality standardization documents, technical rules and/or other harmonisation activities already exist aiming to specify common requirements for admissible (minimum) hydrogen purity levels as well as (maximum) concentrations of key contaminants. The technical standards in general address one specific infrastructure element (e.g. pipeline transport) or end-use (see Table 1-3.)

Table 1-3: Overview relevant hydrogen quality standards, technical rules and further harmonisation activities in Europe

	Standard	Name	Scope	Comment
Transport / Pipeline	CEN/TS 17977:2023 **(2023)**	Gas infrastructure - Quality of gas - Hydrogen used in rededicated gas systems	H_2 pipelines (rededicated NG pipelines)	H_2 quality: **≥98.0%**, Wobbe Index: 42-46 MJ/m³ (15 °C/15 °C) Note: different specifications compared to ISO 14687 Grade A
	EASEE-gas: Common Business Practice 2022 – 001/01 (CBP) **(2022)**	Hydrogen Quality Specification	H_2 pipelines (rededicated NG pipelines)	**≥98.0%** (reference to ISO1467:2019 Grade A, Specification of critical components only) Note: on-site purification for O_2 or sulphur components.
	DVGW G260:2021 (DE) **(2021)**	Technical Rule on gas quality ("Gasbeschaffenheit")	H_2 pipelines (for gases in public infrastructure in Germany)	Gas family 5, group A with **≥98.0%** and group D with **≥99.97%** (reference to EN 17124:2019) Currently under revision to (possibly) include **99.5% (tbc)** as additional "grade" "group A+"
	Fluxys Hydrogen specification proposal (BE) **(2022)**	Hydrogen Specification Proposal	H_2 pipelines (transmission system by Fluxys Belgium)	H_2 quality: **≥98.0%** Aligned with EASEE-Gas (CBP H2), CEN, specifications for UK, NL and DE, + further stakeholder input
	Indicative quality specification for Hynetwork (NL) **(2024)**	Indicative quality and temperature specification for Hydrogen Network Netherland	H_2 pipelines (for Hydrogen Network Netherland)	H_2: **≥99.5%**, indicative only, based on results of DNV/KIWA studies, final decision by Ministry open Note: Former version (2022) with 98%.
End-use	ISO/DIS 14687:2024 (E) **(2024)**	Hydrogen fuel quality — Product specification	End-uses (different)	Different Grades (A-F) for state of hydrogen and end-use **≥98.0% (Grade A) – ≥99.995% (Grade C)**
	EN 17124:2022 **(2022)**	Hydrogen fuel - Product specification and quality assurance for hydrogen refuelling points dispensing gaseous hydrogen - (PEM) fuel cell applications for vehicles	PEM fuel cell (vehicles)	H_2 quality: **≥99.97%** Fuel quality requirements at the dispenser nozzle + risk assessment / probability of occurrence + severity class, impact on fuel cell at certain concentrations

The present analysis screens ongoing activities in selected EU Member States. The results highlight the frontrunner position Belgium, the Netherlands and Germany have on hydrogen quality definitions and requirements – with proposals or indicative specifications already published. From these countries, the transmission system operators (TSOs) as important stakeholders are (among others) promoting a grid specification of >99.5 mol% hydrogen – based upon technoeconomic studies, e.g. by DNV & Kiwa 2023[4].

The regulatory and legislative frameworks for a future hydrogen grid quality is reviewed for further Member States. While the public discussion on future hydrogen quality is less advanced in these other

[3] *Unless stated otherwise, quality specifications in % refer to mol% in this report.*

[4] *DNV and Kiwa (2023). A follow-up study into the hydrogen quality requirements. Available at: https://www.eerstekamer.nl/overig/20231009/rapport_kiwa_dnv/document*

countries, significant differences can be observed, e.g. on the role of repurposed natural gas infrastructure (dominant in Italy or Spain) or a focus on industrial hubs or hydrogen valleys, rather than a national hydrogen grid (e.g. in France or Poland). In any case, these different approaches need to be considered when driving harmonisation activities in gas quality. In this context, the European Network of Hydrogen Network Operators (ENNOH) will play a key role coordinating the planning, development and operation of future hydrogen infrastructure in Europe among the national Hydrogen Transmission Network Operators (HTNOs).

Key insights from stakeholder engagement

The perspectives on a desired hydrogen quality specification in a European hydrogen infrastructure of a broad group of stakeholders– with diverse representation of different groups and regions was collected. Feedback from ~50 stakeholders was received during a survey and follow-up interviews (including established actors from energy and gas sector as well as hydrogen-specific ones).

The overarching learnings from the stakeholder involvement are the following:

- **There is market convergence among stakeholders on dominant future hydrogen end-uses and hydrogen production methods.** The use of hydrogen in chemical feedstock, electricity generation, and the steel industry are expected to be dominant end-uses during the market ramp-up phase. The main production method is expected to be renewable hydrogen (produced by electrolysis using offshore wind and possibly solar in the south), with import (ammonia, LOHC and pipeline) and blue hydrogen being used during the market ramp-up.
- **Stakeholders are split between 98 % and 99.5 % hydrogen on their desired hydrogen purity level in the future hydrogen network.** Arguments for both sides are:
  - **98 %:** Proponents for 98 % hydrogen purity argue that this is purity level is of sufficient quality to meet most demand, that any higher purity level would be uneconomical/infeasible for underground gas storages and that these storages are required in the backbone due to dynamic demand.
  - **99.5 %**: Proponents for 99.5 % hydrogen purity argue that this is an optimum in terms of purification cost, that infrastructure (and some storages) can technically transport and store this purity and that pricing methods for hydrogen will drive the purity level up.
- **Beside the purity level, end-users require stringent contaminant limits on substances that may poison catalysts in industrial processes and fuel cells**. Since feedstock is expected to be a dominant end-user, these stakeholders argue that the backbone specification should be aligned with this view. Furthermore, **stability of gas composition** and hence the impact on physical properties like Wobbe index are important for industrial end users who utilize combustion processes.
- **The requirements of storages might be misaligned with the abovementioned requirements of industrial (feedstock) end-users.** Storages are important for network balancing, however, contaminants from their storages can have a negative impact on industrial processes. Therefore, storages operators are a key stakeholder group in the hydrogen quality standardization process.

Based on the received feedback, recommendations are derived for changes to existing and proposed new standards. Furthermore, three example quality specifications are proposed as basis for cost analysis in this study (see Table 1-4 for details):

1) 98 mol% - particularly suitable for combustion processes with lower quality needs.
2) 99.5 mol% - suitable for many industrial and most end-use applications.
3) 99.97 mol% - required for sensitive applications such as fuel cells or certain chemical processes.

Table 1-4: Proposed specifications for three purity level based on stakeholder input. Existing standards were used as reference to allow to show the changes made.

Property	Example hydrogen specifications		
	>98.0 mol%	>99.5 mol%	>99.97 mol%
Wobbe Index	41.89– 45.89 MJ/m³, (15 °C/15 °C)	43.45-45.89 MJ/m³, (15 °C/15 °C)	n/a
ΔWobbe index	<0.5 MJ/m³ minute		n/a
Water	<250 ppm at <10 bar <60 ppm at >10 bar		<5 ppm
Water Dewpoint	<-8 °C at 70 bar		
Hydrocarbons	<20,000 ppm	<5,000 ppm	< 2 ppm
Oxygen	<10 ppm		
CO and CO_2	<40 ppm (20 ppm each)		<2 ppm (total)
Ammonia	<10 ppm		<0.1 ppm
Inert Gases	<20,000 ppm	<5,000 ppm	< 300 ppm
Halogenated Compounds	<0.05 ppm		
Dust and Particulates	<1 mg/kg		
Total Sulphur	<7 ppm	<3 ppm	<0.05 ppm
Formaldehyde	<10 ppm		<0.01 ppm
Formic acid	<0.2 ppm		
Hydroxides (KOH, NaOH)	<2 ppm		

Conclusions on purification cost analysis

The final element of this study is a cost analysis that assesses the economic impact hydrogen purification has in case of (i) adopting the defined specifications as grid purity and (ii) different configurations of the gas infrastructure (e.g. role of new vs. repurposed pipelines). The aim is to identify the main cost drivers, highlight specific purification cost optimisation potential and derive strategic recommendations that contribute to the realisation of a cost-efficient hydrogen network.

The **methodology** is based on four key steps: (1) literature and market research, (2) definition of the hydrogen supply chain, purification steps and grid configurations, (3) identification of purification cost parameters, and (4) calculation of purification costs at individual supply chain steps and along the overall supply chain. By introducing a modular approach, the presented cost data provide the basis for further analysis taking different market scenarios as well as national characteristics into account.

As a basis for the analysis **purification steps and suitable technologies** are described for the different elements of the supply chain. Purification efforts and costs for removal of specific contaminants (e.g., N_2, CO, CO_2, CH_4, H_2O, sulphur compounds, O_2, NH_3) are summarised in an inventory. The analysis highlights that the choice of purification strategy is crucial for the economic performance of the overall system. While upstream purification at entry points can reduce downstream treatment efforts, it is associated with higher costs, particularly if strict purity requirements must already be met by producers. Furthermore, additional purification may be needed at grid exit points, to ensure high gas quality. Downstream purification at end-users' site, on the contrary, offers higher grid flexibility but results in additional energy consumption and increased operational costs.

Regardless of future infrastructure developments, certain purification steps represent **"no-regret" investments**, as they are essential for ensuring hydrogen quality across the value chain. In particular, purification is always required after production, especially for SMR and ATR processes, where CO, CH_4, and sulphur compounds must be removed via PSA. Likewise, hydrogen transported through repurposed natural gas pipelines will inevitably require membrane separation or PSA to eliminate residual CH_4 and CO_2. The most critical purification needs arise after storage in porous underground formations, where contamination with CH_4, CO_2, and H_2S is unavoidable, necessitating a combination of PSA and cryogenic separation.

In a first step of the cost analysis, a so-called **sensitivity analysis** with variation in the configuration of the infrastructure and end-users' composition is applied. This allows for assessing the impact of a best- vs. a worst-case grid configuration[5] and potential combinations of both on the purification costs. In a second step, the modular set-up of the cost tool is applied to perform a detailed **cost assessment along the overall supply chain** by considering individual scenarios on future market development. In both cases, the cost data is presented as specific purification costs in € per kg hydrogen.

The modular **sensitivity analysis** allows to identify key cost drivers: repurposed natural gas infrastructure and underground storage, particularly porous reservoirs and former natural gas fields, present significant challenges when it comes to high grid specifications. Residual gases from previous use, including methane, carbon dioxide, and sulphur compounds, can affect hydrogen quality over long periods and require more intensive post-storage-purification. Especially in the first years after repurposing, the hydrogen content in stored gas withdrawals can fluctuate significantly, making additional treatment necessary to maintain a consistent network quality. Consequently, a dedicated hydrogen network with new infrastructure ("best case configuration") results in the lowest additional purification costs, as impurities can be minimized in advance. The analysis also highlights that economies of scale play a crucial role: larger, centralized purification units are significantly more efficient than multiple smaller, decentralized facilities. In these cases, however, the economic use of large quantities of tail gas streams (e.g. from PSA) need to be considered.

In the second step, **an example scenario ("reference scenario")** is applied to illustrate the practical application of the modular purification cost data to assess the overall (additional) purification costs along the hydrogen supply chain. For this, the following exemplary distribution of hydrogen across different infrastructure components and end-use applications is considered – derived from literature data on a potential future market set-up. Key assumptions for the grid configuration are:

- 40 % of the hydrogen is transported via newly built pipelines, while 60 % flows through repurposed natural gas pipelines.
- 90 % of the hydrogen is supplied directly to end-users, while 10 % is injected into underground storage facilities. These stored 10 % are then equally split between new and repurposed storage infrastructures, with 5 % allocated to each.

The end-use applications are divided into three (theoretical) groups requiring hydrogen with a certain minimum quality. For the sake of this analysis, the same specifications as derived for the grid are applied (see Table 1-4). It is assumed that 50 % of the overall demand is allocated to applications requiring a minimum purity of 98 mol%, 25 % require >99.5 mol%, and 25 % require 99.97 mol%. Depending on the applied specification in the grid, additional on-site purification is needed. For this specific scenario, the resulting final specific purification costs along the overall supply chain are (i) 1.05 €/kg in case of an assumed grid quality of >98 mol% purity, (ii) 0.78 €/kg (>99.5 mol% grid purity) and (iii) 1.24 €/kg (>99.97 mol% grid purity) In other words, these are the costs that need to be added for purification along the supply chain on top of the levelized cost of hydrogen production (LCOH).

Variations of this reference scenario with different compositions of the hydrogen demand are also presented in the analysis – considering a focus use of hydrogen (=50 % of overall demand) in applications requiring either a low, medium or high hydrogen quality, respectively.

[5] *In the best-case configuration, an infrastructure specially designed for hydrogen is considered. This uses modern materials, advanced monitoring systems and optimised processes, resulting in low overall pipeline cleaning costs. In the worst-case configuration, existing natural gas infrastructures are repurposed. This conversion requires extensive retrofitting and leads to higher purification costs.*

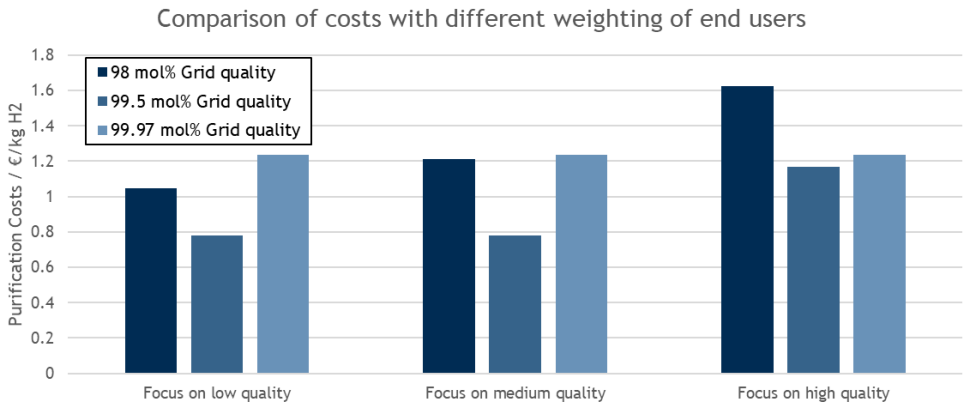

Figure 1-1: Comparison of overall purification costs along the supply chain (transport, storage and demand) under the assumptions of the reference scenario with variations in end-users' composition.

The overall results indicate that – independently of the assumed composition of end-users' demand – the lowest additional purification costs along the supply chain are observed for the cases with a medium grid quality of 99.5 mol% (medium blue bars in Figure 1-1). The specific purification costs in case this specification is applied remain exemptional low (around 0.80 €/kg) for the scenarios with a focus on end-users with low and medium quality requirements. In contrast to that, when a specification of 98 mol% is applied to the grid (dark blue bars) purification costs significantly increase from 1.05 €/kg to up to 1.60 €/kg, when the share of end-users requires high hydrogen quality of above 99.97 mol% increases. The reason is the additional on-site purification needs. In contrast, a high grid quality of >99.97 mol% minimizes additional purification efforts on site – shifting the purification to upstream actors (with costs around 1.25 €/kg for all scenarios).

The observed **main cost drivers** can thus be divided into three categories:

- Firstly, the infrastructure configuration is a significant factor. The conversion of existing natural gas pipelines requires extensive cleaning and flushing processes to remove residues. New hydrogen pipelines, on the other hand, offer the advantage that they can be specially designed to meet high purity requirements. In this context, the significantly higher investment costs of new pipelines compared to repurposed natural gas pipelines, need, however, also be considered.
- Secondly, a particularly significant factor for purification cost is the dependence on storage technology: underground storage facilities – needed for balancing seasonal supply and demand variations – in general, pose a challenge on the system. These can contaminate hydrogen, requiring both pre- and post-treatment processes before reinjection. While newly built salt cavern storage facilities lead to lower purification needs, these are not available all over Europe. Porous media storages, however, require additional purification efforts.
- Thirdly, the investment and operating costs of purification steps increase with increasing purity requirements. Proven technologies such as pressure swing adsorption (PSA) and other developing adsorption technologies play a central role here. The removal of trace elements such as sulphur and nitrogen are particularly cost-intensive. In addition, modern purification technologies such as optimised PSA plants or innovative membrane processes can significantly reduce energy consumption.

Outlook – next steps towards standardisation

Despite the broad scope of this study, the present work has some **limitations** which can suggest avenues for further work. Some key elements include the general lack in experience with hydrogen networks, the highly divers and dynamic character of the regulatory and legislative environment among EU member states as well as international standardisation activities, as well as challenges in the stakeholder involvement regarding the high number of participants but also the lack of industry feedback on purification cost estimations. For the cost analysis, two main limiting aspects need to be

mentioned: (i) the analysis do not provide a system-wide cost optimization as these strongly depend on the expected hydrogen market development. (ii) In addition, the purification steps required at production site before grid injection are not included in the cost analysis as purification efforts itself are technology-specific and, hence, are considered as inherent part of the levelized cost of hydrogen (LCOH).

Nevertheless, the present study provides a comprehensive basis for further standardisation efforts regarding an upcoming European hydrogen grid. In these efforts, it is key to involve stakeholders from different categories: (i) legislative (e.g. regulatory authorities, incl. energy regulators in EU Member States), (ii) independent standardisation organisations like ISO and CEN/CENELEC and (iii) individual national key stakeholders, like grid and storage operators but also other actors along the supply chain.

In summary, the following initiatives should be integrated into future standardization efforts:

- Data on hydrogen quality and purification costs in hydrogen network, including pipelines and storages, should be systematically collected and analyzed to achieve a better understanding of all elements connected to the grid and enable fact-based decision-making.
- Economic feasibility must be incorporated into all standardization decisions to ensure cost-effective grid operation. The assessment should, however, also take the risk of no successful harmonisation process into account, making an option of a step-wise introduction of quality standards and continuous improvement more attractive.
- Harmonization at the EU level is considered important to prevent costly market fragmentation and stranded investments.
- Purification costs must be transparently assessed and allocated to ensure a fair distribution of financial burden.

By integrating these aspects into further standardisation efforts, hydrogen quality standardization will not only be technically robust but also economically sustainable, creating a stable and widely accepted regulatory framework for the European hydrogen market development.

Executive Summary (French Version)

La transition de l'infrastructure gazière européenne du gaz naturel à l'hydrogène et à d'autres gaz renouvelables est un pilier fondamental de la stratégie européenne visant à atteindre la neutralité climatique, mais aussi à atteindre une plus grande indépendance énergétique grâce à la diversification et à la production nationale. Une coordination entre les intérêts des différents acteurs et des États membres sera nécessaire pour permettre et garantir une trajectoire réussie vers la décarbonation. L'harmonisation de la qualité du gaz au sein d'un réseau d'hydrogène gazeux dédié est considérée comme un élément essentiel pour la montée en puissance d'un marché européen de l'hydrogène fortement interconnecté. Des exemples tirés du système naturel existant montrent que les différences entre les pays en ce qui concerne les spécifications de qualité du gaz ou les limites de contaminants posent des limites et des défis au commerce transfrontalier, ce qui nécessite des mesures supplémentaires d'ajustement de la qualité aux points d'interconnexion.

Contrairement au gaz naturel, une infrastructure européenne interconnectée de l'hydrogène n'en est qu'à ses débuts. Étant donné qu'il n'existe pas encore de spécification nationale contraignante pour le gaz, tous les acteurs du marché ont l'occasion de créer une norme de qualité commune appliquée au transport de l'hydrogène par gazoduc en Europe. Les organismes de réglementation peuvent fournir des conseils au cours de ce processus en tenant compte des questions techniques et économiques d'un large éventail d'intervenants concernés afin d'élaborer des normes largement acceptées. À cela s'ajoute le paquet marché de l'hydrogène et du gaz décarboné : avec la directive (UE) 2024/1788 (par exemple les articles 44 et 50) et le règlement (UE) 2024/1789 (par exemple les articles 69 et 72), les États membres de l'UE ainsi que le Parlement européen obligent la Commission européenne à soutenir la poursuite des activités de normalisation internationale sur la qualité de l'hydrogène. Par conséquent, une demande de normalisation est prévue auprès de l'organisme de normalisation compétent CEN/CENELEC dans le but d'obtenir un consensus entre les différentes parties prenantes qui soutient le développement des marchés de l'hydrogène et la future législation en Europe.

La présente étude fournit un contexte technique et une assistance pour cette tâche, en présentant les éléments clés des discussions techniques et économiques dans le contexte de la qualité de l'hydrogène. Dans un premier temps, les principales conclusions de la littérature sur l'impact des différents éléments de la chaîne d'approvisionnement sur la qualité de l'hydrogène ainsi que sur l'effet potentiel des différentes qualités d'hydrogène sur les utilisateurs finaux sont résumées. S'ensuit un aperçu et une comparaison des normes de qualité existantes pour l'hydrogène gazeux. Un résumé d'un large éventail de positions, d'attentes et d'opinions des parties prenantes a été recueilli dans le cadre d'un processus intensif d'interaction avec les parties prenantes et est présenté dans cette étude. Sur cette base, trois spécifications de qualité différentes avec des concentrations d'hydrogène de 98 % mol, 99,5 mol% et 99,97 mol% ainsi que des limites de certains contaminants sont dérivées. L'étude comprend une analyse approfondie des efforts et des coûts de purification liés à l'application de ces spécifications en tant que norme de réseau pour le réseau européen d'hydrogène – à la fois les coûts de purification des différents éléments de la chaîne d'approvisionnement et de l'ensemble de la chaîne d'approvisionnement (c'est-à-dire les pipelines de transport, le stockage souterrain et les différents groupes d'utilisateurs finaux ayant des exigences de qualité différentes). En prenant en compte non seulement la teneur en hydrogène, mais aussi un large éventail de contaminants pertinents, l'étude fournit des informations et des orientations approfondies pour le développement ultérieur de la réglementation et de la normalisation de la qualité du gaz. En outre, la configuration modulaire de l'analyse des coûts de purification permet une analyse individuelle pour chaque État membre de l'UE et ses attentes concernant un futur système d'hydrogène gazeux. Les résultats soutiendront d'autres discussions entre les principales parties prenantes sur l'identification d'une spécification de réseau commune, mais aussi sur les questions sous-jacentes de savoir qui devrait assumer la responsabilité (et les coûts) d'assurer cette qualité.

À la pointe de la technologie – Interaction entre la qualité du gaz et les éléments de la chaîne d'approvisionnement en hydrogène

Afin de permettre une analyse et une discussion basées sur des faits, cette étude présente un aperçu des connaissances et de l'expérience existantes concernant ces aspects liés à la qualité. Dans un premier temps, **l'impact des différents éléments clés de l'infrastructure** tout au long de la chaîne d'approvisionnement en hydrogène, ainsi que la qualité de l'hydrogène gazeux et les contaminations possibles, sont résumés sur la base de la littérature disponible. En fonction de la technologie de production, de transport et de stockage, différentes sources d'impuretés et de contaminants clés sont décrites (voir la Table 1-5). D'après l'analyse, les gazoducs réaménagés et certains sites de stockage souterrains (p. ex. cavités de sel réaménagées et réservoirs de milieux poreux) peuvent être considérés comme des goulets d'étranglement majeurs tout au long de la chaîne d'approvisionnement, car ils peuvent introduire des contaminants dans le flux d'hydrogène gazeux lors du transport et du stockage, ce qui entraîne des efforts de purification considérables.

Table 1-5: Vue d'ensemble des principaux contaminants le long des éléments clés de la chaîne d'approvisionnement en hydrogène

Éléments de la chaîne d'approvisionnement	Sources potentielles	Impuretés / contaminants potentiels (entre parenthèses : indication de probabilité[1])
Production	Électrolyse - AEL	Azote (+), eau (o), oxygène (o), cations (o), argon (-)
	Électrolyse – PEMEL	Azote (o), eau (o), oxygène (o), dioxyde de carbone (-)
	Reformage à la vapeur (SMR) + (PSA)	Monoxyde de carbone (++), azote (+), méthane (o), eau (o), argon (o), formaldéhyde (-)
Conversion	Fissuration de l'ammoniac	Ammoniac (+), azote (+)
Transmission	Conversions de gazoducs	Composants typiques des gaz associés, composants des condensats (+) (décroissant au fil du temps)
	Exploitation et entretien (conduites neuves et réutilisées)	Azote (purge) (o), Lubrifiants / huiles pour compresseurs (compresseurs à pistons) (o)
Stockage souterrain	Cavités salines (nouveauté)	Eau (+), méthane (o), composés soufrés (o), hydrocarbures supérieurs (o)
	Stockage de supports poreux	Eau (+), méthane (++), composés soufrés (+), hydrocarbures supérieurs (+)
	Exploitation et maintenance	Lubrifiants / huiles pour compresseurs (compresseurs à pistons) (o) Glycol (processus de déshydratation) (o)

[1] Probabilité présumée : (++) fréquente, (+) possible, (o) rare, (-) très rare (sur la base de la terminologie utilisée dans Bacquart 2018[6], adaptée aux éléments de transmission et de stockage sur la base de l'analyse qualitative réalisée dans cette étude). Remarque : probabilité indicative seulement.

Dans un deuxième temps, l'étude aborde **les exigences de pureté et l'impact des différents contaminants sur les applications finales.** La Table 1-6 résume les principaux enseignements tirés de la tolérance des différents secteurs d'utilisateurs finaux et des applications en fonction des niveaux de qualité d'hydrogène faibles, moyens et élevés.

En raison de la grande maturité technologique, il existe une bonne compréhension de l'impact des différents contaminants sur les applications de mobilité des **piles à combustible** : Une concentration d'hydrogène ≥ 99,97 mol%[7] est considérée comme la concentration minimale, telle que décrite dans les normes internationales (par exemple, ISO 14687 ou EN 17124). En ce qui concerne leur criticité, les impuretés de CO, H_2S et NH_3 sont généralement considérées comme ayant l'impact le plus négatif sur les performances des piles à combustible. En revanche, **les processus de combustion** à des fins

[6] *Bacquart, T. (2018): Probability of occurrence of ISO 14687-2 contaminants in hydrogen: Principles and examples from steam methane reforming and electrolysis (water and chlor-alkali) production processes model. International Journal of Hydrogen Energy, Volume 43, Issue 26, Pages 11872-11883, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2018.03.084.*

[7] *Sauf indication contraire, les spécifications de qualité en % se réfèrent au mol% (% molaire) dans le présent rapport.*

énergétiques ne sont généralement pas sensibles à la composition du gaz. Cependant, les propriétés de combustion (indice de Wobbe et pouvoir calorifique) du gaz combustible ne doivent pas fluctuer de manière excessive. Certaines industries, où les propriétés des produits sont directement influencées par celles de la flamme (par exemple, la température et la vitesse de la flamme), peuvent toutefois avoir des exigences de qualité plus strictes, comme c'est le cas dans l'industrie du verre. Les secteurs où l'hydrogène est utilisé comme **matière première** ont des exigences de qualité très spécifiques, tant pour la pureté du gaz que pour le niveau toléré et le type de contaminants. Pour limiter l'intoxication des catalyseurs de procédé, des qualités d'hydrogène très élevées (parfois même supérieures à 99,97 mol%) sont souhaitées dans certains procédés, ce qui nécessite une purification sur site.

Table 1-6: Exigences de qualité de différentes applications sans purification supplémentaire sur site

Exigences de qualité par secteur / application		≥ 98 mol% H_2 = qualité « faible »	≥ 99 mol% H_2 = qualité « moyenne »	≥ 99,97 mol% H_2 = qualité « élevée »
Bâtiment (chaleur basse température)		(✓)	(✓)	✓
Énergie / production d'électricité		(✓)**	(✓)**	✓
Mobilité	GLACE	✓	✓	✓
	PEM FC	Ne convient pas	Ne convient pas	✓
PtX		Ne convient pas	✓	✓
Secteur d'activité (exemples)	Granulats de construction (Pierres et sols)	✓	✓	✓
	Papier	✓	✓	✓
	Verre et céramique	✓**	✓**	✓
	Fer et acier	✓*	✓*	✓
	(Pétro-)chimie (matières premières / utilisation non énergétique)	Ne convient pas	✓*	✓

Source : Adapté sur la base de DBI GUT & Frontier (2022).[8] Spécifications de qualité faible et élevée se référant à DVGW G260 Groupe A et D. Veuillez noter: les parenthèses ( ) indiquent que l'aptitude dépend du type d'utilisation ou d'un contaminant spécifique / composant trace*En fonction de la composition des composants traces. **En fonction de la stabilité de l'indice de Wobbe dans le temps.

Paysage actuel de la normalisation et évolution dans certains États membres

Un ensemble complet de documents normatifs, de règles techniques et d'autres activités d'harmonisation existe déjà, visant à spécifier des exigences communes pour les niveaux de pureté minimum d'hydrogène admissibles ainsi que pour les concentrations maximales de contaminants clés. En général, les normes techniques portent sur un élément d'infrastructure spécifique (par exemple, le transport par gazoduc) ou sur l'utilisation finale (voir la Table 1-7.)

La présente analyse passe en revue les activités en cours dans plusieurs États membres de l'UE. Les résultats mettent en évidence la Belgique, les Pays-Bas et l'Allemagne comme des leaders en matière de discussions sur les définitions et les exigences de qualité de l'hydrogène, avec des propositions ou des spécifications provisoires déjà publiées. Dans ces pays, les gestionnaires de réseau de transport (GRT), en tant que parties prenantes importantes, promeuvent (entre autres) une spécification de réseau de >99,5 % molaire d'hydrogène, sur la base d'études technico-économiques, par exemple réalisées par DNV et Kiwa 2023[9].

Les cadres réglementaires et législatifs concernant la qualité d'un futur réseau d'hydrogène sont réexaminés dans d'autres États membres. Alors que le débat public sur la qualité future de l'hydrogène est moins avancé dans ces pays, des différences significatives peuvent être observées, notamment concernant le rôle des infrastructures de gaz naturel réaffectées (dominantes en Italie ou en Espagne)

[8] *DBI GUT & Frontier Economics (2022): H2 Rein - H_2 short study: Hydrogen quality in an all-German hydrogen network, https://www.dvgw.de/medien/dvgw/forschung/berichte/g202140-finalreport-h2shortstudy-engl.pdf*

[9] *DNV and Kiwa (2023). A follow-up study into the hydrogen quality requirements. Available at: https://www.eerstekamer.nl/overig/20231009/rapport_kiwa_dnv/document.*

ou l'accent mis sur les pôles industriels ou les vallées de l'hydrogène, plutôt que sur un réseau national d'hydrogène (par exemple en France ou en Pologne). Quoi qu'il en soit, ces différentes approches doivent être prises en considération dans la conduite des activités d'harmonisation de la qualité du gaz. Dans ce contexte, le réseau européen des gestionnaires de réseaux d'hydrogène (ENNOH) jouera un rôle clé dans la coordination de la planification, du développement et de l'exploitation des futures infrastructures d'hydrogène en Europe, en collaboration avec les gestionnaires de réseaux nationaux de transport d'hydrogène (HTNO).

Table 1-7: Vue d'ensemble des normes de qualité de l'hydrogène, des règles techniques et des activités d'harmonisation en Europe

	Standard	Name	Scope	Comment
Transport / Pipeline	CEN/TS 17977:2023 **(2023)**	Gas infrastructure - Quality of gas - Hydrogen used in rededicated gas systems	H_2 pipelines (rededicated NG pipelines)	H_2 quality: **≥98.0%**, Wobbe Index: 42-46 MJ/m³ (15 °C/15 °C) Note: different specifications compared to ISO 14687 Grade A
	EASEE-gas: Common Business Practice 2022 – 001/01 (CBP) **(2022)**	Hydrogen Quality Specification	H_2 pipelines (rededicated NG pipelines)	**≥98.0%** (reference to ISO1467:2019 Grade A, Specification of critical components only) Note: on-site purification for O_2 or sulphur components.
	DVGW G260:2021 (DE) **(2021)**	Technical Rule on gas quality ("Gasbeschaffenheit")	H_2 pipelines (for gases in public infrastructure in Germany)	Gas family 5, group A with **≥98.0%** and group D with **≥99.97%** (reference to EN 17124:2019) Currently under revision to (possibly) include **99.5% (tbc)** as additional "grade" "group A+"
	Fluxys Hydrogen specification proposal (BE) **(2022)**	Hydrogen Specification Proposal	H_2 pipelines (transmission system by Fluxys Belgium)	H_2 quality: **≥98.0%** Aligned with EASEE-Gas (CBP H2), CEN, specifications for UK, NL and DE, + further stakeholder input
	Indicative quality specification for Hynetwork (NL) **(2024)**	Indicative quality and temperature specification for Hydrogen Network Netherland	H_2 pipelines (for Hydrogen Network Netherland)	H_2: **≥99.5%**, indicative only, based on results of DNV/KIWA studies, final decision by Ministry open Note: Former version (2022) with 98%.
End-use	ISO/DIS 14687:2024 (E) **(2024)**	Hydrogen fuel quality — Product specification	End-uses (different)	Different Grades (A-F) for state of hydrogen and end-use **≥98.0% (Grade A)** – **≥99.995% (Grade C)**
	EN 17124:2022 **(2022)**	Hydrogen fuel - Product specification and quality assurance for hydrogen refuelling points dispensing gaseous hydrogen - (PEM) fuel cell applications for vehicles	PEM fuel cell (vehicles)	H_2 quality: **≥99.97%** Fuel quality requirements at the dispenser nozzle + risk assessment / probability of occurrence + severity class, impact on fuel cell at certain concentrations

Principaux enseignements de l'engagement des parties prenantes

Les points de vue d'un large groupe de parties prenantes sur la spécification de qualité de l'hydrogène souhaitée pour une infrastructure européenne ont été recueillis. Les commentaires d'environ 50 parties prenantes ont été obtenus lors d'une enquête et d'entretiens de suivi (y compris des acteurs établis du secteur de l'énergie et du gaz ainsi que des acteurs spécifiques à l'hydrogène).

Les principaux enseignements tirés de la participation des intervenants sont les suivants :

- **Il existe un consensus parmi les parties prenantes sur les principales utilisations finales futures de l'hydrogène et les méthodes de production.** L'utilisation de l'hydrogène comme matière première chimique, pour la production d'électricité et dans l'industrie sidérurgique devrait dominer pendant la phase de montée en puissance du marché. La production d'hydrogène vert (via l'éolien offshore et éventuellement le solaire dans le sud), les importations (ammoniac, LOHC et pipelines) ainsi que l'hydrogène bleu devraient prédominer durant cette phase.
- **Les parties prenantes sont partagées quant au niveau de pureté de l'hydrogène souhaité dans le futur réseau, avec des positions variant entre 98 % et 99,5 % d'hydrogène.** Les arguments des deux côtés sont les suivants :
  - **98 % :** Les partisans d'une pureté de 98 % estiment que ce niveau est suffisant pour répondre à la plupart des besoins. Ils considèrent qu'une pureté plus élevée serait économiquement non rentable ou difficilement réalisable pour les stockages souterrains de gaz, ces derniers étant nécessaires dans l'infrastructure en raison de la demande dynamique.
  - **99,5 %** : Les défenseurs d'une pureté de 99,5 % soutiennent que ce niveau représente un optimum en termes de coût de purification. Ils font valoir que les infrastructures (y compris certains stockages) peuvent techniquement gérer cette pureté et que les méthodes de tarification de l'hydrogène inciteront à augmenter le niveau de pureté.

- **Outre le niveau de pureté, les utilisateurs finaux exigent des limites strictes concernant les contaminants susceptibles d'empoisonner les catalyseurs dans les processus industriels et les piles à combustible**. Comme les matières premières devraient constituer un usage final dominant, ces acteurs estiment que la spécification de l'infrastructure doit refléter cette exigence. De plus, la stabilité de la composition du gaz, et par conséquent l'impact sur les propriétés physiques telles que l'indice de Wobbe, est cruciale pour les utilisateurs finaux industriels utilisant des procédés de combustion.
- **Les exigences liées aux stockages peuvent différer de celles des utilisateurs finaux industriels (matières premières).** Bien que les stockages soient essentiels pour l'équilibrage du réseau, les contaminants qu'ils peuvent introduire risquent d'affecter négativement les processus industriels. Par conséquent, les opérateurs de stockage représentent un groupe clé de parties prenantes dans la normalisation de la qualité de l'hydrogène.

À la lumière des commentaires reçus, des recommandations sont formulées pour adapter les normes existantes et proposer de nouvelles normes. De plus, trois exemples de spécifications de qualité sont présentés comme base pour l'analyse des coûts dans cette étude (voir Table 1-8).

1) 98 mol%- particulièrement adapté aux processus de combustion avec des besoins de qualité inférieurs.
2) 99,5 mol% - convient à de nombreuses applications industrielles et à la plupart des applications finales.
3) 99,97 mol% - requis pour les applications sensibles telles que les piles à combustible ou certains processus chimiques.

Table 1-8: Spécifications proposées pour trois niveaux de pureté en fonction des commentaires des parties prenantes. Les normes existantes ont été utilisées comme référence pour permettre de montrer les modifications apportées.

Propriété	Spécifications proposées pour l'hydrogène		
	>98,0 mol%	>99,5 mol%	>99,97 mol%
Indice de Wobbe	41,89 - 45,89 MJ/m³ (15 °C/15 °C)	43,45 - 45,89 MJ/m³ (15 °C/15 °C)	n/a
Δ Indice de Wobbe	<0,5 MJ/m³·minute		n/a
Eau	<250 ppm à <10 bar <60 ppm à >10 bar		<5 ppm
Point de rosée de l'eau	<-8 °C à 70 bar		
Hydrocarbures	<20 000 ppm	<5 000 ppm	< 2 ppm
Oxygène	<10 ppm		
CO et CO_2	<40 ppm (20 ppm chacun)		<2 ppm (total)
Ammoniac	<10 ppm		<0,1 ppm
Gaz inertes	<20 000 ppm	<5 000 ppm	< 300 ppm
Composés halogénés	<0,05 ppm		
Poussières et particules	<1 mg/kg		
Soufre total	<7 ppm	<3 ppm	<0,05 ppm
Formaldéhyde	<10 ppm		<0,01 ppm
Acide méthanoïque	<0,2 ppm		
Hydroxydes (KOH, NaOH)	<2 ppm		

Conclusions sur l'analyse des coûts de purification

Le dernier élément de cette étude est une analyse des coûts évaluant l'impact économique de la purification de l'hydrogène en cas (i) d'adoption des spécifications définies comme la pureté du réseau, et (ii) de différentes configurations de l'infrastructure gazière (par exemple, le rôle des nouveaux gazoducs par rapport aux pipelines réaffectés). L'objectif est d'identifier les principaux facteurs de coût,

de mettre en évidence le potentiel spécifique d'optimisation de la purification et d'en tirer des recommandations stratégiques contribuant à la réalisation d'un réseau d'hydrogène rentable.

La **méthodologie** repose sur quatre étapes clés : (1) une revue de la littérature et des études de marché, (2) a définition de la chaîne d'approvisionnement en hydrogène, des étapes de purification et des configurations de réseau, (3) l'identification des paramètres de coût liés à la purification et (4) le calcul des coûts de purification à chaque étape et tout au long de la chaîne d'approvisionnement globale. En introduisant une approche modulaire, les données de coûts présentées fournissent la base d'une analyse plus approfondie prenant en compte différents scénarios de marché ainsi que des spécificités nationales.

Comme point de départ de l'analyse, les **étapes de purification et les technologies appropriées** sont décrites pour les différents segments de la chaîne d'approvisionnement. Les efforts de purification et les coûts d'élimination des contaminants spécifiques (par exemple, N_2, CO, CO_2, CH_4, H_2O, composés soufrés, O_2, NH_3) sont résumés dans un inventaire. L'analyse souligne que le choix de la stratégie de purification est crucial pour la performance économique de l'ensemble du système. Si la purification en amont aux points d'entrée peut réduire les efforts de traitement en aval, elle est associée à des coûts plus élevés, en particulier lorsque des exigences strictes en matière de pureté doivent déjà être respectées par les producteurs. De plus, une purification supplémentaire peut être nécessaire aux points de sortie du réseau afin de garantir une qualité de gaz élevée. À l'inverse, la purification en aval, sur le site de l'utilisateur final, offre une plus grande flexibilité au réseau, mais entraîne une consommation d'énergie supplémentaire ainsi qu'une augmentation des coûts d'exploitation.

Indépendamment du développement futur des infrastructures, certaines étapes de purification représentent des **investissements « sans regret »**, car elles sont essentielles pour garantir la qualité de l'hydrogène tout au long de la chaîne de valeur. En particulier, la purification est toujours nécessaire après la production, en particulier pour les procédés SMR et ATR, où le CO, le CH_4 et les composés soufrés doivent être éliminés par PSA. De même, l'hydrogène transporté par des gazoducs réutilisés nécessitera inévitablement une séparation membranaire ou un traitement PSA pour éliminer le CH_4 et le CO_2 résiduels. Les besoins de purification les plus critiques surviennent après le stockage dans des formations souterraines poreuses, où la contamination par le CH_4, le CO_2 et le H_2S est inévitable, nécessitant une combinaison de PSA et de séparation cryogénique.

Dans une première étape de l'analyse des coûts, une analyse de sensibilité, avec variation de la configuration de l'infrastructure et de la composition des flux destinés aux utilisateurs finaux, est réalisée. Cela permet d'évaluer l'impact d'une configuration de réseau, dans les meilleurs comme dans les pires scénarios, ainsi que des combinaisons intermédiaires sur les coûts de purification. Dans un second temps, la configuration modulaire de l'outil de calcul des coûts est appliquée pour effectuer une évaluation détaillée **des coûts tout au long de la chaîne d'approvisionnement globale** en tenant compte de scénarios individuels sur l'évolution future du marché. Dans les deux cas, les résultats sont présentés sous forme de coûts de purification spécifiques, exprimés en euros par kilogramme d'hydrogène (€ / kg H_2).

L'analyse de sensibilité modulaire permet d'identifier les principaux facteurs de coût. Les infrastructures de gaz naturel et de stockage souterrain réaffectées, en particulier les réservoirs poreux et les anciens champs de gaz, présentent des défis majeurs lorsqu'il s'agit de respecter des spécifications de pureté élevées pour le réseau. Les gaz résiduels provenant d'utilisations antérieures, notamment le méthane, le dioxyde de carbone et les composés soufrés, peuvent affecter durablement la qualité de l'hydrogène et nécessiter une post-purification plus intensive. Ce phénomène est particulièrement marqué au cours des premières années suivant la réaffectation, lorsque la teneur en hydrogène des retraits de gaz stockés peut fluctuer de manière significative, rendant un traitement supplémentaire indispensable pour maintenir une qualité constante du réseau. Par conséquent, un réseau d'hydrogène dédié reposant sur une infrastructure neuve (« meilleure configuration ») permet de réduire au minimum les coûts supplémentaires de purification, les impuretés pouvant être contrôlées en amont. L'analyse souligne également que les économies d'échelle jouent un rôle

déterminant : les grandes unités de purification centralisées sont nettement plus efficaces que plusieurs installations décentralisées de plus petite taille. Toutefois, l'utilisation économique des flux de gaz résiduels (par exemple issus de la PSA) doit être envisagée dans ces configurations.

Dans la deuxième étape, un certain scénario (« scénario de référence ») est appliqué pour illustrer l'application pratique des données modulaires sur les coûts de purification afin d'évaluer les coûts globaux (supplémentaires) de purification tout au long de la chaîne d'approvisionnement en hydrogène. A cet effet, la répartition exemplaire suivante de l'hydrogène entre différents composants d'infrastructure et applications finales est prise en compte – dérivée des données de la littérature sur une éventuelle configuration future du marché. Les principales hypothèses pour la configuration du réseau sont les suivantes :

- 40 % de l'hydrogène est transporté par des gazoducs nouvellement construits, tandis que 60 % circule par des gazoducs réutilisés.
- 90 % de l'hydrogène sont livres directement aux utilisateurs finaux, tandis que 10 % sont injectés dans des installations de stockage souterraines. Ces 10 % stockés sont ensuite répartis à parts égales entre des infrastructures de stockage neuves et réaffectées, soit 5 % pour chacun.

Les applications finales sont regroupées en trois catégories théoriques, selon les exigences minimales de pureté de l'hydrogène. Pour les besoins de cette analyse, les mêmes spécifications que celles définies pour le réseau sont appliquées (voir Tableau 4). Il est supposé que 50 % de la demande globale concernent des applications nécessitant une pureté minimale de 98 mol %, 25 % nécessitent une pureté >99,5 mol %, et les 25 % restants exigent une pureté de 99,97 mol %. En fonction des spécifications de pureté atteintes dans le réseau, une purification complémentaire sur site peut s'avérer nécessaire. Pour ce scénario de référence, les coûts finaux spécifiques de purification tout au long de la chaîne d'approvisionnement globale s'élèvent à : (i) 1,05 €/kg dans le cas d'une qualité de réseau supposée de pureté de >98 mol%, (ii) 0,78 €/kg (pureté du réseau de >99,5 mol%) et (iii) 1,24 €/kg (pureté du réseau >99,97 mol%). En d'autres termes, ces coûts représentent l'effort de purification à ajouter à chaque étape de la chaîne d'approvisionnement, en complément du coût actualisé de production de l'hydrogène (LCOH).

Des variantes de ce scénario de référence, intégrant différentes compositions de la demande en hydrogène, sont également analysées. Elles considèrent une utilisation ciblée de l'hydrogène (50 % de la demande globale) dans des applications nécessitant respectivement une qualité faible, moyenne ou élevée.

Les résultats globaux montrent que, quelle que soit la composition supposée de la demande des utilisateurs finaux, les coûts supplémentaires de purification les plus faibles tout au long de la chaîne d'approvisionnement sont observés lorsque la qualité de réseau est fixée à 99,5 mol % (barres bleues moyennes dans la Figure 1-2). Les coûts spécifiques de purification restent alors modérés, autour de 0,80 €/kg, notamment dans les scénarios mettant l'accent sur des utilisateurs finaux ayant des exigences de qualité faibles à moyennes. En revanche, lorsque la spécification de pureté du réseau est réduite à 98 mol % (barres bleu foncé), les coûts de purification augmentent sensiblement. Ils passent de 1,05 €/kg à 1,60 €/kg dès lors qu'une proportion croissante d'utilisateurs finaux exige une qualité d'hydrogène élevée (>99,97 mol %). Cette hausse s'explique par la nécessité d'une purification complémentaire sur site. À l'inverse, une qualité de réseau élevée (>99,97 mol %) minimise les besoins de purification supplémentaires en aval, en transférant les efforts de traitement vers les producteurs et les opérateurs en amont. Dans ce cas, les coûts de purification restent relativement constants, autour de 1,25 €/kg, quels que soient les scénarios de composition de la demande.

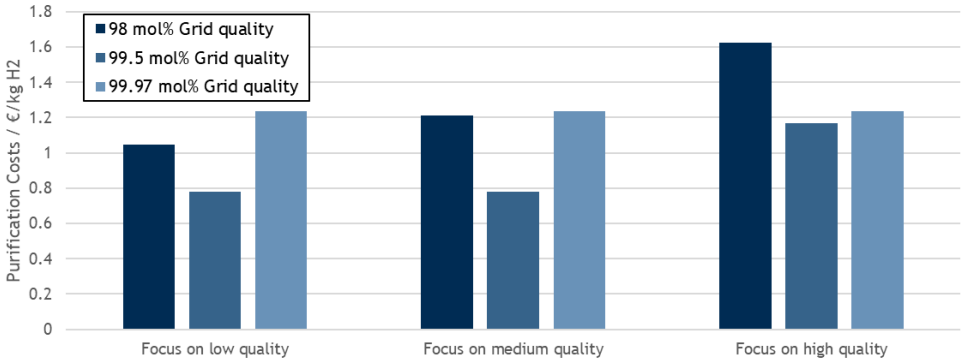

Figure 1-2: Comparaison des coûts globaux d'épuration tout au long de la chaîne d'approvisionnement (transport, stockage et demande) sous les hypothèses du scénario de référence avec des variations dans la composition des utilisateurs finaux.

Les principaux facteurs de coûts identifiés peuvent être regroupés en trois catégories :

- Premièrement, la configuration de l'infrastructure joue un rôle déterminant. La conversion de gazoducs existants nécessite des opérations de nettoyage et de rinçage approfondies afin d'éliminer les résidus de gaz antérieurs. À l'inverse, les nouveaux pipelines dédiés à l'hydrogène présentent l'avantage d'être spécifiquement conçus pour répondre à des exigences élevées en matière de pureté. Toutefois, ces infrastructures impliquent des coûts d'investissement nettement supérieurs à ceux des gazoducs réaffectés.
- Deuxièmement, la dépendance aux technologies de stockage est un facteur clé des coûts de purification. Les stockages souterrains posent généralement un défi en matière de qualité, car ils peuvent contaminer l'hydrogène et nécessitent des traitements préalables et postérieurs avant réinjection. Les cavités salines récemment construites réduisent ces besoins, mais leur disponibilité est limitée en Europe. À l'inverse, le stockage dans des formations poreuses, comme d'anciens réservoirs de gaz naturel, requiert davantage de purification.
- Troisièmement, es coûts d'investissement et d'exploitation des étapes de purification augmentent avec les exigences de pureté. Les technologies comme l'adsorption modulée en pression (PSA) et d'autres procédés d'adsorption jouent un rôle central. L'élimination des impuretés traces, notamment le soufre et l'azote, est particulièrement coûteuse. Cependant, les technologies modernes, telles que les PSA optimisés ou les procédés membranaires innovants, permettent de réduire significativement la consommation énergétique.

Perspectives – prochaines étapes vers la normalisation

Malgré l'ampleur de cette étude, certaines limites subsistent et ouvrent des pistes pour de futurs travaux. Parmi les points clés figurent le manque d'expérience pratique sur les réseaux d'hydrogène, l'évolution rapide du cadre réglementaire et législatif entre les États membres de l'UE, ainsi que les enjeux liés à la normalisation internationale. S'y ajoutent les difficultés d'implication des parties prenantes, en raison du nombre élevé d'acteurs et du manque de retours concrets de l'industrie sur les coûts de purification. Concernant l'analyse des coûts, deux limites principales sont à noter : (i) l'absence d'optimisation des coûts à l'échelle du système, dépendant fortement de l'évolution du marché de l'hydrogène ; (ii) l'exclusion des étapes de purification sur site avant l'injection dans le réseau, celles-ci étant spécifiques à la technologie et intégrées dans le LCOH.

Malgré ces limites, l'étude constitue une base solide pour les futurs efforts de normalisation d'un réseau européen d'hydrogène. Il est essentiel d'impliquer plusieurs catégories de parties prenantes : (i) les acteurs institutionnels et législatifs, tels que les autorités de régulation et les régulateurs de l'énergie des États membres, (ii) les organismes de normalisation indépendants comme l'ISO et le CEN/CENELEC, et (iii) les principaux acteurs nationaux, notamment les gestionnaires de réseaux de transport et de stockage, ainsi que d'autres parties prenantes de la chaîne d'approvisionnement.

En résumé, les recommandations suivantes devraient être prises en compte dans les futurs efforts de normalisation :

- **Collecte et analyse systématiques des données** : Les informations sur la qualité de l'hydrogène et les coûts de purification dans les infrastructures (transport et stockage) doivent être collectées de manière cohérente pour mieux comprendre le réseau et fonder les décisions sur des données fiables.
- **Intégration de la faisabilité économique dans la normalisation** : Chaque décision sur les normes de qualité doit intégrer une évaluation économique, incluant le risque d'un échec d'harmonisation, ce qui peut justifier une approche progressive avec des standards introduits par étapes et une amélioration continue.
- **Harmonisation au niveau européen** : Une normalisation cohérente à l'échelle de l'UE est essentielle pour éviter la fragmentation du marché, les surcoûts et les investissements inefficaces.
- **Répartition transparente des coûts de purification** : Les coûts de purification doivent être évalués et répartis de façon transparente et équitable entre les acteurs de la chaîne de valeur.

En intégrant ces principes dans les futurs travaux de normalisation, il sera possible de garantir non seulement la robustesse technique des standards relatifs à la qualité de l'hydrogène, mais aussi leur viabilité économique. Cela contribuera à créer un cadre réglementaire stable, cohérent et largement accepté, favorisant ainsi le développement du marché européen de l'hydrogène.

1. Introduction

1.1. Motivation

The harmonisation of gas quality within Europe is an important challenge to facilitating cross-border flows and trade. In contrast to the existing situation in natural gas markets, where quality requirements strongly differ among the different countries, the early status of the development of hydrogen infrastructure provides the opportunity for a common approach even before a wide-spread pipeline network is implemented.

The nature of hydrogen as a traded good in line with an accelerated roll-out of a dedicated hydrogen pipeline network requires EU-wide standardisation in different topics along the hydrogen value chain. As indicated in the Roadmap on Hydrogen Standardisation by the European Clean Hydrogen Alliance[10], the gas quality of hydrogen represents a "horizontal aspect", thus a crucial parameter on which a variety of other topics in the hydrogen sector depend.

On the European and international level, several standardisation activities regarding a standardised hydrogen gas quality already exist today. In November 2023, CEN / TC 234 has published CEN / TS 17977 ("Gas infrastructure – Quality of gas – Hydrogen used in repurposed gas systems"), a first attempt in formulating a common standard for the European hydrogen infrastructure. However, with the development of new markets and with the continuous progress in building a European pipeline network for hydrogen, the urgency for defining common quality requirements increase.

The discussion about the identification of an optimal hydrogen quality is, however, not only focused on hydrogen pipelines (new or repurposed ones). It is of direct relevance for different actors along the hydrogen supply chain, including producers, grid and storage operators as well as different end-users – all of them having specific arguments for diverting minimum hydrogen limits, gas properties in general as well as maximum admissible concentrations of a wide set of possible contaminants. Higher grid quality specifications rather shift the purification efforts to upstream elements like production but also transport and storage, while lower qualities specifications applied for the grid result in additional downstream purification (at least for quality-sensitive end-user groups). In addition, also national level activities and perspectives drive the discussion, with some EU Member States being more advanced than others in their discussions and preferences.

In this light, the EU Member States and the European Parliament have recognised a need for harmonised technical specifications by the European Commission including the requirements for hydrogen quality in Articles 44 and 50 of Directive (EU) 2024/1788 and in Articles 69 and 72 of Regulation (EU) 2024/1789 that are setting out common rules for the internal markets for renewable gas, natural gas and hydrogen[11]:

> *"The Commission may lay down common specifications in a network code […] or may adopt implementing acts establishing common specifications], where […] those requirements are not covered by harmonised standards; […]." (Art. 69 of Regulation)*

> *"The Commission is empowered to adopt delegated acts […] by establishing network codes in the following areas: interoperability rules for the hydrogen network, […] as well as hydrogen quality, including common specifications at interconnection points and standardisation, odorization, cost benefit analyses for removing cross-border flow restrictions due to hydrogen quality differences and reporting on hydrogen quality." (Art. 72 of Regulation)*

[10] *European Clean Hydrogen Alliance roadmap on standardisation ECH2A (2023).* https://ec.europa.eu/docsroom/documents/53721/attachments/1/translations/en/renditions/native

[11] Directive (EU) 2024/1788 and Regulation (EU) 2024/1789

A hydrogen gas quality standard is also essential for the implementation of the TEN-E Guidelines[12] which aim to connect the energy infrastructure of EU countries and include, in particular, the goal of an integrated hydrogen backbone.

The aim all of ongoing hydrogen standardisation activities is identifying a reasonable approach that can facilitate consensus finding towards an optimal solution from an overall system perspective, while taking the limitations of different infrastructure elements into account. These activities do not only focus on the level of hydrogen itself, but also on the limits for a wide set of contaminants that may be present in the transported hydrogen gas. With the upcoming standardisation request according to Regulation (EU) 2024/1789, Art 69 (1) (b), the European Commission can thus provide important guidelines towards a rapid consensus finding among all actors.

1.2. Study objective and reading guide

By introducing a common quality standard, a scattered landscape among European Member States can be prevented. The early point in time before large-scale hydrogen pipeline projects and national standards are being implemented offers a unique opportunity for reaching a consensus among relevant actors and allowing each market participant to adjust accordingly from the very beginning. A harmonized standard can thus facilitate cross-border trade and increase the uniformity of end-user equipment design requirements along Europe.

The present study aims at providing the technical background and assistance to the European Commission for these ongoing standardization processes for hydrogen transport networks. This is done by presenting key literature findings, collecting and summarizing a wide set of stakeholder opinions and presenting cost estimations for the case, certain quality specifications would be applied to the European hydrogen infrastructure.

The analysis follows the following structure:

Chapter 2 serves as a brief **background comparing the future hydrogen market with the natural gas market**. Existing challenges and obstacles in cross-border trading in the natural gas markets are described along three examples, to underline the importance of standardisation of the hydrogen quality in a future European infrastructure.

Chapter 3 provides an **overview of the State-of-the-Art** by summarizing existing knowledge on origin and risk of contaminants in the future hydrogen gas infrastructure as well as the impact on different end-use applications. After this, international standards and national rules in twelve European Member States in the context of hydrogen quality are presented, including adopted standards but also relevant ongoing activities on further standardisation, as well as relevant industry studies.

The methodology and **results of the extensive stakeholder engagement** performed in this project are presented in chapter 4. It contains a collection of the perspective a different stakeholder groups along the hydrogen supply chain on future hydrogen quality requirements and presents their arguments for different possible future minimum hydrogen requirements in a dedicated hydrogen grid (i.e. regarding 98 mol%, 99.5 mol% hydrogen purity or even higher). The results are presented according to key issues identified by different stakeholder groups – including the mismatch between hydrogen storage operators and specific end-user quality requirements. Where considered relevant, also further topics, e.g. on metering issues, variations in the Wobbe index as well as safety-related aspects like odorization are briefly covered. As a result, recommendations for maximum contaminant levels are summarized, and **proposals for new and revisions of existing standards** are provided based on stakeholder input. With this work, three hydrogen quality specifications with purity levels of 98 mol%, 99.5 mol% and 99.97 mol% were derived using stakeholders' feedback for changes to existing standards. These specifications also serve as basis for the cost estimations in the following chapter.

[12] *EC (2022): Trans-European Networks for Energy.*

Chapter 5 presents the assumptions and results of the **purification cost analysis.** This assessment focusses on purification costs necessary in case the previously defined quality specifications are applied as "grid standard" and depending on assumed infrastructure configurations. It aims to provide a tool to also reflect potential geographical differences and hydrogen infrastructure planning options across the EU. Based on a definition of certain minimum hydrogen quality levels (98 %, 99.5 % and 99.97 %) as well as of key contaminants, purification needs at different steps along supply chain are identified and the required purification technologies described. Using two extreme assumptions on the configuration of the grid (i.e. a best case and worst case), a range of specific purification costs (in €/kg hydrogen) associated with the purification needs at each step of the supply chain (i.e. transport, storage and end-use) are provided for the different grid quality cases. In addition to this inventory of cost data, a sensitivity analysis is performed taking different configurations of the grid (e.g. share of repurposed pipelines or salt caverns) as well as end-user groups' share in overall hydrogen demand into account. With this, key cost drivers can be identified for a wide set of possible future market scenarios. Exemplary calculations for a reference scenario allow to estimate additional purification costs along the supply chain.

Finally, overall **project results are summarised** and **limitations as well as recommendations** for the possible next steps in the pre-normative research, standardisation process and market design are discussed in Chapter 6.

2. Background – comparison with situation in natural gas markets

The upcoming hydrogen infrastructure development is decisively shaped by the actors, experiences and learnings from the natural gas sector. This is based on the strong similarities between both markets, where pipeline-based infrastructure connects a variety of producers / suppliers and end-users, constituting a natural monopoly and being operated as regulated asset. Also, for building a European hydrogen backbone repurposing of existing natural gas pipelines can represent significant investment savings compared to newly-built pipelines. In addition, several stakeholders and market actors along the natural gas supply chain will transform parts of their business model towards transporting hydrogen instead of natural gas in the future.

In contrast to the natural gas infrastructure that emerged from the regional level and gradually became interconnected over a period of several decades, the development of a supranational hydrogen backbone infrastructure is the basis for all ongoing infrastructure planning activities.

In that context, also a discussion on the harmonisation of the gas quality is needed. Looking at the natural gas market there are several examples, where different national quality specifications hinder cross-border trade and increase the need for additional quality-related measures at interconnection points. In the following, selected examples from the natural gas market are provided to underline the motivation for a harmonised hydrogen gas quality within a future European hydrogen infrastructure. Before that, as a starting point, the gas properties of hydrogen and natural gas are compared in more detail.

2.1. Learnings of relevance for a harmonised gas quality among European Member States

Before having a discussion on the specification of hydrogen and the harmonization of this specification around the EU for repurposed natural gas and newly built hydrogen networks, the differences between both gases should be discussed.

'Hydrogen gas', on the one hand, is composed of one component: hydrogen molecules. Any other molecules present are inherently considered contaminants. Therefore, pure hydrogen gas from one source will behave the same as hydrogen gas from another source. The differences between 'hydrogen' from electrolysis or steam-methane reforming or gasification are solely derived from unwanted components in the gas which vary in each production process.

'Natural gas', on the other hand, is a description for a gas mixture with a variety of molecules. Even though the proportion of these various molecules can change, the combined gas is still considered 'natural gas'. Typical molecules, or components, present in natural gas are those who can provide energy such as methane (CH_4) which represents the main component of the gas (between ~80 and 100 vol%). Other key components that provide heat include C_2H_6 (~0-10 vol%), hydrogen and higher hydrocarbons. But natural gas also includes components which do not provide energy such as N_2 (~0-15 vol%) and CO_2 (~0-3 vol%). The composition of natural gas, and thus the proportion of these components, differs greatly among the different production and transport value chains (e.g. gaseous pipeline transport vs. LNG imports and regasification) and sites (e.g. from the North Sea, US, MENA region or Russia). However, unlike for hydrogen, not all of these minor components are considered unwanted or contaminants.

Therefore, natural gases from different sources behave differently when used in an end-use process such as heating applications. Different physical gas parameters are applied to determine calorific value

(energy per unit of volume), density of the gas, and the Wobbe index (which is a combination of the other two).

Table 2-1 illustrates the difference between hydrogen on the one side and natural gas from three different sources on the other. Despite strongly differing density and calorific properties, the **Wobbe index** that serves as an important parameter to determine the thermal input in combustion-related processes (with the notable exception of combustion engines) has a similar value for both hydrogen and natural gas.

Table 2-1: Comparison of various natural gases and hydrogen (Source: DNV)

Parameter	Pure Hydrogen	Dutch G-gas	Russian gas	Canadian gas
Typical composition[13] [vol%]	100 % H_2	81.3 % CH_4 2.9 % C_2H_6 14.4 % N_2 0.9 % CO_2	98 % CH_4 0.6 % C_2H_6 0.8 % N_2 0.1 % CO_2	95 % CH_4 4.5 % C_2H_6 0.4 % N_2 0.3 % CO_2
Real density, weight per unit of volume at 15 °C and 1 atm. [kg/m³]	0.08	0.7811	0.6887	0.7122
Higher calorific value, per unit of volume including latent heat of vaporization at 15 °C and 1 atm. [MJ/m³]	12.10	32.79	37.61	38.80
Wobbe Index [MJ/m³, 15/15 °C]	45.89	41.07	50.17	50.89

Pure hydrogen will always – in theory – show the same physical properties under the same conditions. In reality, however, the physical properties of 'hydrogen gas' will differ depending on the type and amount of contaminants present. Therefore, the **gas specification for hydrogen** is defined as:

- A minimum **purity level** of hydrogen, e.g. >98 %, representing the hydrogen percentage in the gas by volume.
- Limits for each category of **contaminants** that are considered critical for certain end-users, and which can realistically be introduced into the gas during production, transport, distribution or storage. Typical contaminants are methane, ammonia, oxygen and carbon monoxide.

This, on the contrary, is only partially true for the **specification of natural gases** which are determined by :

- The appropriate **composition** suitable for a specific end-use that requires a certain range of calorific value or density.
- Limits for each category of **contaminants** that are considered critical for certain end-users, and which can realistically be introduced into the gas during production, transport, distribution or storage. Typical unwanted components are ammonia, hydrogen sulphide and carbon dioxide.

Key Takeaway: There is an inherent difference between hydrogen and natural gas. The definition of natural gas includes a long list of various molecules, some combustible, some inert. Even through the variation in physical qualities of the gas is high, it can still be called 'natural gas'. Hydrogen gas, on the contrary, is the sum of hydrogen molecules and unwanted components. Pure hydrogen will always behave in the same way.

[13] *Compositions from DNV gas database.*

2.2. Impact of natural gas quality deviations on cross-border trading

Example 1: Fragmentation in the Dutch natural gas market

The Dutch natural gas system was built in the 1960's after the discovery of the significant resources in the Groningen gas field. The Dutch natural gas specification was built on the gas quality found in the Groningen field. (also called G-gas, see Figure 2-1). G-gas has a unique composition of natural gas, determined by the geological formation in which it was formed. It contains a relatively high fraction of incombustible nitrogen (see Table 2-1).

Nevertheless, due to the significant abundance of the gas field, this low calorific gas composition was distributed all throughout the Netherlands without removing the nitrogen. To accommodate this, residential, commercial and industrial equipment was fine-tuned and designed to handle this gas quality. This fine-tuning process significantly increased the appliances' (emission) efficiency but also reduced the flexibility of the equipment to handle other natural gas compositions. Burners or engines, for example, designed for G-gas are not interchangeable with high calorific gas without the nitrogen.

For natural gas export from the Netherlands to neighbouring countries such as Belgium and Germany, the 'L-gas' specification was created. This is a gas specification with a low calorific value, albeit with a broader specification of components than G-gas. To add to the complexity, the discovery and exploitation of other gas fields in the Netherlands with different, high-calorific, gas compositions, introduced a third specification: 'H-gas'. G-gas, L-gas and H-gas are transported within the Dutch market in multiple networks. Furthermore, L-gas and H-gas are exported across borders to neighbouring countries. This has led to a highly complex, multi-specification network, with various gas blending stations where hydrogen (or nitrogen) is introduced to alter the calorific value of a gas to a required specification. The various export routes can be seen in Figure 2-1.

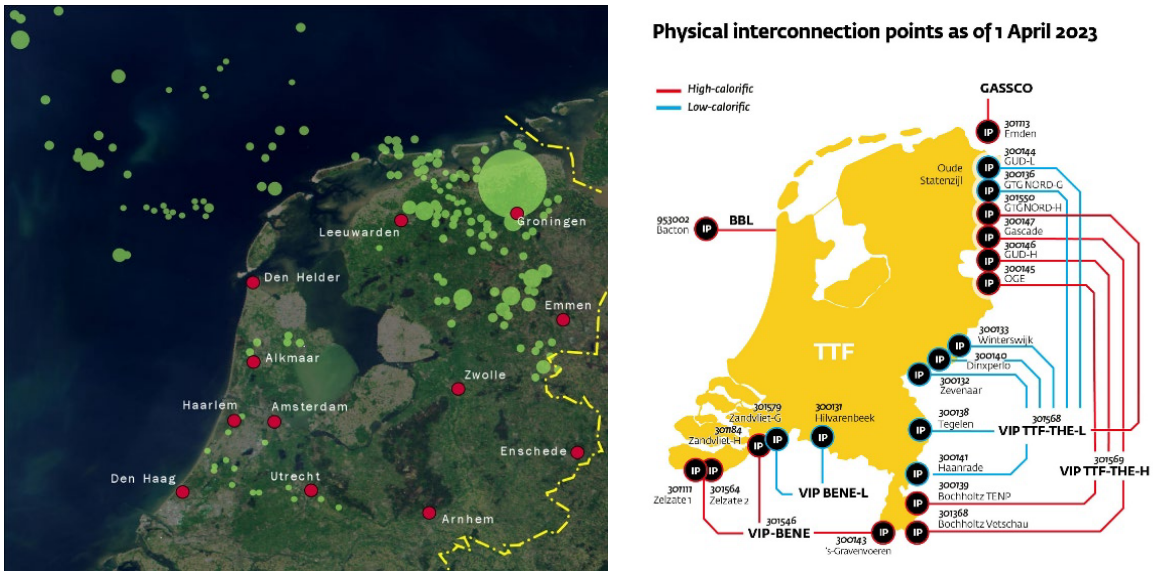

Figure 2-1: (left) Illustration of natural gas production fields in the Netherlands[14]. (right) Overview of cross-border natural gas trade activities in the Netherlands of L and H-gas compositions (Source: Gasunie Transport Services)[15].

In recent decades, an increase of earthquakes near the Groninger gas field has led to the political decision to significantly reduce the production from this field. Since the Dutch internal economy was geared towards low-calorific gas, this has led to:

[14] *Satellite image in public domain with overlay created by WikiMedia: Natural gas NL - Groningen gas field - Wikipedia.*
[15] *Image from Gasunie Transport Services.: Virtual interconnection points (VIPs) › Gasunie Transport Services.*

- The import of high-calorific gas, which needs to be transformed to low-calorific G-gas for the domestic market by admixing nitrogen. A dedicated nitrogen-producing and blending installation is required for this purpose and this huge facility has been built. To meet export demand, high-calorific gas is also admixed with nitrogen for L-gas.
- Industrial users are strongly encouraged , and sometimes required, by the Dutch government to switch from G-gas to H-gas to reduce nitrogen blending costs and G-gas demand on a system level.
- This complex Dutch multiple natural gas quality infrastructure and ability to handle and convert multiple gas compositions for domestic use and export has led to the reputation of the Dutch system as an important European trading hub[16].

In contrast to the Netherlands, Germany decided to steadily transform its L-gas use to H-gas in the timeframe until 2030 by adapting the end-use equipment at each single customer (industry and households). In total, around five to six million end-use applications are to be adapted.

The Dutch example illustrates how historical developments and the decisions to build infrastructure for different gas specifications can affect things such as equipment design, efficiency of equipment and cross border trade. Strict and harmonised specifications increase efficiency and generally reduce emissions. Wider gas specifications allow for a wider range of supply sources and export markets, encouraging trade.

Key Takeaway: The specification of a gas has a significant influence on the local market and neighbouring markets. A broad specification with room for contaminants and variation in composition allows more flexibility in cross-border trade but might have to be refined before being used in end-user equipment. A narrow specification reduces the room for trade but increases the 'quality' of the product and allows end-user equipment to operate more efficiently.

Example 2: Gas quality in the European gas market

Zooming out from the Dutch natural gas system up to the European one shows a similar fragmentation of the market. In 1985, the European nations enacted the Single European Market strategy for liberalization of the EU economy. This significantly impacted the natural gas market, where traditional, long term state contracts were replaced with competitive short-term contracts. This strategy instigated the unbundling of national gas organizations (separation of storage, distribution, production companies) to allow for more freedom for trading parties. Starting from 1998, the EU introduced several Gas Directives to facilitate a competitive natural gas market with strong cross-border trade.

Even though the abovementioned packages encouraged trade, they did not set a specification for natural gas for the EU[17]. Furthermore, although national entities responsible for the gas infrastructure were unbundled and competition increased, the existing infrastructure remained largely intact. Additionally, national end-use equipment remained mostly reliant on local gas compositions as discussed in the previous section. Figure 2-2 shows the current fragmented situation in the EU focusing on admissible Wobbe index (shown: 5 percentile).

Because of the diversity of natural gas specifications between nations, the standardization of natural gas quality throughout the EU has been a challenge. In 2005, EASEE gas approved a recommended business practice on natural gas quality[18]. This, however, was not binding. The European Commission approved a mandate (M/400) to create a harmonized EU H-gas specification using the EASEE gas

[16] *Riemersma, B., Correljé, A. F., & Künneke, R. W. (2020). Historical developments in Dutch gas systems: Unravelling safety concerns in gas provision. Safety Science, 121, 147–157.*
[17] *Correljé, A. (2016). The European natural gas market. Current Sustainable/Renewable Energy Reports, 3(1–2), 28–34.*
[18] *EASEE-gas CPB. Harmonisation of Natural Gas Quality 2005-001/02*

specification as reference. In 2011, a final report[19] was presented by CEN WG 197 on harmonization of the natural gas quality in the EU. The conclusion was that a single Wobbe range is not feasible in the EU due to the differences in end-user equipment requirements which were designed to only handle the local gas due to the reasons explained in the previous subsection.

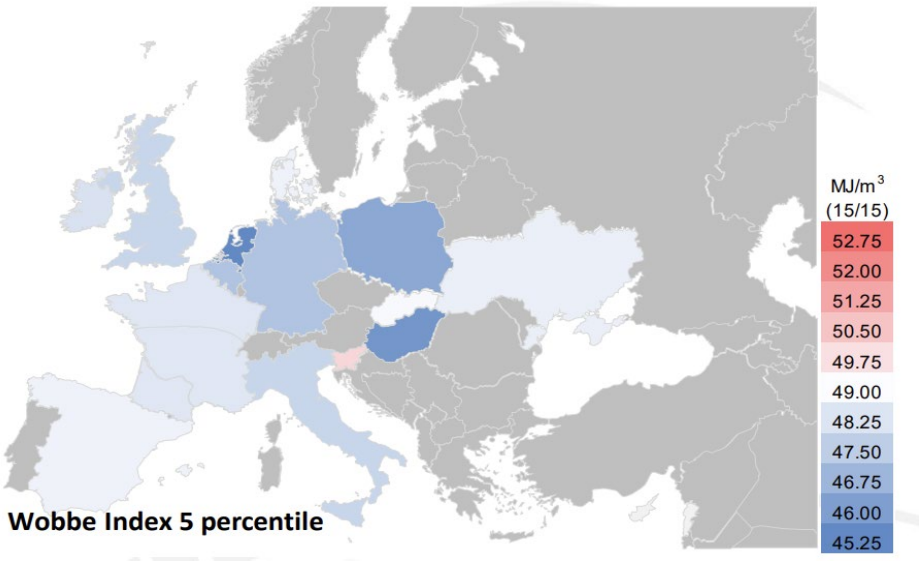

Figure 2-2: Overview of the measured Wobbe index in different countries in Europe. (Source: ENTSOG[20]).

It can thus be concluded that it is critical to perform harmonization of gas quality across the EU, in an early stage of the market development before equipment dependencies on local, national specifications have formed. Remember from Section 2.1 of this chapter that hydrogen will have significant less variation in composition the higher the purity level is. This will reduce the complexity of harmonization. The primary difficulty in hydrogen standardization will be agreement on contaminant limits. Their specific role will also be discussed in the next example.

Key Takeaway: Although there was no successful standardization process of natural gas across the EU, there are inherent differences between natural gas and hydrogen. For hydrogen, standardization limits will focus on contaminant limits, instead of composition and calorific value. Regardless, care should be taken to standardize before end-use equipment and infrastructure becomes too dependent on nationally agreed specifications.

Example 3: Challenges related to increasing biomethane injection volumes in Europe

Another example for quality-induced hurdles in cross-border natural gas trading is caused by different limits for key contaminants in European Member States. These challenges and bottlenecks become relevant e.g. due to increasing volumes of biomethane production and injection.

Increasing the share of biomethane in the natural gas infrastructure is a commonly accepted option in driving the emission reduction of the whole sector. A prerequisite in order to inject biogas into the natural gas grid is the process of biogas upgrading. This is essential as biogas contains significant shares of carbon dioxide and other components that needs to be removed. But even after that process, the upgraded biogas (=biomethane), in general still has a different gas composition compared to average natural gas composition as it contains considerable high shares of methane, and also other contaminants like oxygen, hydrogen or ammonia.

[19] *Findings publicly reported in CEN - CENELEC Sector Forum Energy Management / Working Group Hydrogen Final Report*
[20] *ENTSOG Wobbe Index and Gross Calorific Value in European network. Analysis of ranges and variability. 2017*

In this context, the harmonisation of definitions and gas quality specification is required. The European Biogas Association stresses that '*differentiating between natural gas and biomethane and meticulously defining parameters such as oxygen, sulphur, and carbon dioxide will facilitate biomethane uptake and cross-border trade in the coming years, enabling the sector to deploy 35 bcm by 2030*'[21]. Up to now, however, national biomethane injection specifications differ among European Member States. In 2024, MARCOGAZ published an overview of current biomethane gas quality standards that are required for injected into the natural gas networks.[22] The document contains information for 14 European countries. Beside physical gas properties like gross calorific value, Wobbe index and relative density, also a wide set of possible limits for trace components like water, sulphur, oxygen or carbon dioxide are listed.

Thus, high shares of biomethane (but also hydrogen in case of hydrogen blending) impact the gas quality (and thus hinder possible cross-border trading): it even poses challenges for grid operation on national level. Changes in gas quality will, e.g. impact billing procedures, which are based on calorific properties of the gas. Due to varying gas compositions, gas flow simulations are needed in those cases to project gas distribution in the grid and with that the energy amount delivered to end-customers.

The **maximum content of oxygen** in the gas can be considered as important individual case study. An important step in biogas upgrading before injection is the removal of sulphur to prevent e.g. catalyst poisoning in several applications. This process is often done using oxygen which leads to an average oxygen content of about 0.5 % for European biomethane plants[23] - significantly higher than natural gas which can be considered oxygen-free. Oxygen, however, can impact gas properties during combustion and other uses as well as increase the level of corrosion in storage facilities or 'black powder' formation in high-pressure pipelines. Also, in underground gas storages oxidation reaction can occur and even microbiological growth resulting in formation of unwanted contaminants can be enhanced.[24] Hence, specific strategies for oxygen removal are required. The maximum oxygen content admissible is dictated by the most sensitive grid elements. According to a study by MARCOGAZ, *'permissible oxygen content is dependent on the specific facility and must therefore be assessed case by case. An oxygen limit of 100 ppm or more is acceptable for some Under Ground Storage facilities. More sensitive storage facilities or oxygen sensitive industries require a permissible oxygen concentration of 10 ppm at most.'*[25]

Figure 2-3 shows that **oxygen limits** in the gas grid widely differ among European countries. An interesting example of the impact of an increasing biomethane share in the grid can be seen for Denmark, which aims to cover domestic natural gas demand by 2029 with biomethane. Consequently, due to increasing share of biomethane in the grid, its properties became dominant for the overall gas system. With this, Denmark already faces some challenge in complying with international CEN gas quality standards at interconnection points. To allow for this, Denmark has already increased the oxygen limit to 5,000 ppm (0.5 %) at metering points for biomethane in 2012/13 .[26] At more sensitive grid nodes at entry, storage and transit points, the oxygen content is limited to 1,000 ppm (=0.1 %). Particularly the low oxygen content required at certain interconnection points with underground storage sites 10 ppm (0.001 %) (e.g. in Germany) is considered critical[27]. As a consequence, the cross-border trade is limited in those cases and additional operational costs need to be recovered from the network users.

[21] *European Biogas Association (2024). Biomethane standards: facilitating renewable gas uptake*

[22] *MARCOGAZ (2024). Quality of biomethane required in European countries for injecting into natural gas grid - Update.*

[23] Danish Gas Technology Centre (2022). Cost-efficient handling of oxygen from bio-methane in the European gas grid

[24] *For Latvia, challenges regarding the oxygen level were mentioned in the survey in the context of the connection to Inčukalns Underground Gas Storage (UGS), as elevated oxygen levels can compromise the storage and safety standards.*

[25] *MARCOGAZ (2022). Biomethane Acceptance in Underground Gas Storage Facilities*

[26] *This level serves as a compromise between the costs of upgrading and purifying biogas to biomethane without imposing additional risks to the different infrastructure elements.*

[27] According to EN 16726, the mole fraction of oxygen shall not exceed 10 ppm (0.001 mol %), expressed as a moving 24-hour average, at network entry points and interconnection points. In case, there are no sensible installations in the grid (e.g. underground storage systems), also higher limits of up to 10,000 ppm (1 mol%) may be applied.

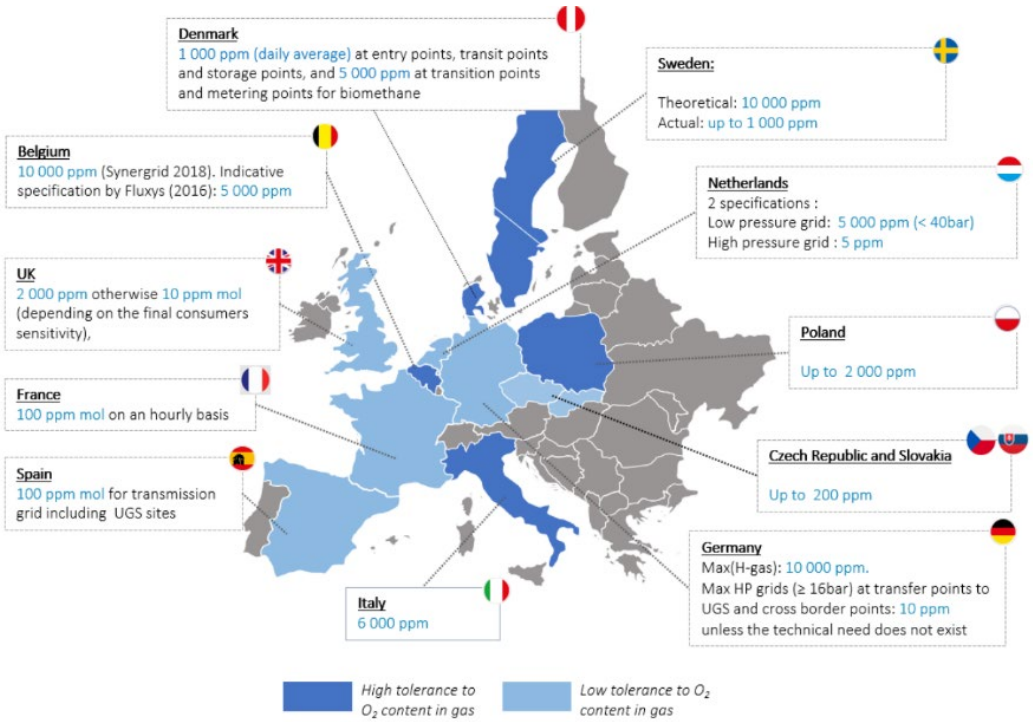

Figure 2-3: Maximum admissible oxygen content in European gas networks (Source: MARCOGAZ[28])

Measures applied in the Danish TSO grid to allow cross-border trading despite the different oxygen limits are e.g. the following:[29]

- Mixing 'domestic' biomethane/natural gas blends with imported natural gas streams (e.g. from Norway) to reduce the overall oxygen share before exporting. Exemplarily, biomethane-rich gas from Denmark is mixed with natural gas from the North Sea or Germany before exporting it to Sweden. In this specific case, also dialogue with grid operators and customers in Sweden allowed for an increase in the admissible oxygen limits from 0.1 % to 0.5 %.
- For other parts, the practice of sectioning was applied, keeping certain grid areas / pipelines free of biomethane by not allowing any biomethane injection. With that measure, the very low oxygen limits of Germany can be ensured.
- Oxygen removal at central grid locations or interconnection points is another option that can be applied (connected with additional costs).

Hence, also in this case, a harmonization of national gas quality specifications would be needed in order to avoid additional costs for grid users and facilitate cross-border gas trade between European Member States.

Key Takeaway: The growing injection volumes of low-carbon gases like biomethane or hydrogen into the natural gas grid pose an additional challenge on natural gas markets, as their impact on gas quality continuously increases. Differing injection specifications as well as national limits for certain contaminant concentrations jeopardize cross-border flows and require additional quality-adjustment measures, as can be seen at interconnection points between Denmark and its neighbouring countries.

[28] MARCOGAZ (2022). BIOMETHANE ACCEPTANCE IN UNDERGROUND GAS STORAGE FACILITIES

[29] Energinet (2022). LONG-TERM DEVELOPMENT NEEDS IN THE DANISH GAS SYSTEM - Energinet's long-term development an 2022 – Needs analysis

3. State-of-the-art – overview hydrogen quality

This chapter provides an **overview of the topic of hydrogen quality** by summarizing existing knowledge on origin and risk of certain contaminants in the future hydrogen gas infrastructure as well as the impact of certain contaminants on different end-use applications (Chapter 3.1).

After this detailed introduction into the topic, existing international standards and national rules and on hydrogen quality are presented, including also relevant ongoing activities on further standardisation as well as relevant industry studies (Chapter 3.2).

3.1. Role and impact of hydrogen quality – a general introduction

3.1.1. Impact of supply chain elements on the quality of hydrogen

The aim of this chapter is to provide an (literature) overview of the impact of different elements of the hydrogen supply chain on the gas quality. This includes the level of hydrogen itself (e.g. 98 mol%), but also information about type, amount and possible sources of contaminants within the gas stream (e.g. CO, CO_2, H_2O, CH_4. etc.).

The analysis focuses on available data and information in literature and serves as basis for following tasks. In cases, where experience with hydrogen quality and the sources of possible contaminants is rare, learnings from stakeholder interaction in task 2 will supplement the information collected below.

The analysis at this stage focusses on those technologies, considered as key infrastructure elements of a future hydrogen system. This covers:

1) hydrogen production via electrolysis or steam methane reforming (SMR)
2) hydrogen import/conversion technologies via ammonia cracking
3) hydrogen transport in newly built hydrogen or repurposed natural gas pipelines
4) hydrogen underground storage technologies: salt caverns as well as porous media storage sites (e.g. aquifers and depleted gas fields)

From an overarching perspective, ISO 17124:2022 on "Hydrogen fuel – product specification and quality assurance for hydrogen refuelling points dispensing gaseous hydrogen – proton exchange membrane (PEM) fuel cell applications for vehicles" provides are comprehensive summary on the impact of contaminants on fuel cells in Annex A. The document, however, also provides an exemplary supply chain evaluation on potential sources of impurities along the supply chain in Annex B. To address the question on how relevant these contaminants and – consequently – how important the respective purification needs for certain applications are, Annex C also provides an exemplary risk assessment for the case of a hydrogen refuelling station (HRS) delivered by pipeline from an off-site SMR. Although the document focusses on mobility with a hydrogen quality requirement of at least 99,97 mol%, the underlying descriptions are an important input for the analysis in this sub-task.

Hydrogen production technologies

Only a limited number of studies have conducted experiments or modelling of the number of contaminants present in hydrogen produced from different methods of production. A literature review Murrigan 2015 compiled methods for assessing the quality of hydrogen and concluded that a minimum of eight different instruments are required to determine the 14 contaminants specified in ISO 14687-2.[30] The resulting high effort needed to test the hydrogen gases is the main reason for the

[30] *Murugan, A. (2015): Review of purity analysis methods for performing quality assurance of fuel cell hydrogen. International Journal of Hydrogen Energy, Volume 40, Issue 11, Pages 4219-4233, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2015.01.041.*

current lack of many studies providing data on the topic. Further information can also be found in the context of the HyDelta project, i.e. in Deliverable 1a.1 – Overview of basic elements for hydrogen purity standard by DNV.[31]

The production pathways that were most often analysed were alkaline (AEL) and PEM electrolysis (PEMEL) as well as steam methane reforming (SMR). Less focus was put on further pathways such as O_2-blown autothermal reforming (ATR), due to a lack of information available, chlor-alkali process due to its upscaling limitations, producing hydrogen as a side product, and hydrogen production from biological origin which was also excluded from ISO14687 due to insufficient available information.[32] Hydrogen from biological sources, however, can contain additional contaminants such as siloxanes or mercury that can affect the performance of hydrogen applications, in particular fuel cells.[33] During the chlor-alkali process, hydrogen is produced as a by-product of chlorine and sodium hydroxide. The most likely contaminants are O_2 (frequent), N_2 and H_20 (both rare), and CO_2 (very rare).[34] Further analysis on the impact of hydrogen as a byproduct are also included in [Oxford 2023]. [35] An overview of several non-electrolytic forms of hydrogen production that were not the focus of this chapter are summarized in Table 3-1. In addition, Table 3-2 provides a list of the different contaminants and their potential sources.

Table 3-1: Summary of example compositions of hydrogen mixtures depending on the production method[36]

Parameters [%]	Coal Gasification	Natural Gas Reforming	Methanol Reforming	Coke Oven Gas	Methanol Purge Gas	Synthetic Residual Gas from NH_3	Biomass Gasification
H_2	25–35	70–75	75–80	45–60	70–80	60–75	25–35
CO	35–45	10–15	0.5–2	5–10	4–8	-	30–40
CO_2	15–25	10–15	20–25	2–5	5–10	-	10–15
CH_4	0.1–0.3	1–3	-	25–30	2–8	-	10–20
N_2	0.5–1.0	0.1–0.5	-	2–5	5–15	15–20	1
Ar	-	-	-	-	0.1–2	-	-
Total sulphur	0.2–1	-	-	0.01–0.5	-	-	0.2–1
H_2O	15.2	-	-	-	-	1–3	-
O_2	-	-	-	-	-	0.2–0.5	-
Other	-	-	-	-	2–5	10–15	0.3

[31] *DNV (2023): D1_A1_HyDelta_Derde_tranche_Overview_of_basic_elements_for_hydrogen_purity_standards.pdf, https://doi.org/10.5281/zenodo.13347786*

[32] *ISO 14687:2024 - Hydrogen fuel quality — Product specification. https://www.iso.org/standard/82660.html*

[33] *Couto, N. (2013): Influence of the Biomass Gasification Processes on the Final Composition of Syngas. Energy Procedia, Volume 36, Pages 596-606, ISSN 1876-6102, https://doi.org/10.1016/j.egypro.2013.07.068.*

[34] *Bacquart, T. (2018): Probability of occurrence of ISO 14687-2 contaminants in hydrogen: Principles and examples from steam methane reforming and electrolysis (water and chlor-alkali) production processes model. International Journal of Hydrogen Energy, Volume 43, Issue 26, Pages 11872-11883, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2018.03.084.*

[35] *Oxford (2023) : Oxford energy : Quantifying vented by-product hydrogen: a case study in China. https://www.oxfordenergy.org/wpcms/wp-content/uploads/2023/11/Insight-140-Quantifying-vented-by-product-hydrogen-a-case-study-in-China.pdf*

[36] *Król, A. (2024): Hydrogen Purification Technologies in the Context of Its Utilization. Energies.; 17(15):3794. https://doi.org/10.3390/en17153794*

Table 3-2: Overview of potential contaminants in hydrogen gas and the identified sources[37]

Contaminants	Identification of Source
N_2, O_2, H_2O, Ar	• All methods of hydrogen production
He	• All methods using natural gas as feedstock (not applicable to methods in which He was removed from the gas during the process)
NH_3	• NH_3 production process in which excess hydrogen is generated • Biogas reforming • Coal gasification producing hydrogen as a byproduct • The method of producing H_2 with hydrazine
Halogen compounds	• A chlor alkali process producing excess hydrogen (excluding methods using ion exchange membranes) • Hydrogen production from biogas produced from waste containing plastics • Coke oven gas • Water electrolysis (only where water quality is not guaranteed in the process by adequate treatment)
Total sulphur compounds	• Steam reforming (the sulphur compounds present in the process are only H_2S) • Catalytic reforming • Partial oxidation • Auto-thermal reforming • Coal gasification (where hydrogen is a byproduct) • Hydrogen production methods where sulphur compounds are used for gas odorization
Total hydrocarbons excluding methane	• All production methods that use fossil fuels
CO	• Steam reforming • Catalytic reforming • Reforming • Partial oxidation • Auto-thermal reforming • Coal gasification (hydrogen is a byproduct)
HCHO, HCOOH	• Other than steam reforming, methods of hydrogen production using crude oil as fuel (steam reforming was excluded because the HCHO and HCOOH contents of the products of this process were found to be significantly lower than specified in the standards)

Due to the described data availability and relevance in future energy system, the following discussion focusses on water electrolysis and steam methane reforming.

Electrolysis

AEL and PEMEL were studied as they have reached the highest technical maturity levels among types of electrolysis. The two technologies differ in the layout of their membranes and structure which can influence the hydrogen purity that can be achieved.

In **alkaline** electrolysis, a membrane, that allows hydroxide ions to pass through it, separates the electrodes and fluid spaces that are filled with an electrolyte solution (typically potassium hydroxide). Therefore, the produced hydrogen can contain electrolyte vapours and other gases that were dissolved in the electrolyte fluid. Additionally, small gas exchanges through the membrane called cross-overs can occur, especially during part-load operation. This can introduce small amounts of oxygen into the hydrogen.

[37] *Król, A. (2024): Hydrogen Purification Technologies in the Context of Its Utilization. Energies.; 17(15):3794. https://doi.org/10.3390/en17153794*

In **PEM** electrolysers, the electrodes and fluid spaces are separated by a proton-conducting membrane. Also, the water for the reaction is supplied without adding electrolytes, differing thereby from AEL. However, the hydrogen produced in PEM electrolysis also contains water vapor and, due to possible gas cross-overs through the membrane (especially during partial load), also small amounts of oxygen. However, this oxygen can be partially converted to H_2O on the precious metal catalysts on the cathode side, resulting in low final oxygen content.

Another potential source of contamination for both types of electrolysers can come from flushing or inertisation of the electrolyser with nitrogen, e.g. during maintenance work.[38] Previous studies[39, 40, 41,42] have identified O_2, N_2, CO_2, and H_2O as possible ISO 14687 contaminants from electrolytic hydrogen production routes, with O_2 being the most probable contaminant. [43]

Electrolyser manufacturer's specifications of their products in [DBI GUT & Frontiers Economics 2022] (11 manufacturers' claims shown in this study) show that the electrolysers by themselves already enable between 99.6 and 99.99 % purity after drying the hydrogen.[44,45] In general, the oxygen content is additionally reduced via a deoxo unit, enabling purities of over 99.99 %, higher than those needed for FCEVs (99.97 %).[46] TSA purification units can be used to increase the purities and set specific levels of H_2O and O_2 (typically 5 ppm).

The **alkaline** electrolysis is presented in the annex of ISO/DIS 19880-8. In Bacquart 2018, the likelihood of individual contaminants was modelled for different production methods. Among them AEL, PEMEL, and SMR. In the analysis for AEL, the following contaminants of were classified into these probability classes, as seen in Table 3-3.[47]

Table 3-3: Likelihood of individual contaminants from different production methods, as modelled in Bacquart 2018

Characteristics	AEL	PEM	SMR
Frequent	None	None	CO
Possible (1 per 10,000):	N_2	None	N_2
Rare (1 per 100,000):	O_2, H_20, K^+ & Na^+	N_2, H_20, O_2	CH_4, H_20, Ar
Very rare (1 per 1,000,000):	Argon	CO_2	CH_2O

Possible nitrogen contaminations can come from inadequate purging after a shutdown. A lever for reducing the frequency of contaminations is increasing the process control, defining clear procedures and ensuring that the operating pressure of hydrogen is higher than the nitrogen pressure. By doing so, the probability of contamination can be reduced to "Rare". The probability of O_2 and H_2O contamination is comparable to the PEM process. Argon is a contaminant in the nitrogen that is used for purging. By reducing nitrogen contaminations, also argon contaminations can be strongly

[38] *DBI GUT & Frontier Economics (2022): H2 Rein - H_2 short study: Hydrogen quality in an all-German hydrogen network, https://www.dvgw.de/medien/dvgw/forschung/berichte/g202140-finalreport-h2shortstudy-engl.pdf*
[39] *Bacquart, T. (2018): Probability of occurrence of ISO 14687-2 contaminants in hydrogen.*
[40] *Consonni, S. (2005): Decarbonized hydrogen and electricity from natural gas. International Journal of Hydrogen Energy, Volume 30, Issue 7, Pages 701-718, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2004.07.001.*
[41] *Kortsdottir (2013): The influence of ethene impurities in the gas feed of a PEM fuel cell. Int. J. Hydrogen Energy 2013, 38, 497–509.*
[42] *Papadias (2009): Hydrogen quality for fuel cell vehicles—A modeling study of the sensitivity of impurity content in hydrogen to the process variables in the SMR–PSA pathway. Int. J. Hydrog. Energy 2009, 34, 6021–6035.*
[43] *Omoniyi, O. (2018): Hydrogen Gas Quality for Gas Network Injection: State of the Art of Three Hydrogen Production Methods. Processes. 2021; 9(6):1056. https://doi.org/10.3390/pr9061056*
[44] *DBI GUT & Frontier Economics (2022): H2 Rein - H_2 short study: Hydrogen quality in an all-German hydrogen network, https://www.dvgw.de/medien/dvgw/forschung/berichte/g202140-finalreport-h2shortstudy-engl.pdf*
[45] *Purity level of produced H_2 after electrolysis (without de-oxo dryer) depends on technology and provider with values >99.6 % quality mentioned in literature. However, high oxygen concentrations would require oxygen removal units at UGS and specific customers. Therefore, de-oxo-units are expected to be implemented to meet grid specifications before injection.*
[46] *DBI GUT & Frontier Economics (2022): H2 Rein - H_2 short study: Hydrogen quality in an all-German hydrogen network, https://www.dvgw.de/medien/dvgw/forschung/berichte/g202140-finalreport-h2shortstudy-engl.pdf*
[47] *Bacquart, T. (2018): Probability of occurrence of ISO 14687-2 contaminants in hydrogen.*

reduced. The electrolyte in AEL is typically KOH or NaOH. The high probability of water being present in the final hydrogen stream also means that there is a high probability of K^+ and Na^+ cations. However, the international standard SAE J2719-2011[48] specifies a threshold for Na, K or KOH of 50 nmol/mol. The probability of cations can be lowered by improving barriers and controls in the respective production plant.[49]

Table 3-4 shows the measured results in [Omoniyi 2021] of contaminants in different hydrogen production methods.[50] For AEL, contaminant levels were below or at the threshold limits established by ISO 14687:2019 Grade D. Only for the maximum particulates concentration were the levels higher than in the Grade D specifications (as were the other two production methods). The authors mention that the reason for this could lie in additional particles from the sampling process. Overall, the low levels suggest that AEL does not introduce contaminants to a level that would affect the use of hydrogen in various applications, including fuel cell electric vehicles, which have especially high standards.

Bacquart 2018 investigated and modelled the likelihoods of individual contaminants being present in hydrogen produced via different methods.[51] The contaminants from **PEM electrolysis** were classified according to the probability of their occurrence in Table 3-3 highlighting the rare occurrence in electrolysis and PEM in particular.

Several sources of potential nitrogen contamination exist. The likelihood of process-internal steps leaking nitrogen is considered very low, due to process barriers being established. A more likely reason could be the use of nitrogen for venting during an emergency shut-down or maintenance. However, implemented procedure requires producers to vent hydrogen for a certain amount of time, after a restart. A problem with the restart procedure would have to have happened. Therefore, the overall likelihood of N_2 contamination is considered to be low.[52]

Water (H_2O) is a reactant in the PEM electrolysis. Water may contaminate the produced hydrogen due to permeation through the PEM membrane, hydrogen water saturated at 60 °C and TSA (temperature swing adsorption) malfunction. Typically, a TSA dryer is integrated into the process and is often already provided by the PEMEL manufacturer. The TSA dryer should remove most of the water content, being set at a maximum of 5 µmol/mol. Additionally, safety mechanisms are installed to catch a TSA malfunction. Therefore, a H_2O contamination was also considered to be rare.

Oxygen (O_2) contamination sources are generation at the anodic side of the cell stack, cross-over through the cell membrane and TSA malfunction. Similarly to the management of water content, the TSA monitors the oxygen content leaving the TSA outlet, alarming the manufacturer when the concentration exceeds 5 µmol/mol. After restarts, the procedure may ensure a venting of produced hydrogen as a safety measure. Due to the barriers in place, O_2 contamination was also considered rare.

Carbon dioxide (CO_2) could come into the system via air or water intake. However, reverse osmosis of the intake water, CO_2 air filters, the use of ion exchange resin, and the low permeability of CO_2 through the PEM membrane are considered efficient barriers for CO_2 contamination.

Several further contaminants, that could be present in other production methods, are not expected to be present, due to them being absent from the production process in PEM electrolysis (e.g. argon, helium, carbon monoxide, formaldehyde, formic acid, hydrocarbons). Concrete contaminant contents

[48] *SAE J 2719-2011 (SAE J2719-2011): Hydrogen Fuel Quality for Fuel Cell Vehicles. Current version: SAE J 2719-2020 - Hydrogen Fuel Quality for Fuel Cell Vehicles.*

[49] *Bacquart, T. (2018): Probability of occurrence of ISO 14687-2 contaminants in hydrogen: Principles and examples from steam methane reforming and electrolysis (water and chlor-alkali) production processes model. International Journal of Hydrogen Energy, Volume 43, Issue 26, Pages 11872-11883, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2018.03.084.*

[50] *Omoniyi, O. (2018): Hydrogen Gas Quality for Gas Network Injection: State of the Art of Three Hydrogen Production Methods. Processes. 2021; 9(6):1056. https://doi.org/10.3390/pr9061056*

[51] *Bacquart, T. (2018): Probability of occurrence of ISO 14687-2 contaminants in hydrogen.*

[52] *Bacquart, T. (2018): Probability of occurrence of ISO 14687-2 contaminants in hydrogen*

of hydrogen produced via PEMEL were tested in [Omoniyi 2021].[53] The hydrogen quality testing results are shown in Table 3-4.

For PEMEL, almost all contaminant levels were below or at the threshold limits established by ISO 14687 Grade D. Only the water and the maximum particulates concentration levels were slightly higher than in the Grade D specifications. The authors mention that the reason for this could lie in additional water and particles introduced in the sampling process. **Overall, the low levels suggest that PEM does not introduce contaminants to a level that would affect the use of hydrogen in various applications, including fuel cell electric vehicles, which have especially high standards.**

Table 3-4: Analysis of ISO 14687:2019 contaminants found in hydrogen production sources by [Omoniyi 2021][54]

Characteristics	Grade D Specification (µmol/mol)	AEL (µmol/mol)	PEMEL (µmol/mol)	SMR (µmol/mol)
Water (H_2O)	5	2.97 ± 0.29	5.87 ± 0.15 [a]	1.46 ± 0.015
Total hydrocarbons except methane (C1 basis)	2	<0.015	<0.015	<0.015
Methane (CH_4)	100	<0.010	<0.010	<0.010
Oxygen (O_2)	5	<0.24	<0.24	<0.24
Helium (He)	300	<28	<28	<28
Nitrogen (N_2)	300	6.06 ± 0.35	6.89 ± 0.37	<0.09
Argon (Ar)	-	-	-	-
Carbon dioxide (CO_2)	2	0.240 ± 0.020	0.61 ± 0.07	0.29 ± 0.09
Carbon monoxide (CO)	0.2	<0.010	<0.010	<0.010
Total sulphur compounds (H_2S basis)	0.004	<0.004	<0.004	<0.004
Formaldehyde (HCHO)	0.2	<0.10	<0.10	<0.10
Formic acid (HCOOH)	0.2	<0.20	<0.20	<0.20
Ammonia (NH_3)	0.1	<0.10	<0.10	<0.10
Total halogenated compounds (Halogenate ion basis)	-	<0.032	<0.032	<0.032
Maximum particulates concentration (mg/kg)	1	1.75 ± 0.36 [a]	1.4 ± 0.6 [a]	1.6 ± 0.6 [a]

Steam methane reforming (SMR) / Hydrocarbon reforming

Reforming is currently the most used method for the production of hydrogen. During reforming, various feedstocks can be used such as natural gas, biogas, naphtha, methanol, and ammonia. Typically, the feedstock is converted into synthetic gas (syngas) and then shift-reacted to produce additional hydrogen and carbon dioxide before being purified. For further information on the process, also see DNV (2023).[55]

The most commonly used purification method is pressure swing adsorption (PSA) [EN 17124:2022] [Brunson et al., 2013]. A large share of hydrogen produced worldwide is produced via steam methane reforming (SMR) in which methane from natural gas is used. SMR results in a product gas with a higher H_2 concentration than other hydrogen production processes from fossil fuels such as O_2-blown autothermal reforming or coal gasification.[56] The catalysts used for the SMR reaction are quickly

[53] *Omoniyi, O. (2018): Hydrogen Gas Quality for Gas Network Injection: State of the Art of Three Hydrogen Production Methods. Processes. 2021; 9(6):1056. https://doi.org/10.3390/pr9061056*

[54] *Omoniyi, O. (2018): Hydrogen Gas Quality for Gas Network Injection: State of the Art of Three Hydrogen Production Methods. Processes. 2021; 9(6):1056. https://doi.org/10.3390/pr9061056*

[55] *DNV (2023): D1_A1_HyDelta_Derde_tranche_Overview_of_basic_elements_for_hydrogen_purity_standards.pdf, https://doi.org/10.5281/zenodo.13347786*

[56] *Bacquart, T. (2018): Probability of occurrence of ISO 14687-2 contaminants in hydrogen: Principles and examples from steam methane reforming and electrolysis (water and chlor-alkali) production processes model. International Journal of Hydrogen Energy, Volume 43, Issue 26, Pages 11872-11883, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2018.03.084.*

contaminated by any trace of sulphur compounds. Therefore, the natural gas fed into the SMR process is already purified via hydrodesulphurization (HDS). The outlet of this process contains less than 50 nmol/mol of H_2S by design and less than 10 nmol/mol in reality, limiting already early in the process the sulphur content that could be unwillingly passed on to fuel cells later on.

Literature suggests that methane (CH_4), nitrogen (N_2), carbon monoxide (CO), and carbon dioxide (CO_2) may be present in the product stream of thermochemical hydrogen production methods, such as steam methane reforming (SMR). Other trace contaminants such as argon (Ar), ammonia (NH_3), formic acid (HCOOH), formaldehyde (HCHO), total hydrocarbons (THC) excluding CH_4, sulphur-containing compounds, and halogens are dependent on the feedstock utilised and on the levels of pre-treatment and purification.[57, 58, 59, 60, 61] While carbon monoxide, hydrogen sulphide, and ammonia impurities would have the most detrimental impact on fuel cell performance, they are also the easiest to remove during purification [Besancon 2008].

Hydrogen of sufficient purity cannot be produced from SMR without further treatment, due to the chemical reactions producing hydrogen and carbon dioxide in a ratio of 4:1. While in theory, a hydrogen purity of 80 % can be achieved, this percentage drops closer to 75 % (at 17 % CO_2) due to the natural gas used as input containing unreacted methane and carbon monoxide as well as inert gases (nitrogen, noble gases), CO_2, and higher hydrocarbons. Even if CO_2 is separated directly from the reformate stream, the requirements for distribution in hydrogen networks are not met by the resulting hydrogen content of around 91 vol.% (with 4.9 % CH_4, 0.2 % N_2, 3.8 % CO) [DBI & Frontier Economics 2022]. [Besancon 2008] states the purities at 94.3 % for SMR (1.4 % CO, 1.7 % CO_2, 0.7 % N_2, 0.6 % Ar, 2.4 % CH_4) and 93.2 % for O_2-blown ATR (1.4 % CO, 1.7 % CO_2, 0.7 % N_2, 0.6 % Ar, 2.4 % CH4). [DBI & Frontier Economics 2022] estimates the purity for ATR after CO_2 separation to be around 94.3 % (5.2 % CO, 0.3 % N_2, 0.2 % CH_4).

Further treatment of the hydrogen output stream is essential and is currently implemented in industrial applications. Pressure swing adsorption (PSA) is the standard method for this purpose [ISO17124:2022], allowing for purities of up to 99.9999 vol.% [DBI & Frontier Economics 2022]. Membrane and cryogenic separation are further separation technologies but can only achieve levels of 98 % purity. For the purpose of >99.99 % purity, also temperature swing adsorption (TSA) could be used, but it is more energy intensive and therefore more expensive.[62]

The analysis of the likelihood of certain contaminations remaining in the final hydrogen stream after SMR and PSA, done in Bacquart 2018, has resulted in the classification of likelihood of contaminants that can be seen in Table 3-3.[63]

Table 3-4 shows the levels of impurities measured in [Omoniyi 2021] for hydrogen produced via SMR (with subsequent PSA purification) against the ISO 14687:2019 Grade D hydrogen standard.[64] For SMR, all contaminant levels were below the threshold limits. The analysis results from this study show CO_2 levels that are four to eight times lower than the ISO 14687:2019 (Grade D) threshold, while the amounts of CH_4, N_2, and CO were significantly below these limits. This suggests a high efficiency of the purification technique used in this conventional process. Apart from Ar and H_2O, which were detected at low levels in the hydrogen from SMR, all other gaseous contaminants specified by ISO 14687:2019

[57] *Bacquart, T. (2018): Probability of occurrence of ISO 14687-2 contaminants in hydrogen*

[58] *Bacquart, T. (2018): Probability of occurrence of ISO 14687-2 contaminants in hydrogen.*

[59] *Consonni, S. (2005): Decarbonized hydrogen and electricity from natural gas. International Journal of Hydrogen Energy, Volume 30, Issue 7, Pages 701-718, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2004.07.001.*

[60] *Kortsdottir (2013): The influence of ethene impurities in the gas feed of a PEM fuel cell. Int. J. Hydrogen Energy 2013, 38, 497–509.*

[61] *Papadias (2009): Hydrogen quality for fuel cell vehicles—A modeling study of the sensitivity of impurity content in hydrogen to the process variables in the SMR–PSA pathway. Int. J. Hydrog. Energy 2009, 34, 6021–6035.*

[62] *Consonni, S. (2005): Decarbonized hydrogen and electricity from natural gas. International Journal of Hydrogen Energy, Volume 30, Issue 7, Pages 701-718, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2004.07.001.*

[63] *Bacquart, T. (2018): Probability of occurrence of ISO 14687-2 contaminants in hydrogen*

[64] *Omoniyi, O. (2018): Hydrogen Gas Quality for Gas Network Injection: State of the Art of Three Hydrogen Production Methods. Processes. 2021; 9(6):1056. https://doi.org/10.3390/pr9061056*

were below the detection limits of the used analysis. Only the maximum particulates concentration levels were slightly higher than in the Grade D specifications. The authors mention that the reason for this could lie in additional particles introduced in the sampling process, and are therefore not representative in this specific case.[65] This is in line with [Aarhaug, 2015], who came to the same conclusion, that after PSA treatment, all analyzed contaminants were below the threshold.[66] **Overall, the low levels suggest that SMR including PSA purification does not introduce contaminants to a level that would affect the use of hydrogen in various applications, including fuel cell electric vehicles, which have especially high standards. SMR without PSA, however, would only reach around 94 % purity which would not be high enough to inject into the grid.**

Hydrogen conversion technologies

Ammonia cracking

A possible future import vector for hydrogen to Europe is ammonia, imported via ship from abroad. The hydrogen that is bound to nitrogen in the ammonia molecule can be released via a process called ammonia cracking.

While huge ammonia cracking plants are under consideration as an option for future hydrogen import, there are currently no such large ammonia crackers in operation in the world. Most commercially available solutions provide an electric-based furnace with a production capacity of 1 to 2 tons per day. These commercial units typically generate a forming gas (a mixture of H_2 and N_2) for various industrial applications and rarely incorporate additional steps to produce hydrogen at high purities.[67] Plants for this are currently in the prototype phase, so conclusive statements about the residual ammonia and nitrogen content cannot yet be made. However, according to BASF, (including purification steps) a high hydrogen purity similar to Group D quality, or $H_2 \geq 99.97$ mol %, can be expected.[68]

Ammonia reformers produce a gas stream containing hydrogen, high nitrogen contents and remaining ammonia that has not been cracked. The product stream contains 69 % H_2, 23 % N_2, and 8 % NH_3 (ammonia).[69]

A particular challenge is the large amount of nitrogen in the gas stream after hydrogen cracking. Multistep processes have been proposed to meet the fuel cell standard, for instance using an absorbent to remove the uncracked ammonia directly after the cracking process and then a second stage that removes the other gases and contaminants. Purification was not required in historical ammonia cracking applications, but will be needed, when the produced hydrogen is injected into the hydrogen pipeline network. Using hydrogen from ammonia will require high purities: application in FCEVs, for example, would require low levels particularly for nitrogen (300 ppm) and ammonia (<0.1 ppm), according to ISO 14687-2.[70]

To achieve a high yield of hydrogen (greater than 99.9 %) and maintain low ammonia content in the produced hydrogen, a nearly complete conversion of ammonia is necessary. Due to ammonia's high reactivity and corrosiveness, it could compromise the purity of hydrogen during the following end-uses. During the initial step of recovering the uncracked ammonia, an absorption/desorption process using the high solubility of ammonia in water is typically used. This leads to a reduction in ammonia content from around 8 % to 0.06 %. However, this value still lies significantly above the fuel cell grade

[65] *Omoniyi, O. (2018): Hydrogen Gas Quality for Gas Network Injection: State of the Art of Three Hydrogen Production Methods. Processes. 2021; 9(6):1056. https://doi.org/10.3390/pr9061056*
[66] *Aarhaug, T. A. (2015). HyCoRA – Hydrogen Contaminant Risk Assessment Grant agreement no : 621223 Measurement of hydrogen quality variation at various HRS with different fuel feedstock.*
[67] *Jackson, C. (2019): Ammonia to Green Hydrogen Project. Project supported by Siemens and Engie.*
[68] *DBI GUT & Frontier Economics (2022): H2 Rein - H_2 short study: Hydrogen quality in an all-German hydrogen network, https://www.dvgw.de/medien/dvgw/forschung/berichte/g202140-finalreport-h2shortstudy-engl.pdf*
[69] *Jackson, C. (2019): Ammonia to Green Hydrogen Project. Project supported by Siemens and Engie.*
[70] *ISO 14687:2024 - Hydrogen fuel quality — Product specification. https://www.iso.org/standard/82660.html*

level of 0.1 ppm for ammonia, requiring additional filtering steps.[71] During the experiments and testing done in [Jackson 2019], filtering has led to a minimum hydrogen purity of 99.9975 % with NH_3 being below the detection limit of the FTIR (0.3 ppm).[72] The hydrogen quality was therefore adequate for its use in fuel cells, but the testing setup will need to be scaled up and conducted in order to test under future real-world conditions. After the ammonia recovery unit, to recycle uncracked ammonia back to the reforming unit, nitrogen is typically eliminated from the gas utilizing a liquefaction cycle. Hereby a hydrogen purity of 99.97 % can be achieved.[73]

For hydrogen intended for the grid, conventional PSA technology can achieve the desired purity. Apart from PSA, the filtering of the gas using membrane-based filtering techniques is a field that is currently in a stage of significant development. Multistage separation processes might be suitable if the plan would be to supply high quality hydrogen to both the grid and fuel cell applications in an energy efficient manner[74] Current challenges hereby are with ensuring that these steps are compatible and cost effective.[75] For moderate purities, i.e. heating or a 98 % purity grid, polymeric membranes work well in filtering out nitrogen and could economically achieve purities of 98 %. Membranes offer a more compact solution to traditional filtering mechanisms, though few have reached commercialization. Various types of membranes for separating hydrogen from other gases have been explored in the literature, including palladium, metal, polymer, carbon, and metal-organic frameworks. Research and development in ammonia cracking and subsequent filtering is currently ongoing.

Hydrogen transport technologies

Hydrogen transport via gas pipeline is considered to be the most economic and relevant transport mode for the transport of large quantities of hydrogen over short to medium distances. For the discussion about possible impurities introduced into the gas / hydrogen stream, it needs to be differentiated between newly built assets and those, which have been used for other gases (mainly for natural gas) before. Table 3-5 summarizes key contaminants due to pipeline transport.

Table 3-5: Overview of possible gas contaminants due to hydrogen transport via pipeline based on EN 17124:2022

Pipeline type	Potential impurities / contaminants	Potential sources	Major risks
Newly built H_2 pipeline	N_2, O_2 N_2, O_2, CO_2 H_2O Halogens Hydrocarbons	(Improper) purging after maintenance Air intake Wrong drying after pressure hydraulic test Cleaning material during maintenance Residuals of compressor oils / lubricants	Very unlikely for all (N_2, O_2 as major risk due to improper purging)
Repurposed natural gas pipeline	In addition: CH_4 and other NG traces Odorants TEG	Former use for natural gas Odorization Dehydration processes	Contamination from former use will reduce over time

New hydrogen pipelines

DBI GUT & Frontier Economics 2022 concludes that transporting of high-quality hydrogen via a pipeline system is, in principle, possible without major issues.[76] Examples from industrial hydrogen

[71] *Jackson, C. (2019): Ammonia to Green Hydrogen Project. Project supported by Siemens and Engie.*
[72] *Jackson, C. (2019): Ammonia to Green Hydrogen Project. Project supported by Siemens and Engie.*
[73] *Jackson, C. (2019): Ammonia to Green Hydrogen Project. Project supported by Siemens and Engie.*
[74] *Ashcroft, J (2022): Centralised and Localised Hydrogen Generation by Ammonia Decomposition. A technical review of the ammonia cracking process. Johnson Matthey Technology Review, Volume 66, Issue 4, Oct 2022, p. 375 – 385. DOI: https://doi.org/10.1595/205651322X16554704236047*
[75] *Ashcroft, J (2022): Centralised and Localised Hydrogen Generation by Ammonia Decomposition.*
[76] *DBI GUT & Frontiers Economics (2022): H_2-Rein H_2 short study: Hydrogen quality in an all-German hydrogen network*

networks in Europe and the US show long-term experience and some specific learnings. Linde operates its hydrogen network in Leuna, Germany, with a H_2 quality level ≥99.96 mol % and quality levels of 99.99 vol % are reported for the hydrogen network in US, Texas. It should, however, be noted that these pipelines have not been used for the transport of other gases / materials before.

According to the exemplary risk assessment in EN 17124:2022, Annex C, possible contaminations within these networks can source from air intake (e.g. N_2. O_2, CO_2), from purging after maintenance (N_2), from wrong drying after pressure hydraulic test (e.g. H_2O) or from cleaning material during maintenance (halogens). In addition, also hydrocarbons as residuals of compressor oils / lubricants may be introduced into the hydrogen stream. [DBI GUT & Frontier Economics 2022], however, note that despite the use of no oil-free compressors in the hydrogen network in Texas, US, the limits for hydrocarbons are not violated.

In general, EN 17124:2022 Annex B describes the risk of contamination of any kind to be "very unlikely"[77] under normal conditions. Maintenance of pipeline systems poses the major risks of contamination of new pipelines, with N_2 and O_2 being potentially present after (improper) purging process with nitrogen. In addition, the following impurities introduced during dedicated H_2 pipeline transportation are considered as "very unlikely": CO_2, H_2O, CO, CH_4, He, Total Sulphur (TS), NH_3, Total Hydrocarbons (THC), HCHO, HCOOH, Halogens

Repurposed hydrogen pipelines

The situation of potential contamination is different for natural gas pipelines that are repurposed for the use of hydrogen. In these cases, traces of substances related to its former use need to be considered. These include, beside methane itself, also various compounds that occur as deposit or condensate within the pipeline or that are adsorbed on the wall of the pipeline: Hydrocarbons and sulphur compounds, which are present in natural gas or result from odorization (mainly at distribution level), or components from biogas/biomethane injection and gas processing may be present [DBI GUT & Frontier Economics 2022]. Further potential contaminants are liquid drop-outs like triethylene glycol (TEG) from gas dehydration processes or pipeline dust. Some of these substances may even accumulate in certain areas or the pipeline grid (e.g. in underwater pipelines or valves) [*Tezel 2021*].

While several aspects of the risk and severity of contamination are not fully understood, [Wesenbeeck 2022] concludes that the effect of NG residues depend on history (incl. treatment, odorization and cleaning) of the pipe and that these residues are likely to diminish with time after using the pipeline for hydrogen.[78] Still, currently, it is under discussion to what extent a hydrogen quality above 99,97 % can be guaranteed in repurposed pipelines. [DBI 2020] argues that especially the 2 ppm limit for hydrocarbons (existing e.g. in German G260 gas family 5 group D with 99,97 mol%) can be seen critical (at least during a transition phase) and has been repeatedly exceeded in measurements.[79] Similar results were found in the context of an interview-based study performed by Frontiers Economics and DBI GUT in 2024. The study also mentions possible purification measures that may be used to increase the quality, however, not all impurities will be prevented. [80] The study also mentions that, up to now there, are no long-term experience with the repurposing of natural gas pipeline to hydrogen yet. There are, however, general experience in converting gas pipelines. Examples mentioned include the

[77] *According to EN 17124:2022, "very unlikely" is described as "Contaminant above threshold never been observed for this source / supply chain / station".*

[78] *Wesenbeeck, P. (2022): Repurposing natural gas pipelines and the effect on H2 quality. Presentation at ENTSOG GAS QUALITY & HYDORGEN WORKSHOP, 11/07/2022. Available online: https://www.entsog.eu/sites/default/files/2022-11/4.1%20Repurposing%20natural%20gas%20pipelines%20and%20effect%20on%20H2%20quality%20-%20Peter%20van%20Wesenbeeck%20%28GASUNIE%29.pdf*

[79] *DBI (2022): Wasserstoffqualitätsanforderungen - Anforderungen der ISO/DIS 14687 bzw. DIN EN 17124 an die verschiedenen Wasserstoffqualitäten und Auswirkungen hinsichtlich H2-und H2-Gemischtransport sowie resultierende Vermarktungs- und Einsatzmöglichkeiten für Gasversorger*

[80] *Frontier Economics & DBI (2024): Interview-basierte Analyse aktueller Entwicklungen zur Wasserstoffqualität. Study for GETH2 and DVGW. Available online: https://www.frontier-economics.com/media/n12a0myg/frontier-dbi-best-practice-studie-zu-wasserstoffqualitaet-fuer-get-h2-dvgw-januar-2024-stc.pdf*

substation of mains gas / coke oven gas with natural gas, low-calorific gas (L gas) with high-calorific gas (H gas) as well as the substitution of odorants within the last decades in Germany.

Accordingly, the current standard for repurposed pipelines described in CEN/TS 17977:2023 (Gas quality – quality of gas – hydrogen used in rededicated gas systems) introduced a minimum hydrogen content of 98 mol-%. The standard developed by CEN/TC234 aims to present a suitable quality level taking different motivation of hydrogen producers, grid-operators and end-users into account. In addition, it considers the presence of liquid and solid deposits in repurposed natural gas pipeline which may limit the achievable H_2 quality (at least in the early time after repurposing). In this context, the document says:

> *"Over time of use of a rededicated infrastructure, the amounts of constituents and contaminants which are due to the previous use of the infrastructure will significantly decrease. However, at the time of publication of this document no time frame can be estimated. The original amounts of contaminants, their nature, the flow rate (i.e. the velocity and the total volume) of hydrogen will influence this process"*

Further practical experience of pipeline repurposing was described by DNV at the ENTSOG gas quality & hydrogen workshop 2022.[81] Based on results in context of the HyNetwork project, a cleaning procedure was developed and conducted for NG pipeline conversion to hydrogen. As a result of several measurements in the 2018-2022 period, the project team concluded that "no contaminants/ components were found that can be originally related to the former natural gas transport". The authors, however, also indicate that no gas flow within the pipeline in case of a standstill may cause desorption of certain components from the inner pipe and cause a (temporary) increase of that components in the gas phase.

Stoehr et al. 2023 summarise findings of investigation of different pipeline elements from high-pressure natural gas grid in Austria after exposure to hydrogen in the context of the HyGrid project.[82] Contaminants identified include odorants, hydrocarbons, sulphur compounds as well as ammonia and atmospheric components. For all these substances, solid matter (sediments) within the pipeline were identified as main source of impurities, present especially in pipes used for natural gas for a long time. At the same time, the authors describe maximum levels to be rather low (6 nmol/mol to 10 µmol/mol) and hence allowing a 98 % hydrogen level in the grid according to ISO 14687 Grade A. Also here, authors identified standstill of gas flow as relevant factor to increase levels of sulphur and halogenated compounds and thus, these factors should be avoided in real operation.

An ongoing project called PilgrHYm[83] aims to evaluate different materials and components from the European gas grid on their suitability for future hydrogen transport. The project considered both, safety as well as material integrity issues.

In summary, cleaning procedure of repurposed pipelines (so-called pigging, see Figure 3-1) in line with continuous monitoring of hydrogen quality at critical grid nodes is key to guarantee constantly high hydrogen levels with minimal concentrations of contaminants. The need for additional purification, however, will depend on the actual purity requirements of end-users.

[81] *Top, H. (DNV) (2022): Conversion of a natural gas pipeline to hydrogen transport and the effects of impurities on the hydrogen quality. Presentation at ENTSOG GAS QUALITY & HYDORGEN WORKSHOP, 11/07/2022. Available online: https://www.entsog.eu/sites/default/files/2022-11/4.2%20Conversion%20of%20a%20natural%20gas%20pipeline%20to%20H2%20and%20effects%20of%20impurities%20-%20Henk%20Top%20%28DNV%29.pdf*

[82] *Stöhr, T., Reiter, V., Scheikl, S., Klopčič, N., Brandstätter, S., & Trattner, A. (2024). Hydrogen quality in used natural gas pipelines: An experimental investigation of contaminants according to ISO 14687: 2019 standard. International Journal of Hydrogen Energy, 67, 1136-1147. https://doi.org/10.1016/j.ijhydene.2023.09.305*

[83] *Pre-normative research on integrity assessment protocols of gas pipes repurposed to hydrogen and mitigation guidelines, see https://pilgrhym.eu/.*

Figure 3-1: Deposits from a gas transport pipeline, second cleaning pigging (Source: DBI[84])

Hydrogen underground storage technologies

Hydrogen storage will be a pivotal element of a future hydrogen transportation network, balancing mismatches in supply and demand. Existing underground hydrogen storage (UHS) facilities exist in form of salt caverns and porous media storage sites like depleted gas and oil fields or saline aquifers:

The Technology Monitoring Report 2023 prepared by TCP-Task 42[85] describes the different types of potential underground storage sites as follows:

Salt caverns (typical storage capacity: 100-250 GWh): "Hollow cylindrical voids in a rock salt formation in the subsurface created by salt solution mining. These voids are irregular in morphology but typically these are on the scales of a diameter of several tens of meters and heights of several hundreds of meters. The bottom of caverns is located at depths of up to two kilometres."

Salt caverns and the required operating technologies exist for a wide range of materials, including natural gas, oil, brine or chemicals, but also other gases like nitrogen, helium and even hydrogen. Within Europe, most salt caverns are located in central Europe, in countries like the Netherlands, Germany, France and Great Britain.

Depleted gas fields (100 – 20.000 GWh): "Storage capacity defined by the pore space in a (once) gas-bearing rock formation. This typically concerns sandstone carbonate intervals. The storage volume results from prior extraction of hydrocarbons. Gas fields are sealed by impermeable cap rocks such as mudstones and rock salt, which are proven to be a capable seal for natural gas. The seal integrity for hydrogen gas is being tested."

Aquifers (100 – 20.000 GWh): "Storage capacity defined by the porous, water bearing rock formations. The presence of a secure and gas-tight seal must generally be proven by geological investigations, exploration drilling and injection tests."

Within Europe, porous media storages in from of depleted gas or oil fields or aquifers are the main storage technology for gas storage, especially in regions with no potential for salt cavern storage.

Lined (hard) rock caverns (10 – 30 GWh): "Man-made tunnels and caverns built in low permeable rock formations. The secure containment for gases is generally achieved by lining the cavern walls with a gas-tight material."

[84] *DBI GUT & Frontiers Economics (2022): H_2-Rein H_2 short study: Hydrogen quality in an all-German hydrogen network.*
[85] *IEA Hydrogen TCP-Task 42 (2023), "Underground Hydrogen Storage: Technology Monitor Report"*

While there are around 450 existing rock cavern sites (unlined, e.g. for crude oil, refined products or LPG), there is only one lined cavern for natural gas in Skallen, Sweden, which started operation in 2002 and has a capacity of around 40,000 m^3. As part of the HYBRIT project, a first pilot cavern for hydrogen was built at Svartöberget in Luleå, Sweden (Operation test period: 2022-2024, 100 m^3 capacity).[86]

When it comes to hydrogen quality and possible contamination due to the storage process, it needs to be noted that the experience with large-scale underground hydrogen storage (UHS) is rare.

Although there is long-time experience with storage of high-purity hydrogen in an industrial context based on four salt caverns sites (three of them in the US and one in the UK), there is no case of grid-related hydrogen underground storage. In the existing storage sites, hydrogen quality of minimum 95 % has been reported by Diamantakis et al. 2024 and IEA Hydrogen TCP-Task 42 [87]. However, these facilities are operated with a static feedstock of hydrogen supply and, hence, rather controlled operation conditions. In addition, underground storage of town gas (gas mixture composed of around 50 % hydrogen and other gases like methane, CO, CO_2 and nitrogen) was done in porous reservoirs over several decades providing some experience on storage integrity and hydrogen losses.

In general, gas storage operators (for natural gas as well as for hydrogen in the future) receive gas from the grid in line with grid quality specifications and need to ensure that gas reinjected meets the same quality requirements. Depending on the quality that is withdrawn from the gas storage reservoir, additional purification steps may be required for hydrogen before and after injection (see below).

Table 3-6 provides a summary of main findings of the literature research done in this task. The analysis, however, shows that research and discussion in literature mostly focuses on the aspects of general feasibility, safe operation and containment of the gas reservoir. Therefore, it must be noted that as of today, several uncertainties and research gaps associated with contaminants and hydrogen quality aspects in case of UHS exist.

Table 3-6: Overview of possible gas contaminants in the context of underground gas storage

UHS type	Potential Impurities / contaminants	Potential sources	Major risks
Salt cavers	H_2O	Brine	likely
	Sulphur Compounds	Brine, Microbiological activity	possible
	Higher Hydrocarbons	Compressor oils, diesel blanket	possible
	CO_2, CH_4	Residual gases in cavern wall or dissolved in brine	possible
Aquifers, depleted gas fields	H_2O	Underground reservoir	likely
	CH_4	Residual gas in cavern (decreasing concentration), biological activity	likely
	Sulphur Compounds	Biological activity	likely
	Higher Hydrocarbons	Compressor oils, blanket	possible

Salt caverns

In general, salt caverns are considered to be a key technology for underground hydrogen storage with typical volumes of up to 500.000 m^3 (or around 133 GWh of Hydrogen).[88] Based on existing experience with hydrogen storage in salt caverns, different potential sources for contamination of the stored hydrogen gas exist:

[86] *Johansson, Fredrik & Spross, Johan & R. Damasceno, Davi & Johansson, Jan & Stille, Håkan. (2018): Investigation of research needs regarding the storage of hydrogen gas in lined rock caverns: Prestudy for Work Package 2.3 in HYBRIT Research Program 1.*

[87] *IEA Hydrogen TCP-Task 42 (2023), "Underground Hydrogen Storage: Technology Monitor Report"*

[88] *Małachowska, A., Łukasik, N., Mioduska, J., & Gębicki, J. (2022). Hydrogen storage in geological formations—The potential of salt caverns. Energies, 15(14), 5038. https://doi.org/10.3390/en15145038*

- Brine residues
  Absorption of moisture from brine residues are considered to be the main contamination of gas for salt caverns.[89]
- Residues of former use for natural gas (or other gases) (for repurposed caverns only)
  In case, existing salt caverns are rededicated for hydrogen, residues resulting from natural gas may even be present after cleaning the cavern with brine, as the gas may be trapped in some pockets in the underground formations.
- Microbiological activity:
  Despite high salinity, microbiological activity can, in generally, also occur in salt caverns and it has been observed in some cases. Still, literature pronounces that additional research is needed. Dopffel et al. 2024 discusses the impact of microbiological activity on salt caverns. [90]
  Several anaerobic (oxygen-free) metabolisms by microorganisms like bacteria or archaea exists, however, the authors describe that sulphate reduction, methanogenesis and acetogenesis will be the dominant ones, forming H_2S, CH_4 and acetate (CH_3COOH). In summary, due to the environmental conditions (high salinity) and lower survey area for potential biofilm formation, the issue of unpredictable reactions by bacteria or archaea is considered less critical as for porous media storage sites (see below).

Other potential sources for contaminations by higher hydrocarbons are e.g. the diesel blanket, used as protection to prevent fast upward leaching. In addition, residues from compressor oils can be present. An interview-based study among German stakeholders[91] showed that even for salt caverns, a hydrogen quality standard above ISO14687 Grade A (≥98 mol%) is not considered to be economically viable, as beside drying, desulphuration and dehydrocarbonisation also PSA would be required. The hydrogen storage sites, therefore are considered to be the pivotal element / bottleneck for higher quality levels within the grid.

Porous media storages

For regions, where not salt formations exist, porous media storages are the key technology for natural gas storage. In total, they account for about 70 % of gas storage facilities in Europe. It can be differentiated between depleted gas (and oil) fields on the one hand and aquifers on the other hand. A key difference between both storage types results from the fact that for former gas fields a high amount of data from former exploration activities exist and thus gas reservoir properties are better understood. This facilitates estimating the risk of side reactions and contaminations.

In contrast to that, depleted gas fields have the "burden" of having high methane concentrations in the underground site. Therefore, a transition period will occur with lower hydrogen and higher methane concentrations in the withdrawn gas stream during a first phase. According to a comprehensive report by the Hydrogen TCP-Task 42 [92] this also presents a major challenge for on-site gas separation technologies: a combination of e.g. membrane and PSA may be required to receive to purified gas streams for hydrogen and natural gas, both being in line with pipeline specifications. It should be noted that the composition of the withdrawn gas can fluctuate depending on operation conditions. In case, PSA tail gas is to be reinjected into the gas reservoir, varying gas flows and compositions as well as low pressure levels may provide another challenge for compressor operation.

[89] *DBI GUT & Frontiers Economics (2022): H_2-Rein H_2 short study: Hydrogen quality in an all-German hydrogen network*

[90] *Dopffel, N., An-Stepec, B. A., Bombach, P., Wagner, M., & Passaris, E. (2024). Microbial life in salt caverns and their influence on H2 storage–Current knowledge and open questions. International Journal of Hydrogen Energy, 58, 1478-1485. https://doi.org/10.1016/j.ijhydene.2024.01.334*

[91] *Frontier Economics & DBI (2024): Interview-basierte Analyse aktueller Entwicklungen zur Wasserstoffqualität. Study for GETH2 and DVGW. Available online: https://www.frontier-economics.com/media/n12a0myg/frontier-dbi-best-practice-studie-zu-wasserstoffqualitaet-fuer-get-h2-dvgw-januar-2024-stc.pdf*

[92] *IEA Hydrogen TCP-Task 42 (2023), "Underground Hydrogen Storage: Technology Monitor Report"*

Experience from industry (see Stakeholder input from task 2) on porous media and depleted gas fields show, that guaranteeing qualities above 98 % may be challenging. Key contaminants are methane (from methane formation in the storage) as well as water and sulphur compounds.

Microbiological activity by bacteria or archaea is another potential concern when it comes to contaminations of hydrogen and even hydrogen losses. Different mechanisms of hydrogen consuming reactions are known forming e.g. methane, hydrogen sulphide or acetate. Although, specific characteristics that may reduce risk of microbiological activity have been identified like high salinity, high temperature and low levels of carbon sources or sulphate[93], the risk and severity of these contaminations is highly site-specific.

Storage operation

Compressors for underground storage

While piston (reciprocating) compressors are available for hydrogen, hydrogen underground storage requires significant upscaling of compressor capacity. Intermittent compressor operation is another significant challenge that needs to be overcome. In any case, use of compressor oils / lubrications can be identified as further potential source for contamination.

Pre-Treatment

Before entering the storage site, certain limits for trace elements and contaminants need to be guaranteed in order to prevent or limit risk of biological activity within the reservoir. Based on feedback of a storage operator (see Task 2), limits for sulphur compounds (5-20 ppm), CO and CO_2 were mentioned. Additionally, all particles larger than 3 µm need to be removed. Accordingly, depending on grid specifications, desulphuration and other pre-treatment may be required before gas enters the UHS, in order to limit the need and cost for post-treatment.

Post-Treatment

Due to the risk of potential contamination in the context of hydrogen underground storage, gas treatment facilities will be necessary as part of the above-ground facilities. These include dehydration technologies (i.e. glycol dryers) to reduce water content as well as especially PSA technology to increase the hydrogen content to 98-99.9 %. In case, the withdrawn hydrogen content from the storage reservoir is below 80 % (which will be a relevant scenario during a transition period of formerly natural gas storage sites), also a combination of a membrane technology with a PSA may the most economic solution.

Overview

Table 3-7 summarizes identified major contaminants and trace components for the major parts of the hydrogen supply chain.

In summary, the following conclusion can be drawn:

- AEL (alkaline electrolysis) and PEMEL (polymer electrolyte electrolysis) do not introduce contaminants to a level that would affect the use of hydrogen in various applications (99.6 % - 99.95 % after drying the hydrogen), even reaching the quality level needed for fuel cell electric vehicles after standard procedure filtering via PSA (pressure swing adsorption; >99.999 %) or deoxo unit (>99.99 %). Reaching Grade D seems to be feasible without major issues.
- Steam methane reforming as well as ammonia cracking require post-purification with PSA to achieve high hydrogen purity levels (e.g. >99.97 % for fuel cell application) and remove critical contaminants. For ammonia, many reformer and filter technologies are still under

[93] *Huynh, D.N, Wager. M. (2023): HyStories Deliverable D3.4: Synthesis of the risks and actions to correct these risks depending on the environment* https://hystories.eu/wp-content/uploads/2023/12/Hystories_D3.4-0-Microbial-risks-and-mitigation-measures.pdf

development and, hence, are connected to higher uncertainties (esp. for crackers). Reaching a quality > grade A, however, may be realistic in the future.

- The supply chain element transport via pipelines itself is not considered as being critical from a perspective of contamination as long-time experience with industrial hydrogen pipeline networks show. **Repurposed pipelines, however,** have the disadvantage that during a transition phase, different contaminations based on former use with natural gas may be present. Accordingly, intensive cleaning and purging procedures may be needed. Within a highly interconnected grid with several feed-in facilities, prevention of contamination will be more difficult compared to industrial point-to-point pipelines. In total, quality grades >A should, however, not be problematic.
- The situation is different for **underground hydrogen storage**. Existing storage sites in UK and the US in salt caverns only guarantee a minimum hydrogen level of 95 %. Contaminations from brine, natural gas residues in the reservoir / cushion gas as well as a range of possible microbiological reaction under extreme conditions in the storage facility may add different contaminants into the stored hydrogen gas. Pre- and post-treatment of hydrogen will be required to ensure injection of a stable quality back into the grid. Achieving hydrogen quality grade A may be feasible. Still, hydrogen underground storage sites may be considered as important bottleneck for a higher hydrogen quality from an overall system perspective.[94]
- **Large-scale piston compressors** required for pipeline and storage operation bear the risk of introducing lubricant / compressor oils into the gas.

Table 3-7: Overview of main contaminants along key elements of the hydrogen supply chain

Supply chain elements	Potential sources	Potential Impurities / contaminants
Production	Electrolysis - AEL	Nitrogen (+), water (o), oxygen (o), cations (o), argon (-)
	Electrolysis – PEMEL	Nitrogen (o), water (o), oxygen (o), carbon dioxide (-)
	Steam reformation (SMR) + (PSA)	Carbon monoxide (++), nitrogen (+), methane (o), water (o), argon (o), formaldehyde (-)
Conversion	Ammonia cracking	Ammonia (+), nitrogen (+)
Transmission and Distribution	Converted natural gas pipelines	Typical associated gas components, trace odorants (sulphur), condensate components (decreasing over time)
	Operations and maintenance	Nitrogen (purging) Lubricants / compressor oils (piston compressors)
Storage	Underground storage	Water, methane, sulphur compounds, higher hydrocarbons
	Operations and maintenance	Lubricants / compressor oils (piston compressors) Glycol (dehydration processes)

Probability: (++) frequent, (+) possible (o) rare (-) very rare (based on terminology used in Bacquart 2018).
No probability analysis performed for cases without rating.

3.1.2. Impact of hydrogen and its most common contaminants on infrastructure components, materials, and end-use applications

The following chapter provides an overview on the impact of different contaminants and impurities in the hydrogen gas stream, and hence, gas quality, on the use of hydrogen in different end use applications and the respective supply chain elements (e.g. hydrogen refuelling station for application in the mobility sector). Aim of this task is to discuss the impact of hydrogen and its most common

[94] *see also Frontier Economics & DBI GUT (2024). Interviewbasierte Analyse aktueller Entwicklungen zur Wasserstoffqualität. Studie im Auftrag von GETH2 und DVGW. Available at: https://www.frontier-economics.com/media/n12a0myg/frontier-dbi-best-practice-studie-zu-wasserstoffqualitaet-fuer-get-h2-dvgw-januar-2024-stc.pdf*

impurities on the lifetime, performance and safety of components required for application in different end-use sectors, namely mobility, industry and power sector as well as heating.[95]

In the past, different stakeholder surveys took place to gather information about the hydrogen quality requirements of different end-users. One major activity was performed in the context of the GERG project on "removing the technical barriers to use hydrogen in natural gas networks and for (natural) gas end-users (in cooperation with CEN). The results were documented by Bourfaied et al. 2021[96] In 2022, CEN & CENELEC also launched a survey on "Hydrogen quality in industrial applications".[97] In this case, however, no public results could be found to this stage of the study.

A sector-specific analysis is key to take the different quality requirements and tolerance of each application into account. CEN/TS 17977:2023 on the quality of hydrogen in rededicated gas systems already states that e.g. high temperature processes and gas engines or gas turbines can work with hydrogen of a much lower minimum hydrogen concentration than applications, where hydrogen is used as a chemical reactant, both as feedstock in industry, but also for fuel cell applications.

Within the study on grid quality by DNV & Kiwa 2023[98], data from a combination of market and literature research, stakeholder feedback and expert estimates were used to derive bandwidth of minimum possible hydrogen purity level, acceptable for different (industrial) end-users in a best-case and worst-case szenario.

Table 3-8: Indicate overview of bandwidths of minimum hydrogen purity level for different end-use applications (best and worst case assumptions) based on DNV & Kiwa 2023.

Category	Technology	Bandwidth of minimum hydrogen purity level %						
		97.0	98.0	98.5	99.0	99.5	99.9	99.99
Power	Gas turbine							
Industrial heat	Burner							
Oil refinery	Various processes							
Ammonia / fertilizer	Haber-Bosch process							
Steel	Blast furnace, DRI							
Chemical feedstock	Methanol, peroxides, etc.							
Chemical (others)	Food, coolant							
Mobility	Fuel cell							

Note: in bright blue: additional / deriving requirements based on literature data.

Beside the minimum level of hydrogen, however also a more specific analysis of the key contaminants is required, to identify the actual purification need. Recently published ISO/DIS 14687:2023(E) provides quality levels for hydrogen and maximum contaminant concentrations for different hydrogen applications (see Table 3-9). [99]. Gaseous hydrogen is described by Type I Grades A-F.

[95] *Please note: the interplay of gas quality and key infrastructure elements like pipelines, underground storages and compressors, was already discussed in sub-task 1.4.*

[96] *Boufaied A. et al (2021): H2PNR: Removing barriers for the successful introduction of hydrogen in the natural gas grid: WP9: Quality Requirements for Industrial Users – a survey – Summary Report. See also: https://www.gerg.eu/projects/hydrogen/removing-the-technical-barriers-to-use-of-hydrogen-in-natural-gas-networks-and-for-natural-gas-end-users/*

[97] *see CEN-CLC JTF H2qInd - Survey on hydrogen quality in industrial applications (2022-09-30). Available at: https://www.clean-hydrogen.europa.eu/media/news/survey-hydrogen-quality-industrial-applications-2022-09-30_en*

[98] *DNV and Kiwa (2023). A follow-up study into the hydrogen quality requirements. Available at: https://www.eerstekamer.nl/overig/20231009/rapport_kiwa_dnv/document*

[99] *ISO/DIS 14687:2023(E) – Hydrogen fuel quality — Product specification, now published as ISO 14687:2025.*

Table 3-9: Hydrogen and hydrogen-based fuel classification by application based on ISO/DIS 14687:2023(E).

Type	Grade	Category	Applications	Hydrogen fuel index (min. mol%)
Type I Gas	A	-	**Gaseous hydrogen; residential/commercial combustion appliances** (e.g. boilers, cookers and similar applications)	98.0
	B	-	**Gaseous hydrogen; industrial fuel for power generation and heat generation** except PEM fuel cell applications	99.90
	C	-	**Gaseous hydrogen; aircraft and space-vehicle ground support systems** except PEM fuel cell applications	99.995
	D[abc]	-	**Gaseous hydrogen; PEM fuel cells for road vehicles**	99.97
			PEM fuel cells for stationary appliances	
	E	1	Hydrogen-based fuel	50
	E	2	Gaseous hydrogen	99.9
			Internal combustion engine applications	
	F[c]	1	Gaseous hydrogen; internal combustion engine vehicular applications	98.0
	F[c]	2	Gaseous hydrogen; internal combustion engine stationary applications	98.0

[a] Grade D may be used for other fuel cell applications and internal combustion engines in vehicular and stationary applications, including on and non-road vehicles.
[b] Grade D may be used for PEM fuel cell stationary appliances alternative to grade E category 3.
[c] Fuel cells can be contaminated by lower grade hydrogen, such as Grade F hydrogen into PEM fuel cell vehicles. Care should be taken to ensure cross contamination does not occur in the supply chain nor when dispensing into vehicles or other systems.

Beside these global standardisation activities, also different national activities exist on defining certain quality standards for different applications. One example is the standardisation landscape in China. Yang et al 2019 summarizes the existing standards for different hydrogen application.[100] Here four pure hydrogen related standards with different purity requirements are described (status as of 2019).

1) Hydrogen – Part 1: Industrial hydrogen (GB/T 3634.1-2006)
2) Hydrogen – Part 2: Pure hydrogen, high pure hydrogen and ultra-pure hydrogen (GB/T 3634.2-2011)
3) Hydrogen for electronic industry (GB/T 16942-2009)
4) Fuel specification for proton exchange membrane fuel cell vehicles – Hydrogen (GB/T 37244-2018)

In both cases, the existence of different quality requirements is a consequence of the appliance-specific tolerance against different kinds of contaminants in the hydrogen gas stream.

Transport sector / Mobility

Fuel cell electric vehicles (FCEV)

For commercial applications, hydrogen fuel cell mobility today mainly focusses on PEM fuel cells and their application in vehicles like passenger cars, busses and trucks. Other applications are either in a very low development state (e.g. fuel cells for aviation) or their application is largely related to stationary use (e.g. SOFC application in the maritime sector). Consequently, the following overview will only cover requirements for PEM fuel cells.

Hydrogen is already commercially provided for PEM fuel cell vehicles today, and the EN 17124:2022 international standard on fuel specification exists.[101] The document not only describes product

[100] *Yang, Y., Wang, G., Zhang, L., Zhang, S., & Lin, L. (2019). Comparison of hydrogen specification in national standards for China. In E3S Web of Conferences (Vol. 118, p. 03042). EDP Sciences.*
[101] *EN17124:2022: Hydrogen fuel - Product specification and quality assurance for hydrogen refuelling points dispensing gaseous hydrogen - Proton exchange membrane (PEM) fuel cell applications for vehicles*

specification (and quality assurance) for hydrogen as a fuel. It also comprises an informative Annex A, which summarizes the impact of impurities that may be present in hydrogen on different vehicle components like stack, other fuel cell components as well as the complete powertrain. Despite the comprehensive overview, the document also states that "there is still need for fundamental research regarding the impact of a combination of the different impurities on the fuel cell power train", as most investigations so far are limited to the effect of single impurities only. Table 3-10 summarizes the effect of different contaminants on the components of a fuel cell vehicle. Similar explanations are also provided in Annex A of the draft version of ISO/DIS 14687:2023(E)[102].

Table 3-10: Impact of different impurities on FC components based on EN 17124:2022

Contaminants / impurities	Relevant FC / HRS components	Effect	Comment
Inert Gases: Argon, Nitrogen	Fuel cell	- lower cell potential (dilution and diffusion effect) - power losses, increased fuel consumption, loss of efficiency - permanent damage due to hydrogen starvation possible	Low (Occurrence of N_2 due to purging operation)
Oxygen	General (FC, HRS), on-board storage system	- risk of reactive gas mixtures - possible reaction with metal hydride storage material	-
Carbon Dioxide	General, Fuel cell	- dilution effect - catalytic reaction to CO (see below)	-
Carbon Monoxide	Fuel cell	- catalyst poisoning (binds at Pt sites, reducing ECSA)	High criticality (Risk of irreversible degradation)
Methane	General	- dilution effect	-
Water	H_2 dispensing system, On-board storage, Fuel cell	- potential formation of ice (in on-board vehicle tank or fuel cell) - corrosion of metallic components - water-soluble impurities to absorb/block functional groups of ionomer (membrane)	-
Total sulphur compounds (e.g. H_2S, SO_2, COS, CS_2, CH_3SH)	Fuel cell	- severe catalyst poisoning (adsorption on and reaction with Pt to form platinum sulphide)	High criticality (Risk of irreversible degradation)
Ammonia	Fuel cell	- irreversible FC degradation (blocking functional groups of ionomer by NH_4^+) - catalyst poisoning	High criticality (Risk of irreversible degradation)
Total Hydrocarbons	Fuel cell	- catalyst poisoning - decomposition to CO (see above)	Criticality depends on type of hydrocarbon
Formaldehyde	Fuel cell	- formation of CO (see above) under certain operation conditions	Contamination can be recovered
Formic Acid	Fuel cell	- formation of CO (see above) under certain operation conditions	Contamination can be recovered
Halogenated Compounds (i.e. Cl_2)	Fuel cell	- catalyst poisoning (irreversible effect)	-
Helium	Fuel cell	- lower cell potential (dilution and diffusion effect)	Low criticality, but separation potentially challenging

[102] *ISO/DIS 14687:2023(E) – Hydrogen fuel quality — Product specification, now published as ISO 14687:2025.*

Contaminants / impurities	Relevant FC / HRS components	Effect	Comment
Solid and liquid particulates (Aerosols)	General	- blocking of filters, valves, etc. - catalyst poisoning, membrane degradation - impact on storage system, sensors,	Also station operation fluids (e.g. cleaning agents, oils, lubricant oils, siloxanes, ionic liquids, decomposition products thereof, additives, metals, metal oxides and ions)

[1] ECSA: electrochemically active surface area

A comprehensive review on the impact of different contaminants and the chemical reactions was prepared by Cheng et al. 2006.[103] The report shows that even trace amounts of impurities present in the hydrogen fuel gas (or air streams) have the potential to significantly damage anode, membrane or cathode of the fuel cell due to poisoning reactions, i.e. irreversible adsorption on catalytic sites or reducing proton conductivity of the membrane. The authors also underline that these effects particularly occur at low temperature operation.

With regard to the criticality, carbon monoxide, hydrogen sulphide and ammonia impurities are typically seen as those contaminants, with the most negative effect on PEM fuel cell performance. Besancon et al. 2009, however also state that these contaminants, at the same time, can easily be removed via state-of-the-art purification techniques.[104] Hence, from a purification point of view, inert gases (present e.g. in hydrogen streams produced via SMR, but even more in ATR or coal gasification) are described to be more challenging to be removed, although these mainly have a dilution effect on hydrogen.

A probability analysis of different contaminants relevant for fuel cell mobility was performed by Bacquart et al. 2018.[105] Based on that analysis, contaminations with the highest probability to be present in the gas stream after purification at production site are CO (frequent) and N_2 (possible) for SMR + PSA as well as O_2 (frequent) for Chlor-alkali process + membrane purification. Contaminants with a rare likelihood over all technologies are CH_4, H_2O and Ar (SMR), N_2 and H_2O (chlor-alkali) and N_2, O_2 and H_2O for water electrolysis.

Beside PEM fuel cell applications for vehicles (Grade D), the newly revised ISO/DIS 14687:2023(E)[106] also covers hydrogen quality requirements for other PEM fuel cell applications, i.e. as for stationary appliances (Grade E). Although minimum hydrogen content is less strict compared to mobility applications Grade D, the general effect described in Table 3-10 of the different contaminants can be considered to be similar.[107] High-temperature fuel cells (MOFC, SOFC) that do not contain noble-metal catalysts like platinum, in general can be considered less sensitive to contaminations.

[103] *Cheng, X., Shi, Z., Glass, N., Zhang, L., Zhang, J., Song, D., ... & Shen, J. (2007). A review of PEM hydrogen fuel cell contamination: Impacts, mechanisms, and mitigation. Journal of Power Sources, 165(2), 739-756. https://doi.org/10.1016/j.jpowsour.2006.12.012*

[104] *Besancon, B. M., Hasanov, V., Imbault-Lastapis, R., Benesch, R., Barrio, M., & Mølnvik, M. J. (2009). Hydrogen quality from decarbonized fossil fuels to fuel cells. International Journal of Hydrogen Energy, 34(5), 2350-2360. https://doi.org/10.1016/j.ijhydene.2008.12.071*

[105] *Bacquart, T., Murugan, A., Carré, M., Gozlan, B., Auprêtre, F., Haloua, F., & Aarhaug, T. A. (2018). Probability of occurrence of ISO 14687-2 contaminants in hydrogen: Principles and examples from steam methane reforming and electrolysis (water and chlor-alkali) production processes model. international journal of hydrogen energy, 43(26), 11872-11883. https://doi.org/10.1016/j.ijhydene.2018.03.084*

[106] *ISO/DIS 14687:2023(E) – Hydrogen fuel quality — Product specification, now published as ISO 14687:2025.*

[107] *ISO/DIS 14687:2023(E), now published as ISO 14687:2025, see Table 1 and Table 4.*

Internal combustion engines (ICE) vehicles

Fuel quality requirements and the rationale behind the selection of relevant impurities to be measured for ICE applications of hydrogen are covered in (informative) Annex F in ISO/DIS 14687:2023(E). Beside vehicular applications (Grade F-1), also stationary applications of internal combustion engines are described (Grade F-2).[108]

In general, the fuel quality specification of Grade F-1 of a minimum concentration of 98.0 % hydrogen is less strict than for PEM fuel cell applications described above, providing a higher flexibility regarding non-electrolytic hydrogen production pathways including SMR or ammonia cracking. It should, however, be noted that in case of markets with strict vehicle CO_2 emission requirements, rather low thresholds for hydrocarbons (including methane), CO_2 and CO are imposed to limit CO_2 emissions of the vehicle. In these cases, higher purity requirements of e.g. 99.5 %mol may be needed.

Table 3-11: Impact of different impurities on ICE applications based on ISO/DIS 14687:2023(E)

Contaminants / impurities	Relevant components	Effect	Criticality / comment
Total gases without calorific value	ICE	- reduction of energy intake of engine	
Sulphur	ICE	- catalyst poisoning	- reflects EGT performance comparable to diesel engines
Water	Fuel delivery and tank system	- condensation	- similar as for Grade D
Particulate concentration	Fuel delivery and tank system	- blocking of filters	- similar as for Grade D
Hydrocarbons (including methane), CO_2 and CO	ICE	- increase of CO_2 emissions due to combustion	- limited in markets with strict vehicle CO_2 emissions

While Table 3-11 summarises impact of contaminants on the provision of hydrogen for mobile application, slight adaptions need to be considered in case of stationary applications. These include the water limit as well as the admissible particulate concentration. In both cases, a case-specific limit is recommended, taking also the fact into account, that stationary applications will not be supplied via a dispenser, but are either connected to a pipeline or receive deliverables via trailer.

Other sectors

ISO/DIS 14687:2023(E) also specifies three additional quality grades for gaseous hydrogen that may be used for applications other than PEM fuel cell. The quality grades specified are 98.0 % (Grade A), 99.90 % (Grade B) and 99.995 % (Grade C).[109] In contrast to PEM applications, the document however does not describe the impact of different impurity levels on the appliances. One reason certainly is that many applications for hydrogen, e.g. in heating or power generation, are currently fuelled by natural gas and the development of hydrogen-ready turbines or combustion engines are ongoing. For other applications, however, the fact that no industry-wide application standard exist is due to the very site- and case-specific purification requirements, e.g. when hydrogen is (already or in the future) being used as a feedstock (i.e. in chemical industry, refining or steel production). Existing applications today often are supplied via on-site hydrogen production (SMR) or via a locally confined (industrial) hydrogen grid. Due to high hydrogen offtake volumes, site-specific hydrogen purification to the minimum quality requirements often is performed.

[108] *ISO/DIS 14687:2023(E), now published as ISO 14687:2025, see Table F.1.*
[109] *ISO/DIS 14687:2023(E), now published as ISO 14687:2025, see Table 5.*

The following chapter may be subject to major revisions, taking input of the stakeholder feedback in task 2 into account. Further information on the quality requirements for industrial users can be found in Boufaied A. et al (2021).[110]

DBI GUT & Frontier Economics 2022 present an overview of hydrogen quality requirements in different end-use sectors, focussing on energetic use of hydrogen.[111] In general, the study concludes that "a statement on the quality requirements of the individual (sub-)sectors is not possible in a generally valid manner in every case." Table 3-12 summarises key findings for different applications. It shows that, while most applications can deal with Grade D hydrogen (>99.97 mol%), also lower qualities may be suited for several applications.

Table 3-12: Quality requirements of different application without further on-site purification

Quality requirements by sector / application		≥ 98 mol% H_2 = "low" quality	≥ 99 mol% H_2 = "medium" quality	≥ 99.97 mol% H_2 = "high" quality
Building (low temperature heat)		(✓)	(✓)	✓
Energy / power generation		(✓)**	(✓)**	✓
Mobility	ICE	✓	✓	✓
	PEM FC	Not suitable	Not suitable	✓
PtX		Not suitable	✓	✓
Industry (examples)	Construction aggregates (Stones and soils)	✓	✓	✓
	Paper	✓	✓	✓
	Glass and ceramic	✓**	✓**	✓
	Iron and steel	✓*	✓*	✓
	(Petro-) chemistry (feedstock / non-energy use)	Not suitable	✓*	✓

Source: Adapted based on DBI GUT & Frontier (2022)[112]. Low- and high-quality specifications referring to DVGW G260 Group A & D.
Please note: parathesis ( ) indicate that suitability depends on type of use or specific contaminant / trace component
*Dependent on the composition of trace components.
**Dependent on stability of the Wobbe index over time.

In the following, each sector is addressed / main applications are addressed individually.

Low temperature heat (households)

Today, burners working with natural gas are the major low temperature heat application in several countries. However, also heat pumps increasingly gaining attention. In case, low temperature heat shall be provided with hydrogen-fuelled burners, the fuel quality requirements can be considered as relatively low. According to DBI GUT & Frontiers Economics 2022[113], these systems in general are rather insensitive to the composition of the fuel gas and even robust against fluctuations in gas composition (and hence Wobbe index variations) within certain limits. One example for fuel specifications are derived from a pilot project in the UK, the so-called Hy4Heat project. Table 3-13 lists the quality requirements within that project. It should, however, be noted that in terms of emissions, already small differences in hydrogen purity level as well as operation conditions can have a significant impact.[114]

[110] *Boufaied A. et al (2021): H2PNR: Removing barriers for the successful introduction of hydrogen in the natural gas grid: WP9: Quality Requirements for Industrial Users – a survey – Summary Report. See also: https://www.gerg.eu/projects/hydrogen/removing-the-technical-barriers-to-use-of-hydrogen-in-natural-gas-networks-and-for-natural-gas-end-users/*

[111] *DBI GUT & Frontiers Economics (2022): H_2-Rein H_2 short study: Hydrogen quality in an all-German hydrogen network*

[113] *DBI GUT & Frontiers Economics (2022): H_2-Rein H_2 short study: Hydrogen quality in an all-German hydrogen network*

[114] *Gurbuz, H. (2018). The effect of H2 purity on the combustion, performance, emissions. Energy Costs Therm Sci, 24, 315.*

Table 3-13: Fuel gas composition recommended in the Hy4Heat project[115][116]

Components	Value	Explanations
Hydrogen (at least)	98 mol %	Compromise between cost and performance
CO	20 (µmol/mol)	Based on production limit from reforming
H_2S	≤ 5 mg/m³ 3.5 ppm (µmol/mol)	Component protection from GSMR:1996
Total sulphur	≤ 50 mg/m³ 35 ppm (µmol/mol)	
Oxygen	≤ 0.2 mol %	
Dew point of hydrocarbons	−2°C	GSMR:1996 and EASEE gas
Dew point of water	−10°C	
Methane, carbon dioxide, CO_2, hydrocarbons	≤ 1 % mol %	
Total argon, nitrogen, helium	≤ 2 % mol %	Avoidance of transport costs through higher inert proportions (ISO 14687-2019) and the limitation of fluctuations in the Wobbe index
Wobbe band	42–46 MJ/m³	
Impurities	The gas should not contain any solid, liquid, or gaseous components that endanger the safe operation of pipes and end use.	

Energetic use (power sector)

The energetic use of hydrogen for power generation is limited to the application in gas turbines and gas engines. While burners in gas turbines are not so much sensitive towards impurities in the gas, fluctuations in gas quality resulting in different burning properties described by the Wobbe index present a more detailed challenge. DBI GUT & Frontiers Economics 2022 describe a fluctuation limit of +/- 5 % in the Wobbe index, which is considered not to be relevant for high hydrogen quality. In general, Grade A (>98 mol%) is considered to be suitable for gas turbines (see Table 3-14).

A similar situation is described for gas engines. A rather stable gas combustion is considered more relevant than the actual quality and contaminants. Different trace components like CO, CO_2, N_2, CH_4 and other hydrocarbons are in generally not critical. For other gas parameters (e.g. sulphur content, dew point of water, dust / particles and other contaminants) comparable properties as today's requirements for natural gas should be considered (see e.g. EASEE-gas: Common Business Practice 2022 – 001/01 (CBP)[117] or Hy4Heat[118].

Table 3-14: Hydrogen quality requirements for gas turbines and gas engines (Source: based on DBI GUT & Frontiers Economics 2022)

Application	Parameter	Limits	Comments
Gas turbines	Heating value and fluctuation in Wobbe index	+/- 5 %	If necessary, rate of change must be defined.
	Hydrogen quality	>98 mol %	Quality Grade A (ISO 14687) considered as suitable basis
Gas engines	Heating value and fluctuation in Wobbe index	+/- 5 %	If necessary, rate of change must be defined.

[115] *Boufaied A. et al (2021): H2PNR: Removing barriers for the successful introduction of hydrogen in the natural gas grid: WP9: Quality Requirements for Industrial Users – a survey – Summary Report. See also: https://www.gerg.eu/projects/hydrogen/removing-the-technical-barriers-to-use-of-hydrogen-in-natural-gas-networks-and-for-natural-gas-end-users/*

[116] *Future Fuels CRC: RP1.4-02 Future fuel use in type B and industrial equipment - Final report. https://www.futurefuelscrc.com/project/future-fuels-end-use-type-b-appliances-and-industrial-equipment-rp1-4-02*

[117] *EASEE-gas: Common Business Practice 2022 – 001/01 (CBP)*

[118] *Hy4Heat: WP2: Hydrogen quality standards. see https://www.hy4heat.info/wp2*

Application	Parameter	Limits	Comments
	CO, CO_2, N_2, CH_4, other hydrocarbons	-	No effects to be feared as long as Wobbe index and heating value is compiled with
	Sulphur, dew point of water / hydrocarbons, dust / particles, other	-	Comparable limits as for today's use of natural gas are expected

Energetic use (high temperature heat)

Hydrogen application in industrial furnaces to produce high temperature heat can be seen as a critical aspect regarding a uniform hydrogen quality definition. Due to a high variety of possible applications and the impact of burning behaviour (e.g. temperature, but also contaminants) on product properties, in several cases a narrow range of hydrogen quality variations need to be guaranteed. This is especially the case for glass industry, but potentially also other industrial applications.

According to DBI & Frontiers Economics 2022, up to today, no detailed studies on quality requirements of industrial furnaces exist. For many applications (e.g. paper or steel production) DBI & Frontiers Economics 2022 suggest that ISO 14687 Grade A (>98 mol%) or even worse may be sufficient, as long as the impurity levels (e.g. CO_2, N_2, sulphur) are comparable to today's level in natural gas. In addition, fluctuation in combustion properties (Wobbe index and heating value) need to stay within a certain range (e.g. less than +/- 2 %).

Feedstock (steel industry, refinery and chemical industry)

In contrast to end-uses of hydrogen mentioned so far, the application of hydrogen as feedstock or bulk chemical is already widely deployed today, making up for around 90 % of existing hydrogen use in chemical or petroleum industry.[119] Further applications with a smaller market share are precision chemical applications, where an oxygen-free atmosphere is used to prevent oxidation (e.g. semiconductor production) or for cooling applications.

In general, hydrogen use as a feedstock show considerable higher requirements with regard to hydrogen quality than for the thermal use in combustion processes. Some key applications for hydrogen and the general impact of contaminants in the feed gas are summarized below.

Ammonia production

Ammonia production via the Haber-Bosch process for fertilizer industry today represents the largest industrial application of hydrogen. State-of-the-art plants comprise on-site hydrogen production via SMR from natural gas. Already today, pre-treatment of the natural gas to remove sulphur compounds as well as post-treatment via absorption or adsorption (PSA) processes to remove CO_2 are required.

The sensitivity of ammonia production towards specific contaminants is due to the different catalysts used at different stages of the process (e.g. Fe-based, also Ru-based). Here, production of high-quality hydrogen via electrolysis processes can be seen as advantageous compared to established (on-site) hydrogen production via SMR that requires further purification.[120] Especially sulphur, fluorine, chlorine (compounds), phosphorus and arsenic are catalyst poisons with irreversible effect and, hence, need to be removed. In addition, deactivation of the catalyst occur by O_2, CO and CO_2, resulting in a admissible

[119] *Boufaied A. et al (2021): H2PNR: Removing barriers for the successful introduction of hydrogen in the natural gas grid: WP9: Quality Requirements for Industrial Users – a survey – Summary Report. See also: https://www.gerg.eu/projects/hydrogen/removing-the-technical-barriers-to-use-of-hydrogen-in-natural-gas-networks-and-for-natural-gas-end-users/*

[120] *Patonia, A. & Poudineh, R. (2020): The key challenges of ammonia production. Available at: https://www.jstor.org/stable/pdf/resrep30957.9.pdf*

contamination limit at ppm-level. Based on Bourfaied et al. 2021[121], the following maximum permissible impurities for ammonia synthesis can be stated (see Table 3-15).

Methanol production

Methanol production takes place using syngas (a mixture of H_2, CO and CO_2) that is normally provided via SMR. Similar to ammonia, also methanol production comprises catalytic processes. Preventing poisoning of those catalysis (e.g. Cu, Zn) by ensuring a high hydrogen quality with very low levels of sulphur and chlorine compounds is therefore key. A low sulphur level (< 50 ppb) is ensured by a desulphurization of the feed natural gas. Different other species with impact on catalysts are considered to be in the low ppb range, including Halogenic species, iron or nickel. The maximum permissible impurities listed for methanol synthesis are listed in Table 3-15: [122]

Fischer–Tropsch synthesis

Fischer–Tropsch synthesis is used in the so-called PtL processes to produce hydrocarbons from syngas under the use of iron or cobalt as catalysts. Based on available data in literature, the limits of catalyst poisons in the syngas feed can be stated as followed:[123]

Table 3-15: Examples for hydrogen quality requirements for hydrogen used as substrate in chemical reactions (Source: DBI & Frontiers Economics (2022), Król, A. et al. (2024)) [124]

Parameter	Ammonia Synthesis	Methanol Synthesis	Fischer–Tropsch Reaction
Total sulphur	<1 ppb	<50 ppb	<0.06-1 ppm
Halogens (F, Cl, Br, I, At)	<1 ppb (for F, Cl)	<1 ppb	<10 ppb
Carbon dioxide	<5 ppm	no data	no data
Carbon monoxide	<5 ppm	no data	no data
Oxygen	<5 ppm	no data	no data
Water vapour	<30 ppm	no data	no data
Total nitrogen	no data	<0.5 %	50 ppb
Methane	as low as possible	<3.0 %	no data
Inerts (Ar, He)	as low as possible	no data	no data
Iron	no data	<5 ppb	no data
Nickel	no data	<5 ppb	no data
Hydrochloric acid (HCl)	no data	2 ppb	no data
Hydrogen cyanide	no data	no data	10 ppb
Ammonia	no data	no data	10 ppmv
Nitrogen oxides	no data	no data	0.2 ppmv

Refineries

Within refining processes, hydrogen is used for different hydrotreating procedures, namely hydrodesulphurization (to remove sulphur), hydrocracking (to break-up longer-chained hydrocarbons) and hydro conversion. By removing several contaminants with hydrogen from the petroleum fractions, a high quality of the final product can be ensured.

[121] *Boufaied A. et al (2021): H2PNR: Removing barriers for the successful introduction of hydrogen in the natural gas grid: WP9: Quality Requirements for Industrial Users – a survey – Summary Report. See also:* https://www.gerg.eu/projects/hydrogen/removing-the-technical-barriers-to-use-of-hydrogen-in-natural-gas-networks-and-for-natural-gas-end-users/

[122] *Boufaied A. et al (2021): H2PNR: Removing barriers for the successful introduction of hydrogen in the natural gas grid: WP9: Quality Requirements for Industrial Users – a survey.*

[123] *Spath & Dayton (2003): Preliminary Screening — Technical and Economic Assessment of Synthesis Gas to Fuels and Chemicals with Emphasis on the Potential for Biomass-Derived Syngas. Available online:* https://www.nrel.gov/docs/fy04osti/34929.pdf

[124] *Król, A. et al. (2024): Hydrogen Purification Technologies in the Context of Its Utilization. Energies.; 17(15):3794.* https://doi.org/10.3390/en17153794

Due to the different processes in oil refining, bandwidth for hydrogen purity level presented in Table 3-8 ranges from 97–99.5 %. Also, Boufaied A. et al (2021) describe that usually, industry-grade hydrogen with 99.5 % may be used. However, even in some cases, trace components like CO or CO_2 may be challenging so that even 99.5 % may not be sufficient. According to a presentation by EIGA at the PENTA forum[125], a quality above 99.8 % is required. Some impurities can act as catalyst poison in specific processes, which is why the oxygen content should be below 0.0005 % (=50 ppm).

Steel production

In general, hydrogen can be used as a fuel (for energetic use or injection into blast furnace process) or as a feedstock / reducing agent in DRI process in steel industry. Depending on the use, different H_2 quality requirements will be present (see also section on high temperature heat above). In literature, however, no limits for critical trace contaminants could be identified for the process.

As the dominant DRI process, the MIDREX® technology (using natural gas as a feedstock to produce hydrogen as reduction agent) is considered to not depend on high purity hydrogen. Based on specifications of Primetals Technologies, a hydrogen purity of 99.8 % is required for the process to produce virgin metallics (DRI or HBI) from limp iron ore or pellets. [126] This quality requirement is, in line with the assessment by DNV & Kiwa 2023 (see Table 3-8) with a indicative bandwidth of minimum hydrogen quality level for DRI between 99.0 and 99.5 %. Boufaied A. et al (2021) indicate that in general a wide spectrum of hydrogen to carbon monoxide ratios between 0.5 and 3.5 may be acceptable for the DRI process in an electric arc furnace (EAF). In contrast to that, McKinsey & Company 2020[127] describe that the reduction of iron ore in form of DR pellets requires a hydrogen purity >99.999 % (Hydrogen 5.0).

Learnings from the stakeholder interaction in Chapter 4 indicate that steel industry rather prefers higher quality standards in order to minimize possible contaminations (e.g. sulphur or ammonia). Impurities in hydrogen can reduce the efficiency of the reduction reaction and degrade the steel quality.[128] Contaminants like moisture, oxygen, nitrogen, and sulphur compounds influence reaction kinetics and the steel's final properties. Accordingly, a strict monitoring and control of hydrogen purity is required throughout production.

However, further analysis and discussion with relevant industry stakeholders is needed to verify these statements.

3.2. Standardisation landscape

In this chapter, an overview of existing standards is made. First, the international standards are compiled including relevant CEN and ISO documents on hydrogen quality. After this, the national hydrogen standardization landscape for EU MS is discussed, including ongoing activities and future work on the topic. Although the stakeholder assessment is presented in Chapter 3, some insight of stakeholders is included here to sketch a complete picture of national interests.

3.2.1. Overview international standards and standardisation activities on hydrogen quality

As already pointed out in the previous chapters, a wide range of different standard documents, technical rules and/or other harmonisation activities already exist aiming to specify common

[125] *EIGA (2024): Enabling H2 together Through EIGA Safety and Technology. Presentation at Workshop of the Pentalateral Energy Forum in March 2024,*

[126] *Hall, W., Millner, R., Rothberger, J., and Singh, A., Shah, C.K. 2021. Green Steel through Hydrogen Direct Reduction: A study on the role of hydrogen in the Indian iron and steel sector. New Delhi: The Energy and Resources Institute (TERI). Available at: https://www.teriin.org/sites/default/files/2021-08/policybrief-green-steel.pdf*

[127] *McKinsey & Company (2020): Decarbonization challenge for Steek . Hydrogen as a solution for Europe. Available at: https://www.mckinsey.com/~/media/McKinsey/Industries/Metals%20and%20Mining/Our%20Insights/Decarbonization%20challenge%20for%20steel/Decarbonization-challenge-for-steel.pdf*

[128] *See https://www.processsensing.com/en-us/industries/Measurements-for-hydrogen-purity-in-steel-production.htm.*

requirements for admissible (minimum) hydrogen purity levels as well as (maximum) concentrations of key contaminants. These documents in general cover certain infrastructure elements (e.g. pipeline transport) or end-use specifications. An overview of key documents including a short explanation is included in Table 3-16.

Table 3-16: Overview relevant hydrogen quality standards, technical rules and further harmonisation activities in Europe

Standard / document	Name	Scope	Comment
Transport / Pipeline			
CEN/TS 17977:2023 **(2023)**	Gas infrastructure - Quality of gas - Hydrogen used in rededicated gas systems	H_2 pipelines (rededicated NG pipelines)	H_2 quality**: ≥98.0 %,** Wobbe Index: 42-46 MJ/m³ (15 °C/15 °C) Note: different specifications compared to ISO 14687 Grade A
EASEE-gas: Common Business Practice 2022 – 001/01 (CBP) **(2022)**	Hydrogen Quality Specification	H_2 pipelines (rededicated NG pipelines)	**≥98.0 %** (reference to ISO1467:2019 Grade A, Specification of critical components only) Note: on-site purification for O_2 or sulphur components.
DVGW G260:2021 (DE) **(2021)**	Technical Rule on gas quality ("Gasbeschaffenheit")	H_2 pipelines (for gases in public infrastructure in Germany)	Gas family 5, group A with ≥**98.0 %** and group D with ≥**99.97 %** (reference to EN 17124:2019) Currently under revision to (possibly) include **99.5 % (tbc)** as additional "grade" "group A+"
Fluxys Hydrogen specification proposal (BE) **(2022)**	Hydrogen Specification Proposal	H_2 pipelines (transmission system by Fluxys Belgium)	H_2 quality: **≥98.0 %** Aligned with EASEE-Gas (CBP H2), CEN, specifications for UK, NL and DE, + further stakeholder input
Indicative quality specification for HyNetwork (NL) **(2024)**	Indicative quality and temperature specification for Hydrogen Network Netherland	H_2 pipelines (for Hydrogen Network Netherland)	H_2: ≥**99.5 %,** indicative only, based on results of DNV/Kiwa studies, final decision by Ministry open Note: Former version (2022) with 98 %.
Applications / End-use			
ISO/DIS 14687:2023 (E) **(2024)**	Hydrogen fuel quality — Product specification	End-uses (different)	Different Grades (A-F) for state of hydrogen and end-use **≥98.0 % (Grade A) – ≥99.995 % (Grade C)**
EN 17124:2022 **(2022)**	Hydrogen fuel - Product specification and quality assurance for hydrogen refuelling points dispensing gaseous hydrogen - (PEM) fuel cell applications for vehicles	PEM fuel cell (vehicles)	H_2 quality: **≥99.97 %** Fuel quality requirements at the dispenser nozzle + risk assessment / probability of occurrence + severity class, impact on fuel cell at certain concentrations

3.2.2. Overview on national standards and legislation on hydrogen quality in selected Member States

There is a large diversity of positions regarding H_2 quality in the investigated EU Member States. Some countries can be named as "**front runner" countries (the Netherlands, Belgium & Germany)**, as TSOs from those countries are converging towards a uniform 99.5 % quality standard in repurposed pipelines. This convergence on the 99.5 % quality level is twofold: it is the expected quality which is able to be guaranteed in repurposed networks on a technical level, and some TSO's believe it is the economic optimum in terms of purification costs. Other countries, however, are not active regarding H_2 quality requirements. Available European H_2 standards have not yet been translated into domestic ones. In this subchapter, the adoption of standards in EU member states will be discussed. An overview of EU member states and their ongoing national regulatory activities regarding hydrogen quality can be seen in Table 3-17.

Primary standardization activities centre around the Netherlands, Germany and Belgium. At a workshop of the Pentalateral Energy Forum in March 2024, TSOs from Germany, Belgium and the Netherlands announced the **launch of a 'pre-normative initiative' of Hydrogen Network Operators (HNOs), proposing a common 99.5 % H_2 quality specification**. Support for this initiative also comes from TSOs in Austria, Switzerland and Luxembourg.

So far, The Netherlands have been most active in pushing for a 99.5 % standard, as the government-financed DNV/Kiwa study (2023)[129] has **identified 99.5 % as an economic optimum for the country** and in June 2024, an 'indicative specification' including 99.5 % purity was proposed for the Dutch HyNetwork.[130] However, the final decision on the purity will be made by the Ministry of Economic Affairs and Climate Policy (EZK). Similarly, **Germany is also moving towards a 99.5 % standard**: The responsible standardization body DVGW is currently revising its GDVGW G260 H_2 standard, with the goal of establishing a purity standard of 99.5 %.

Table 3-17: Hydrogen Standards across selected EU Member States

Country	Existence of national standards / specifications	Inspired by	H_2 Quality levels required	Most important national gas quality specifications
Austria	yes	ISO 14687	98 – 99.97 %	OEVGW H B100:2023; OEVGW H E310 (H_2 injection stations)
Belgium	No, proposal	EASEE-gas CBP	Proposed: 98 % Goal: 99.5 %	Fluxys Hydrogen specification proposal
Germany	Yes	EN 17124, ISO 14687	98 % -99.5 % - 99.97 %	DVGW G260:2021
Czech Republic	Yes	ISO 14687	98 – 99.97 %	ČSN ISO 14687-1; ČSN ISO 14687-2
Denmark	No	CEN/TS 17977	98 % (preliminary)	CEN/TS 17977 as preliminary specification
Finland	No	ISO 14687	-	ISO 14687 mentioned in guide on H_2 fuel
France	No	-	-	-

[129] *DNV and Kiwa (2023). A follow-up study into the hydrogen quality requirements. Available at: https://www.eerstekamer.nl/overig/20231009/rapport_kiwa_dnv/document*

[130] *HyNetwork (2024a). Indicative quality and temperature specification for Hydrogen Network Netherlands. Available at: https://www.hynetwork.nl/media/jokhjtcb/indicative-quality-and-temperature-specification.pdf*

Country	Existence of national standards / specifications	Inspired by	H_2 Quality levels required	Most important national gas quality specifications
Italy	No	-	-	-
Netherlands	No, proposal	-	Proposed: 99.5 %	Indicative quality specification by HyNetwork
Poland	No	-	-	-
Spain	No	EN 16726	-	Mentioned in enagas Protocols for System Technical Management
Sweden	No	-	-	

In May 2024, the EU adopted its hydrogen and gas decarbonisation package, which consists of Directive (EU) 2024/1788 and Regulation (EU) 2024/1789. Amongst other issues, the legislation introduces a new regulatory framework for dedicated hydrogen infrastructure, mandating Member States to assign hydrogen transmission network operators (HNOs/HTNOs) to be responsible for a country's H_2 network. Furthermore, the EU's legislation package sets the foundation for the European Network of Network Operators for Hydrogen (ENNOH) – a new entity to be established from 2025 onwards, with the purpose of coordinating the planning, development and operation of the EU's hydrogen transmission infrastructure, including for instance the development of network codes and monitoring of the implementation. National HNOs/HTNOs will be eligible to join ENNOH.

Even before the law was adopted, **Belgium** became the first country to translate it into national law by passing a domestic "Hydrogen Act", which served as the basis for assigning the status of Hydrogen Transmission Network Operator (HTNO) to the company Fluxys. **Fluxys Hydrogen is also part of the mentioned, informal initiative pushing for a 99.5 % H_2 quality standard**. According to the new Belgian law, the country's HTNO is also responsible for setting and controlling quality standards for the hydrogen transported in its pipelines.

Besides the three front runner countries, the other countries investigated differ largely in their activities on H_2 quality. Whilst not as active as the other three, **Austria** has translated ISO standards into domestic ones (OEVGW H B100) and strongly calls for harmonization of European hydrogen standards within the gas system. The **Czech Republic** has also translated ISO standards into domestic standards, but does not support any specific purity requirement for the use in repurposed pipelines. In **Denmark**, there is currently a lively discussion about a preference between the 98 % and the 99.5 % standard.

Other countries have quite ambitious plans to use hydrogen and have plans to build H_2 infrastructure, but the debate on hydrogen purity is not very present. **Finland** is a good example: The Baltic country recently announced ambitious plans to become one of the EU's lead suppliers of emissions-free hydrogen, but there is no mention of the hydrogen purity debate in the country. Similarly, **Spain** has already named its current gas TSO enagas to be the country's provisional HTNO and has ambitious H_2 pipeline plans – matters related to H_2 purity do not however play a large role in those plans. **Sweden** discusses potentials and plans to produce hydrogen by carbon capture and reforming of biogenic gases due to limited availability of (renewable) electricity. There has also been no specific discussions or positions regarding H_2 quality.

In countries without domestic H_2 standards, network codes used for natural gas can serve a starting point for the development of H_2 standard preferences, (i.e. for non-fuel cell applications). Most of the network codes for the gas transmission grids from the different TSOs refer to the standard EN 16726.

This standard is currently under revision and the updated version is planned to be published in April 2025.

Regarding a **dedicated private H_2 pipeline infrastructure**, five of the twelve Members States investigated reported to the EU (in 2022) that there are currently 100 % H_2 pipelines in place in their country.[131] Amongst these are countries like Germany, which has announced ambitious plans to expand its infrastructure or Belgium, which currently has the largest H_2 pipeline network in Europe (613 km). However, other countries with ambitious infrastructure plans, like Austria, Finland, Italy or Spain, do currently not have any existing H_2 infrastructure in place.

3.2.3. National activities on hydrogen quality for a future hydrogen infrastructure – country fiches

Overview

This chapter provides a summary of the literature research as well as stakeholder feedback on ongoing activities regarding harmonisation of H_2 quality on national levels. Different activities, studies discussions and relevant aspects have been identified including national plans for the build-up of H_2 infrastructure.

In context of the current and planned hydrogen market as well as hydrogen quality requirements, the Netherlands, Belgium and Germany are identified as most active group, so-called "front runners". The following section presents a brief summary of current activities for each of the selected MS (i.e. the Netherlands, Belgium, Germany as well as Austria, Czech Republic, Denmark, Finland, France, Italy, Poland, Spain and Sweden).

"Front runners"

Netherlands

- The Netherlands is **moving towards a minimum hydrogen purity standard of 99.5 %** for its national transmission network, reflecting stakeholder preferences and feasibility studies.
- « Do it once, do it right » approach, preference towards stable conditions among stakeholders
- The country is developing a robust regulatory framework to support hydrogen integration, leveraging existing gas regulations while drafting new laws specific to hydrogen.
- The responsibility for ensuring hydrogen purity is increasingly placed on producers, with transmission operators playing a key role in enforcing network standards and supporting pilot projects.
- Construction on the first section of the dedicated national transmission network has started.

In the Netherlands, there is a **detailed discussion about H_2 purification levels** going on, including the question of who has to pay for additional purification efforts. The **DNV/Kiwa 2022 report[132] recommends 98 % purity** for the national transmission network. The results were based on projected hydrogen demand volumes of different end-use sectors in the Netherlands. There were, however, some discussions among several stakeholders in the hydrogen industry[133], particularly those involved in refining, steel production, and electricity generation: A market consultation, held by the Ministry of Economic Affairs and Climate Policy (EZK), has shown that a majority of the stakeholders prefer a

[131] *European Union Agency for the Cooperation of Energy Regulators (ACER) (2022). Opinion 08/2022 on the Review of Gas and Hydrogen National Network Development Plans to assess their consistency with the EU ten-year network development plan – Annex III: Hydrogen, Biomethane injections, and Related Network Adaptations. Available at: https://www.acer.europa.eu/sites/default/files/documents/Official_documents/Acts_of_the_Agency/Opinions/Opinions%20Annexes/ACER_Opinion_08-2022-Annex_III.pdf*

[132] *DNV and Kiwa (2022). Kwaliteitseisen voor waterstof t.b.v. het transportnet. Available at: https://open.overheid.nl/documenten/ronl-385383e0a0db4e2db9f6c1688273f9fefa0c4857/pdf*

[133] *Clifford Chance (2023a). Focus on hydrogen: regulatory developments in the Netherlands. Available at: https://www.cliffordchance.com/content/dam/cliffordchance/briefings/2023/04/focus-on-hydrogen-regulatory-developments-in-the-netherlands-april-2023.pdf*

hydrogen purity requirement higher than 98 %. Generally, too high standards will hinder grid access, while too low standards may deter potential off-takers due to the high purification costs associated with lower-quality hydrogen. For instance, a key criticism was that the research assumes 98 % hydrogen purity is adequate for refining, steel production, electricity generation, and heating systems. However, in practice, the requirements for refining and steel production vary[134], with many parts of these sectors needing higher hydrogen purity, and stringent contaminant limits.

Following the results of the market consultation, **DNV/Kiwa 2023**[135] expanded the study to assess an optimal level for purity of hydrogen in the national transmission network from a societal perspective and what specifications would be suitable for a hydrogen quality of 99.5 %. Based on conducted interviews, it was concluded that contamination from retrofitted natural gas pipelines and salt cavern storage is minimal and does not prevent **achieving a hydrogen quality of at least 99.5 %,** provided the sulphur limit is set at 3 mol ppm. Additionally, almost all respondents prefer stable specifications, without an adjustment after a couple of years. Compared to the previous specification, the maximum sulphur content and the maximum temperature were lowered and additional requirements were added on the allowable Wobbe-index and the maximum hydrocarbon dewpoint.[136] The **hydrogen purification cost model they used in this study indicates that by 2035, a 99.5 % hydrogen specification is likely to be more optimal than a 98.0 % gas quality specification**.[137] However, a new study by DNV for EASEE-gas is being conducted on the EU level, which will reveal more about this economic optimum.

A higher backbone quality standard comes with implications for the purification stages and for the responsibility regarding this, shifting the responsibility from consumers to producers of hydrogen:

[134] *Clifford Chance (2023b). Regulating hydrogen in the Netherlands. Available at: https://www.cliffordchance.com/content/dam/cliffordchance/briefings/2023/04/Client-briefing-hydrogen-April-2023.pdf*
[135] *DNV and Kiwa (2023). A follow-up study into the hydrogen quality requirements. Available at: https://www.eerstekamer.nl/overig/20231009/rapport_kiwa_dnv/document*
[136] *Doelman, M. (Kiwa) & Turkstra, J. W. (DNV) (2023): Optimal gas quality parameters for the Dutch hydrogen backbone. Presentation at the ENTSOG Gas Quality workshop 15.11.2023.*
[137] *DNV and Kiwa (2023). A follow-up study into the hydrogen quality requirements. Available at: https://www.eerstekamer.nl/overig/20231009/rapport_kiwa_dnv/document*

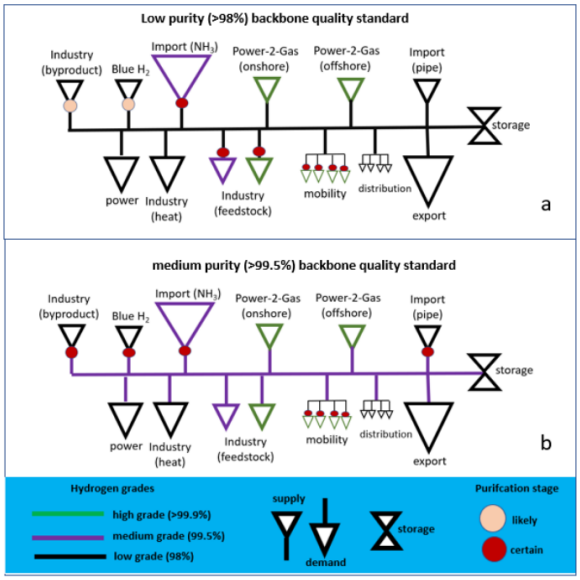

Figure 4: illustration of the consequences of a specific hydrogen backbone purity standard for the main supply/ demand players and their likely or certain requirement to invest in pressure swing adsorption (PSA) purification stages. The purpose of this study is to determine the total system cost impact of the red and light red dots for 98% v. 99.5%.

Figure 3-2: Illustration of the consequences of a specific hydrogen backbone purity standard for the main supply/demand players (Source: DNV & Kiwa (2023)[138])

Currently, the Dutch TSO prefers a minimum H_2 purity of 99.5 % in transmission networks, however they are still in dialogue with neighbouring countries about this.[139] According to HyNetwork,[140] there is increasing support for a minimum purity requirement of 99.5 % in neighbouring countries and several transport companies in Germany, Belgium and the Netherlands have started working on a joint specification based on 99.5 % purity. HyNetwork Services (HNS), a subsidiary of Gasunie (the TSO), will be appointed as the grid operator of the national hydrogen grid (HTNO) in 2025, according to Clifford Chance (2023a).[141] The Hydrogen network specification of HyNetwork in 2024[142] has set the standard for the transmission at values following the new DNV/Kiwa report, i.e. a Wobbe Index of 45.99 - 48.35 MJ/m³ [25/0 °C] and required hydrogen purity of 99.5 mol% minimum. This specification, however, is indicative and the **final decision about the purity level will be taken by the Ministry of Economic Affairs and Climate Policy (EZK)** (as of end of 2024).

HyNetwork is developing a national hydrogen network in the Netherlands to connect the supply and demand for CO_2-free hydrogen.[143] This network will link five industrial clusters with each other, international locations, hydrogen storage, and import facilities. The infrastructure will predominantly utilize existing assets, complemented by new constructions where necessary. The Hydrogen Network Netherlands project will be rolled out in phases, with the objective of full completion by 2030.

The first dedicated open access hydrogen pipelines are to start operations in 2025 – 2026 in The Netherlands, according to a presentation held at the PENTA forum in 2024[144]. A first 30-km section will

[138] *DNV and Kiwa (2023). A follow-up study into the hydrogen quality requirements. Available at: https://www.eerstekamer.nl/overig/20231009/rapport_kiwa_dnv/document*
[139] *PENTA (2024) - Pentalateral Energy Forum - Workshop on Hydrogen Quality, 20 March 2024, Brussels.*
[140] *HyNetwork (2024a). Indicative quality and temperature specification for Hydrogen Network Netherlands. Available at: https://www.hynetwork.nl/media/jokhjtcb/indicative-quality-and-temperature-specification.pdf*
[141] *Clifford Chance (2023a). Focus on hydrogen: regulatory developments in the Netherlands. Available at: https://www.cliffordchance.com/content/dam/cliffordchance/briefings/2023/04/focus-on-hydrogen-regulatory-developments-in-the-netherlands-april-2023.pdf*
[142] *HyNetwork (2024a). Indicative quality and temperature specification for Hydrogen Network Netherlands. Available at: https://www.hynetwork.nl/media/jokhjtcb/indicative-quality-and-temperature-specification.pdf*
[143] *HyNetwork (2024b). The Hydrogen network Netherlands: a vital building block for the energy transition. Available at: https://www.hynetwork.nl/en*
[144] *PENTA (2024) - Pentalateral Energy Forum - Workshop on Hydrogen Quality, 20 March 2024, Brussels.*

be running in Rotterdam and start operations in 2025 - 1.200 km are planned in total.[145] Most of the network will consist of repurposed natural gas pipelines, in addition to some purpose-built new hydrogen pipelines.

Belgium

- Belgium was the first country to translate new EU legislation on hydrogen infrastructure into national law (even pre-emptively)[146], by passing its "Hydrogen Act" and assigning the status of HTNO to Fluxys.
- Whilst not an official position, Fluxys is part of a coalition proposing a 99.5 % H_2 purity standard, so it is expected that this can be considered as the country's overall position, since Fluxys bears the responsibility of establishing H_2 quality standards as HTNO.

The Belgian government has taken steps to create a legal framework for a quality standard for hydrogen to be established. In its National Hydrogen Strategy (2022)[147], the government stated that a gas quality standard will be established by the Hydrogen Transmission Network Operator (HTNO) in cooperation with the Belgian Federal Commission for Electricity and Gas Regulation (CREG), following Belgian H_2 law.

In July 2023, the government passed a so-called "Hydrogen Act"[148], which aims to regulate the operation of hydrogen networks. The law presents a framework to appoint one single HTNO for the entire Belgian territory: Within around half a year after the publication of the Hydrogen Act, an HTNO must be designated by ministerial decree, selected upon criteria such as the quality of business plan, candidate's experience or territorial coverage of the pipelines. The HTNO shall be appointed for a 20-year term, according to the law. Amongst other responsibilities such as reliable network operation, establishing and controlling quality standards of the hydrogen transported in the network was also named as a task for the HTNO in the "Hydrogen Act". Following the implementation of the "Hydrogen Act", the company Fluxys Hydrogen was appointed as HNO in April 2024[149]. There are already more than 600 km of hydrogen pipelines in operation in Belgium, making the Belgian H_2 network the largest in Europe.[150] Some of the pipelines had previously already been managed by Fluxys. The other pre-existing network operators now have the chance to perform their current contracts and apply to designate the HTNO as an independent operator, according to the "Hydrogen Act".

Belgium was the first country to grant the specific regulatory role of HTNO to a company, even before the European Council approved the EU's hydrogen and Gas Decarbonisation Package[151], which includes new regulation to prevent monopolies on hydrogen production, transportation and storage[152]. Amongst other rules, the law requires "horizontal unbundling" of gas transmission network operators and operators of H_2 infrastructure, which means that Fluxys' hydrogen subsidiary will have to be legally separated from its gas parent company.

[145] *Burgess, J. (2023). Netherlands begins construction of national hydrogen pipeline network. Available at: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/102723-netherlands-begins-construction-of-national-hydrogen-pipeline-network*

[146] *European Commission (2024). Hydrogen and decarbonised gas market. Available at: https://energy.ec.europa.eu/topics/markets-and-consumers/hydrogen-and-decarbonised-gas-market_en*

[147] *Belgium government (2022). Vision and strategy: Hydrogen Update October 2022. Available at: https://economie.fgov.be/sites/default/files/Files/Energy/View-strategy-hydrogen.pdf*

[148] *Hendrice, R. (2023). Belgian parliament adopts pioneering law on hydrogen transport. Available at: https://www.deloitte.com/be/en/services/tax/blogs/belgian-parliament-adopts-pioneering-law-on-hydrogen-transport.html*

[149] *Fluxys (2024). Fluxys hydrogen appointed as "Hydrogen Network Operator" in Belgium. Available at: https://www.fluxys.com/en/press-releases/fluxys-belgium/2024/240426-press-fluxys-hydrogen-appointed-hydrogen-network-operator-belgium*

[150] *Nauta Dutilh (2023). Belgium's first-ever hydrogen law: three key insights. Available at: https://www.fluxys.com/en/press-releases/fluxys-belgium/2024/240426-press-fluxys-hydrogen-appointed-hydrogen-network-operator-belgium*

[151] *European Commission (2024). Hydrogen and decarbonised gas market. Available at: https://energy.ec.europa.eu/topics/markets-and-consumers/hydrogen-and-decarbonised-gas-market_en*

[152] *Martin, P. (2024). European Parliament approves hydrogen and low-carbon gas markets package, with focus on hard-to-abate industries. Available at: https://www.hydrogeninsight.com/policy/european-parliament-approves-hydrogen-and-low-carbon-gas-markets-package-with-focus-on-hard-to-abate-industries/2-1-1626259*

This legislative approach of Belgium leaves the HTNO with a large degree of freedom when it comes to establishing quality standards for hydrogen transported in its network. Before being appointed as HTNO, Fluxys had already published several hydrogen specification proposals. In 2022, Fluxys published a specification proposal[153] for its then owned share of the Belgian hydrogen transmission network, **suggesting an H_2 purity of > 98 % mol**, closely aligning its recommendation with the Common Business Practice of EASEE-gas[154]. The proposal includes further specifications such as the maximum share of hydrocarbons and further particles such as CO_2, CO or NH_3. The requirements are applicable at the points where the (not odourised) hydrogen is entering and leaving the transmission network.

However, Fluxys Hydrogen is part of an international group of HNOs (together with OGE, Thyssengas and HyNetwork) that have started cooperating to **propose a common 99.5 % H_2 quality specification**. It remains to be seen whether this will translate into an official national standard. Now, Fluxys argues that the 99.5 % hydrogen quality level is optimal, with a Belgian stakeholder citing the following reasons:

Germany

- There are existing standards on H_2 quality in Germany, differing between the use for most applications (Grade A: 98 % purity) and for all applications including fuel cells (Grade D: 99.97 % purity).
- The standards are currently under revision by the responsible authority, with the tendency of establishing a 99.5 % purity standard.
- DVGW has proposed information on hydrogen odorization in 2021. The standardization body for the gas and water industry plans to integrate H_2 into the NG standard G280 on odorization.
- Germany is quite active with plans for its H_2 network, aiming to have a network of 9,700 km in place by 2032. However, these infrastructure plans do not include specific H_2 quality requirements.

Whilst there are no hydrogen quality specifications written into German law, the German Energy Industry Act (EnWG, § 113c)[155] specifies that – until overruled by legislative activity – the set of rules imposed by the German Technical and Scientific Association for Gas and Water (DVGW) apply regarding hydrogen applications.

The most important standard on hydrogen/gas quality is the technical rule DVGW G260[156], which includes requirements for the specification of fuel gases as well as pre-conditions for gas transportation, storage and industrial applications. Regarding hydrogen quality, the standard differentiates between two grades: Grade A and Grade D. Grade A includes a purity level of ≥ 98 mol % and is suitable for all purposes except fuel cells - including transport in (re)directed pipelines. The standard is similar to CEN TS 17977[157], EASEE-Gas CBP[158] and ISO 14687[159] Grade A. Grade D, which is identical with DIN 17124[160] and taken from ISO 14687 Grade D, specifies a purity level of ≥ 99.97 mol %. Hydrogen of this standard is suitable for all purposes including fuel cells. Furthermore, DVGW is currently conducting a review process for hydrogen quality in dedicated systems, **aiming at**

[153] *Fluxys (2022). Hydrogen Specification Proposal. Available at: https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://www.fluxys.com/-/media/project/fluxys/public/corporate/fluxyscom/documents/energy-transition/h2/2022-04-28---hydrogen-specification-proposal---april-22.pdf&ved=2ahUKEwj-8liSqP6GAxVU3AIHHUG4BOUQFnoECBkQAQ&usg=AOvVaw3-1LvQtyc6Y5UD7Sq3KM2a*

[154] *EASEE-gas (2022). Common Business Practice. Available at: https://easee-gas.eu/news/easee-gas-publishes-quality-specification-for-hydrogen-carried-through-gas-or-dedicated-networks*

[155] *Energiewirtschaftsgesetz (2005). § 113c Übergangsregelungen zu Sicherheitsanforderungen; Anzeigepflicht und Verfahren zur Prüfung von Umstellungsvorhaben. Available at: https://www.gesetze-im-internet.de/enwg_2005/__113c.html*

[156] *DVGW (2021a). G 260- 09/2021. Available at: https://shop.wvgw.de/G-260-Arbeitsblatt-09-2021/310700*

[157] *CEN/TS 17977 (2023). Gas infrastructure - Quality of gas - Hydrogen used in rededicated gas systems. Available at: https://www.nen.nl/en/nvn-cen-ts-17977-2023-en-318030*

[158] *EASEE-gas (2022). Common Business Practice. Available at: https://easee-gas.eu/news/easee-gas-publishes-quality-specification-for-hydrogen-carried-through-gas-or-dedicated-networks*

[159] *ISO 14687 (2019). Hydrogen fuel quality — Product specification. Available at: https://www.iso.org/standard/69539.html*

[160] *DIN 17124 (2018). Hydrogen fuel - Product specification and quality assurance - Proton exchange membrane (PEM) fuel cell applications for road vehicles. Available at: https://www.dinmedia.de/de/norm/din-en-17124/287690204*

developing a standard of Grade A+, a quality situated between Grades A and D. The hydrogen purity goal of this revision process is said to be 99.5 %.

Besides standards on hydrogen quality, DVGW has also set standards on hydrogen odorization: DVGW Information Gas No. 25 Odorisation of hydrogen and hydrogen-rich gases (2021)[161] entails regulation on the odorization of hydrogen. DVGW is planning to integrate these standards into its odorization standard for natural gas (DVGW G 280 Odorisation).[162]

Germany currently operates (local) industrial H_2 networks (private) and recently announced plans for the construction of a 9,700 km long hydrogen core network in the country.[163] 60 % of the future network will consist of re-dedicated natural gas pipelines, whilst 40 % of the network will have to be newly built. The network is planned to be completed by 2032, with a capacity of around 280 TWh, more than double of Germany's predicted hydrogen demand for 2030.

In its current gas network, Germany allows an H_2 blending limit of max. 10 % vol., only if no "sensitive" costumer such as natural gas filling stations are connected to the network. In the latter case, only 2 % are accepted.

The German Energy Industry Act (EnWG, §28q)[164] regulates that the future hydrogen network will be operated by the current gas transmission system operators (TSOs). Unlike most other European countries who have one single certified TSO, Germany has a total of 16 TSOs, 12 of which are organized in the association FNB Gas.[165] In July 2024, FNB Gas submitted a 'joint application for the hydrogen core network'.[166] The deadline for the submission of the application had been extended several times due to missing state aid approval of the EU Commission. A state aid of 3 billion € for the development of the German H_2 core network has eventually been approved in June 2024.[167] FNB Gas' formal proposal includes an overall network length of 9.666 km, 60 % of which will be built from existing gas pipelines.

Whilst the draft document includes detailed plans for the hydrogen pipelines, it does not entail any specifications regarding the hydrogen quality within the pipeline network. However, there are indications that Germany will strive for an H_2 purity standard of 99,5 %. As mentioned above, DVGW is striving for a 99,5 % purity standard in its revision process of DVGW G260. Furthermore, German TSOs Thyssengas and OGE are part of an HTNO-initiative proposing a 99.5 % H_2 specification, with TSO Gasunie Deutschland said to also support this initiative. According to a TSO-driven initiative pushing for a 99.5 % H_2 purity standard, studies have found that 99.5 % H_2 purity is an economic optimum in Germany and the Netherlands, and that first conversion projects within both countries have shown that this purity level can be maintained through proper cleaning of the pipelines. Lastly, multiple project partners such as DIN or DVGW are currently working in a project named "Standardization roadmap for hydrogen technologies",[168] aiming to provide a framework for technical regulations on hydrogen quality in order to support the market acceleration of hydrogen technologies. The results of

[161] *DVGW (2021b). Gas-Information Nr. 25 2021-08: Odorierung von Wasserstoff und wasserstoffreichen Gasen. Available at: https://www.dvgw-regelwerk.de/plus#technische-regel/dvgw-gas-information-nr.-25/82164c*

[162] *DVGW (2018). Arbeitsblatt G 280 2018-12: Gasodorierung. Available at: https://www.dvgw-regelwerk.de/plus/#technische-regel/dvgw-arbeitsblatt-g-280/40c11f*

[163] *BMWK (2023). Germany pressing ahead with the building of a core hydrogen network. Available at: https://www.bmwk-energiewende.de/EWD/Redaktion/EN/Newsletter/2023/11/Meldung/topthema.html*

[164] *Energiewirtschaftsgesetz (2005). § 28q Wasserstoff-Kernnetz. Available at: https://www.gesetze-im-internet.de/enwg_2005/__28q.html*

[165] *FNB Gas (2024a). About FNB Gas. Available at: https://fnb-gas.de/en/*

[166] *FNB Gas (2024b). Joint application for the hydrogen core network. Available at: https://fnb-gas.de/wp-content/uploads/2024/07/2024_07_22-Joint-Appllication-Core-Network_Translation.pdf*

[167] *Vertretung in Deutschland (2024). Entwicklung des Wasserstoff-Kernnetzes: EU-Kommission genehmigt mit 3 Mrd. Euro ausgestattete deutsche Beihilferegelung. Available at: https://germany.representation.ec.europa.eu/news/entwicklung-des-wasserstoff-kernnetzes-eu-kommission-genehmigt-mit-3-mrd-euro-ausgestattete-deutsche-2024-06-21_de*

[168] *DIN (2024a). Standardization roadmap for hydrogen technologies supporting the market ramp-up. Available at: https://www.din.de/en/innovation-and-research/standardization-roadmap-for-hydrogen-technologies*

the roadmap[169] have been published in July 2024, as well as a management summary[170] of them (both in German).

Other EU Member States

Austria

- There has been some level of activity regarding H_2 quality in Austria. ISO standards have been translated into national standards, but which standard shall apply in pipeline networks remains open.
- The Austrian government has recognized the importance of standardization on the EU level and repeatedly called for it.
- Austria has published plans for the construction of its domestic H_2 pipeline network, but no standard has been specified.

Austria has recently included hydrogen quality in its strategic orientation, having set its first nation-wide guidelines on hydrogen purity in 2023. The OEVGW H B100 standard applies the purity grades from ISO 14678, differentiating between **'Type I Grade A' (98.0 % mol % H_2)** and **'Type I Grade D' (99.97 mol % H_2)**. According to the standards, Grade A hydrogen is usable in applications such as combustion engines, gas devices and cookers, whilst Grade D hydrogen is necessary for fuelling stations and vehicles referring to the standard ÖNORM EN 17124. Furthermore, Austrian TSO Gas Connect Austria is said to support an industry initiative pushing for a common 99.5 % H_2 quality standard. Besides these standards on hydrogen purity, the OEVGW H E310 standard regulates planning, construction and initial inspection of hydrogen injection stations – both for hydrogen and gas grids.

In its National Hydrogen Strategy[171] (in German), published in 2022, Austria's Federal Ministry of Climate Action, Environment, Energy, Mobility, Innovation and Technology stated that there should be a clear priority on the use of pure hydrogen and the development of pure hydrogen networks due to the high demand of pure hydrogen. A specific number defining what is meant by "pure" is not provided. Austria currently uses hydrogen of grade A in redirected pipework, whilst further tests are necessary for the integration of Grade D hydrogen. In its strategy, the Ministry further emphasizes the need for efforts to harmonize hydrogen tolerances within the European gas system, as differences in the domestic hydrogen tolerances might undermine a common gas quality and investments. Whilst pure hydrogen is preferred, Austria allows some form of H_2 blending into the natural gas networks: The Austrian Gas Quality Standard G B210 allows a maximum H_2 concentration of 3-5 % in the natural gas transmission networks, depending on the gas composition.

Austria's Hydrogen Strategy further addresses the need for hydrogen pipeline infrastructure in the country, as Austria currently does not yet have an H_2 pipeline network in place. In the strategy, it is emphasized that the country is mainly planning to re-dedicate its existing gas pipelines for the use of hydrogen, but also considering building new hydrogen pipelines where necessary. It is further mentioned that transporting hydrogen separately from natural gas should be preferred over blending hydrogen into the current gas grid. For both approaches, the Ministry stresses the need for uniform EU-wide standards and limits. Furthermore, the importance of Austria's gas grid due to its central geographic location in the EU is mentioned, underlining the importance and potential of using this infrastructure for hydrogen in the future.

In Austria, AGGM Austrian Gas Grid Management AG is responsible for managing international gas transit pipelines crossing Austria. Furthermore, AGGM is responsible for ensuring that each gas user

[169] *DIN (2024b). Normungsroadmap Wasserstofftechnologien 2024. Available at: https://www.din.de/resource/blob/1117948/76fb04f12b9dd231fb27d41d1f0840c3/normungsroadmap-wasserstofftechnologien-2024-data.pdf*

[170] *DIN (2024c). Management Summary: Normungsroadmap Wasserstofftechnologien 2024. Available at: https://www.din.de/resource/blob/1117946/28e083dc7bdcce448fa92be93a8dc74e/management-summary-nrm-wasserstofftechnologien-2024-data.pdf*

[171] *BMK (2022). Wasserstoffstrategie für Österreich. Available at: https://www.bmk.gv.at/themen/energie/energieversorgung/wasserstoff/strategie.html*

receives the required amount of natural gas from its supplier. In cooperation with grid operators, AGGM has published an H_2 roadmap[172] on the hydrogen transport infrastructure, building on the National Hydrogen Strategy. According to the roadmap, 1.400 km of existing gas pipelines need to be re-dedicated for the use of hydrogen until 2050, whilst only 300 km of gas pipeline must be newly constructed for the parallel transport of hydrogen and methane.

Whilst there are national H_2 standards in Austria, there is no law regulating which is to be used at which point of the H_2 value chain. There has been no specific legislative activity on hydrogen quality in Austria. Recent legislation on hydrogen include the "Wasserstoffförderungsgesetz (WFöG)"[173] of 2024, which regulates domestic subsidies for renewable hydrogen production and a law on standards for the infrastructure of alternative fuels[174] including hydrogen, which was passed in 2018 and translated EU directive 2014/94/EU into domestic law.

Czech Republic

- ISO Hydrogen standards have been implemented into national standards, differentiating between the use for PEM fuel cells and other applications. Even though not explicitly mentioned, the use of ISO 14687 standard implies purity levels of 98 % (other applications) and 99.97 % (PEM fuel cells)
- The Czech Republic is aware of its central role in the construction of European Hydrogen Infrastructure and is involved in several projects.
- Lack of legislation and H_2 measurements have been identified as major barriers towards hydrogen development.

In July 2021, the government of the Czech Republic approved the country's Hydrogen Strategy[175], which remains the country's most important strategic document on hydrogen. The government approved an update of the strategy in July 2024[176]. Classifying hydrogen by its purity is mentioned in the strategy, hereby citing the Czech technical standard ČSN ISO 14687, which represents an implementation of the International Standard ISO 14678:2019. The standard is differentiated into ČSN ISO 14687-1, which concerns all applications except PEM fuel cells and ČSN ISO 14687-2, which applies to PEM fuel cells.
In the Czech Hydrogen Strategy, it is emphasized that purity requirements may be defined by the specific use, as hydrogen for PEM fuel cells requires the highest chemical purity, whilst purity requirements are not as high for other applications. However, the strategy does not name any specific numbers regarding purity levels, but to cite its standard. Furthermore, it is mentioned that measuring equipment and control systems to ensure hydrogen purity levels need to be established.

Whilst 100 % H_2 networks are already available in local industrial clusters in the Czech Republic, there are also plans to construct hydrogen pipeline networks, however no concrete purity specifications for hydrogen transport in pipelines are mentioned. In its Hydrogen Strategy, the Government stresses that it would be relevant to direct international hydrogen pipelines primarily from the country's western and eastern neighbours, namely Germany, Slovakia (possibility to import from Ukraine and Northern Africa) and Austria.
The country's exclusive TSO – Net4Gas – is part of several international projects to develop hydrogen infrastructure, such as the Central European Hydrogen Corridor (CEHC)[177] or the Czech German

[172] *AGGM (2024). H2 Roadmap: Wasserstoff als Energieträger der Zukunft. Available at: https://www.aggm.at/energiewende/h2-roadmap/*
[173] *Österreichisches Parlament (2024). 318/ME XXVII. GP - Ministerialentwurf – Gesetzestext. Available at: https://www.parlament.gv.at/dokument/XXVII/ME/318/fname_1612852.pdf*
[174] *Österreichisches Parlament (2018). Regierungsvorlage: Bundesgesetz zur Festlegung einheitlicher Standards beim Infrastrukturaufbau für alternative Kraftstoffe. Available at: https://www.parlament.gv.at/dokument/XXVI/I/137/fname_693177.pdf*
[175] *Ministry of Industry and Trade of the Czech Republic (2021). The Czech Republic's Hydrogen Strategy. Available at: https://www.mpo.gov.cz/assets/cz/prumysl/strategicke-projekty/2021/9/Hydrogen-Strategy_CZ_2021-09-09.pdf*
[176] *Ministry of Industry and Trade of the Czech Republic (2024). Government approved the update of the Hydrogen Strategy of the Czech Republic. Available at: https://www.mpo.gov.cz/en/guidepost/for-the-media/press-releases/government-approved-the-update-of-the-hydrogen-strategy-of-the-czech-republic--282178/*
[177] *Central European Hydrogen Corridor (CEHC) (2024). Project. Available at: https://www.cehc.eu/cehc-project/*

Hydrogen Interconnector (CGHI)[178] initiative. In the medium term, hydrogen transport is to take place both in blended form with natural gas and in separate, pure H_2 pipelines. With regard to H_2 blending, a 2 % concentration is currently allowed, but the H_2 measurement systems in pipelines are not yet sufficient. By 2025, accepting 5 % H_2 volume at cross-border interconnection points is desired. On the long-term, the focus of Net4Gas will be on repurposing existing natural gas framework. For this purpose, Net4Gas has tasked DNV[179] to evaluate the suitability of various hydrogen and natural gas mixtures in its pipelines, from 2 % volume share to 100 %.

A major problem of hydrogen infrastructure development is the lack of legislation in the Czech Republic, an issue that was even also mentioned in the Hydrogen Strategy[175]. Hydrogen is not one of the commodities monitored by the Czech Statistical Office and there is no regulation on the injection of hydrogen into the gas system. Within the scope of the Czech Energy Act, hydrogen is not even defined as a gas, it is rather formally anchored only as a transport fuel. According to law firm CMS[180], regulatory shortcomings are "a key barrier to greater development of hydrogen projects in the Czech Republic."

Denmark

- There is no official H_2 quality standard in place yet, but discussions are ongoing. It is currently not possible to observe a tendency of this discussion, but the options seem to be either 98 or 99.5 mol % .
- Denmark has announced plans for a national H_2 pipeline network as well as cross-border infrastructure with Germany. However, these plans do not specify H_2 quality requirements. Denmark's H_2 infrastructure will most likely mainly consist of new pipelines, as existing gas pipelines will remain in use for several years.

There is currently no official hydrogen quality standard in place in Denmark yet. In a workshop by Danish TSO Energinet[181] in January 2024, it was stated that the European standard CEN/TS 17977 serves as preliminary specification for hydrogen in Denmark, with possible supplementary national amendments and departures expected. The standard prescribes a hydrogen purity level of ≥ 98 mol. %. Whilst Danish legal gas quality requirements do not yet specify hydrogen limits for blending or pure hydrogen, the gas quality ordinance (§§ 27-29; §§53-55) stipulates that the hydrogen quality injected into the natural gas network shall be at least 98 Vol.-%. In the workshop by Energinet mentioned above, participants were asked to discuss the pros and cons of different hydrogen quality specifications, namely between an H_2 purity of ≥ 98 mol % or ≥ 99.5 mol % and a water content limit of ≤ 20 ppm or ≤ 60 ppm.

Denmark does not yet have 100 % hydrogen pipelines operating in the country, but the government reported to the EU[182] that it has plans to develop a hydrogen network. The Danish TSO is Energinet, which is responsible for both the electricity and the gas networks, but the government officially stated in 2022, that the future operator of the hydrogen system would still be undecided. Concrete plans for hydrogen infrastructure include a declaration of intent with Germany, agreeing to "cooperate on advancing the roll-out of transmission infrastructure for green hydrogen between western Denmark and northern Germany from 2028, enabling a large-scale transmission interconnector for green

[178] *Czech German Hydrogen Interconnector (CGHI) (2024). Home. Available at: https://www.cghi.eu/*
[179] *Slater, N. (2022). DNV to evaluate hydrogen suitability of Czech Republic natural gas pipeline. Available at: https://www.dnv.com/news/dnv-to-evaluate-hydrogen-suitability-of-czech-republic-natural-gas-pipeline-224937/*
[180] *Janíček, L.; Reichmann, L. (2021). Hydrogen Law, Regulations & Strategy in the Czech Republic. Available at: https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/czech-republic*
[181] *Energinet (2024). Hydrogen Quality & Grid connection – Workshop 18 January 2024. Available at: https://en.energinet.dk/media/1hhh3ycx/hydrogen-quality-and-grid-connection-market-dialogue-18-01-2024.pdf*
[182] *European Union Agency for the Cooperation of Energy Regulators (ACER) (2022). Opinion 08/2022 on the Review of Gas and Hydrogen National Network Development Plans to assess their consistency with the EU ten-year network development plan – Annex III: Hydrogen, Biomethane injections, and Related Network Adaptations. Available at: https://www.acer.europa.eu/sites/default/files/documents/Official_documents/Acts_of_the_Agency/Opinions/Opinions%20Annexes/ACER_Opinion_08-2022-Annex_III.pdf*

hydrogen."[183] Furthermore, the Danish government and opposition parties signed an economic framework for an H_2 pipeline network on the Jutland peninsula in April 2024.[184] The framework specifies that the hydrogen pipeline would be built and operated by the state-owned TSO Energinet.

According to a report by the Danish Energy Agency (p.127)[185], only a minor part of the existing natural gas network will be converted to hydrogen transmission, due to the extensive biogas/biomethane production in Denmark and Danish commitments to transport natural gas from Norway to Poland (EPII). Whilst Denmark legally allows the injection of H_2 volumes into the gas transmission network, it currently has a limit of 0 % in place, due to safety concerns and the use of natural gas as feedstock in industrial processes. Therefore, H_2 blending is practically impossible in Denmark. According to the EU-funded project "Documentation demands for hydrogen infrastructure" (2023)[186], dialogue between parties is ongoing regarding this matter, as Denmark intends to launch a National Hydrogen Strategy. Quality and delivery specifications of natural gas are laid out by TSO Energinet.[187]

Finland

- There is no H_2 quality standard in place in Finland and stakeholders already indicate that the discussion becoming more prominent along with the plans to become a leading hydrogen producer.
- Finland has indicated its intent to become a lead producer and supplier of green hydrogen in the EU. In this context, its TSO Gasgrid is highly engaged in several H_2 pipeline projects, both domestically and in cooperation with regional partner countries.

Finland currently does not have separate legislation or specific quality standards on hydrogen in place, but H_2 is considered to be a hazardous chemical. Whilst there is no legislative standard, a guide published by the Finnish Safety and Chemicals Agency (tukes)[188] mentions the International standard ISO 14687 for the use of H_2 as a fuel.

Whilst lacking standards, the Finnish government has adopted a resolution in 2023[189], aiming to become one of Europe's leaders in the hydrogen economy by producing more than 10 % of the EU's emissions-free hydrogen by 2030. Whilst there are currently no 100 % H_2 pipelines in place, Finnish gas TSO Gasgrid has been mandated to promote the development of domestic and cross-border hydrogen transmission infrastructure. For this purpose, a subsidiary of Gasgrid – Gasgrid Vetyverkot Oy (Gasgrid Hydrogen Network) – has been established in 2022. Several routing options are currently evaluated, both domestically as well as in the Baltic Sea region. According to Olli Sipilä, the CEO of Gasgrid, the investment decisions for Finland's hydrogen infrastructure are intended to be made by 2026 and projects should be completed by 2030.[190] Furthermore, Gasgrid recently signed a Memorandum of Understanding[191] to coordinate and facilitate hydrogen infrastructure in the Baltic

[183] *Transport Advancement (2024). Germany, Denmark Agree Green Hydrogen Infrastructure Roll-out from 2028. Available at: https://www.transportadvancement.com/railway/germany-denmark-agree-green-hydrogen-infrastructure-roll-out-from-2028/*

[184] *Collins, L. (2024). Denmark agrees to finance hydrogen pipeline network – if sector meets five conditions. Available at: https://www.hydrogeninsight.com/policy/denmark-agrees-to-finance-hydrogen-pipeline-network-if-sector-meets-five-conditions/2-1-1622183*

[185] *Danish Energy Agency (2017). Technology Data for Energy Transport. Available at: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_energy_transport.pdf*

[186] *FORCE Technology; Danish Gas Technological Centre (DGC) (2023). Fyrtårn Syd Project. Available at: https://www.dgc.dk/media/rs4fr5bi/guideline-documentation_demands_for_hydrogen-infrastructure-sept-2023.pdf*

[187] *Energinet (2020). Quality and Delivery Specifications. Available at: https://en.energinet.dk/media/dcsao0oy/app-1-quality_and_delivery_specifications.pdf*

[188] *Tukes (2024). Safety of hydrogen handling and storage. Available at: https://tukes.fi/en/safety-of-hydrogen-handling-and-storage*

[189] *Ministry of Economic Affairs and Employment (2023). Government adopts resolution on hydrogen – Finland could produce 10% of EU's green hydrogen in 2030. Available at: https://valtioneuvosto.fi/en/-/1410877/government-adopts-resolution-on-hydrogen-finland-could-produce-10-of-eu-s-green-hydrogen-in-2030*

[190] *Gasgrid Finland (2024a). Finland – a great hydrogen power. Could hydrogen be the next Finnish success story? Available at: https://gasgrid.fi/en/2024/07/15/finland-a-hydrogen-great-power-could-hydrogen-be-the-next-finnish-success-story/*

[191] *Redakcja, O. (2024). Gas transmission system operators from the Baltic Sea region have signed a MoU to accelerate the development of hydrogen infrastructure. Available at: https://offshorewindpoland.pl/en/gas-transmission-system-operators-from-the-baltic-sea-region-have-signed-a-mou-to-accelerate-the-development-of-hydrogen-infrastructure/*

Sea region, together with TSOs from eight further Baltic Sea countries. Several development projects are currently ongoing – if all projects proceed as planned, the H_2 infrastructure in the Baltic Sea region could grow to 5,000 km by 2030.[192]

Whilst TSO Gasgrid has not yet set hydrogen quality standards, such standards are in place for natural gas, as specified in the 'Rules for gas transmission 4.0' (2022).[193]

France

- Domestic focus on industrial hydrogen use: France's hydrogen activities are concentrated in industrial hubs, particularly for refineries and ammonia production
- French politics focus more on domestic hydrogen production, whereas stakeholders from the H_2 industry are more positive towards H_2 imports
- Regional Infrastructure Development: While large-scale national pipelines are not the central point in the discussion in France, regional projects like the MosaHyc and H2Med pipelines are under development to enhance local hydrogen infrastructure.
    - 100 % H_2 dedicated pipelines exist only locally for industrial purposes, not ran by TSO
- H2-Blending into NG-pipelines seems to be a bigger topic in France than in neighbouring countries
    - the current maximum H_2 concentration accepted by the TSO in the natural gas transmission network is 6 %vol
    - aim for 2030: 10 % H_2 in NG pipelines
- Legislation and a political strategy regarding hydrogen purity is lacking in France
- In the stakeholder investigation it was found that at least one French transmission operator could guarantee 99.5 % hydrogen in their network. However, the ability of DSO networks to distribute this quality of hydrogen is uncertain.

In France, the focus of hydrogen activities is on the industrial centres. Hydrogen is primarily used in refineries, which account for almost half of consumption, and in ammonia production, which accounts for around a third. A nationwide hydrogen network seems not to be the political focus in France[194], even though there are some regional activities on pipeline construction like the Franco-German MosaHyc pipeline and the H2Med (former called BarMar).[195][196] Another example is Engie, an energy company, which aims to construct 700 km of dedicated hydrogen pipelines by 2030.[197] Primary initial industrial demand is expected to come from steel refining, sustainable aviation fuels and ammonia production in France on the short term as stated by a French stakeholder:

- SAF: Numerous new projects of SAF have already been announced (e.g. by Verso Energy and Engie) and should start production as of 2030 or 2035, with the aim at exporting SAF in Europe

- Ammonia: Ammonia production is subject to RED III objective of 42 % RFNBO H_2 in industry consumption in 2030 and 60 % in 2035, with some announced dedicated hydrogen projects (e.g. Lhyfe in Normandy for YARA plant in Gonfreville L'Orcher). However, shifting from SMR to electrolytic hydrogen would require significant process changes and capex investments as

[192] *Gasgrid Finland (2024b). Making Finland the world's most attractive hydrogen economy country. Available at: https://gasgrid.fi/en/development/finland-into-the-most-attractive-hydrogen-economy-country-in-the-world/*
[193] *Gasgrid Finland (2023). Rules for Gas Transmission. Available at: https://gasgrid.fi/wp-content/uploads/Rules-for-gas-transmission-4.0_clean_non-binding-English-version.pdf*
[194] *Bouacida, I. (2023). France's Hydrogen Strategy: Focusing on Domestic Hydrogen Production to Decarbonise Industry and Mobility. Available at: https://publications.rifs-potsdam.de/rest/items/item_6002974_3/component/file_6002976/content*
[195] *Collins, L. (2024). 'Final investment decision' taken on €110m Franco-German hydrogen pipeline project MosaHYc. Available at: https://www.hydrogeninsight.com/industrial/final-investment-decision-taken-on-110m-franco-german-hydrogen-pipeline-project-mosahyc/2-1-1625333*
[196] *Meillaud, L. (2024). BarMar and H2MED: Partners making progress on both sides of the cross-border hydrogen pipeline. Available at: https://hydrogentoday.info/en/barmar-h2med-hydrogen/*
[197] *Bouacida, I. (2023). France's Hydrogen Strategy: Focusing on Domestic Hydrogen Production to Decarbonise Industry and Mobility. Available at: https://publications.rifs-potsdam.de/rest/items/item_6002974_3/component/file_6002976/content*

heat produced from SMR is currently used as a heat source for the ammonia and fertilizers production processes.

- Steel: Steel manufacturing (H_2 DRI) is also subject to RED III objectives about RFNBO hydrogen, and projects have already been announced (GravitHy in Fos-sur-Mer, south of France, and Arcelor Mittal in Dunkerque) with a start date in 2030 or 2035

The political priority is to develop a domestic industry sized to meet national demand, which is seen as a more secure sourcing strategy than relying on imports. In contrast to that, neighbouring countries are pushing for more ambitious cross-border trade of hydrogen. These different views have generated political tensions within the European Union and in particular in the Franco-German relationship, since France is focusing more on its domestic hydrogen industry than on trade within the EU.[198] However, from an industry perspective, hydrogen imports are seen less critical in France: France Hydrogene (an organization of 450 members that brings together the stakeholders of the French hydrogen sector across the entire value chain) has expressed more favourable views on imports.[199] For example its member Engie has announced that three quarters of its targeted electrolyser capacity of 4 GW by 2030 will be produced outside France.[200] Nevertheless, France Hydrogene is in favour of cross-border transmission tariffs.

In France, there are no special regulations in place regarding hydrogen purity for the pipeline network. The TSOs for the gas networks in France are GRTgaz and Teréga. In the operational code of GRTgaz[201] there are several ISO standards mentioned

In general, there are several points regarding hydrogen in the transmission network, according to ACER[202]:

It is legally/regulatory possible to inject or allow H_2 volumes into the gas transmission Network and the current maximum H_2 concentration accepted by the TSO in the natural gas transmission network is 6 %vol. The main justification to set up such an hydrogen limit in terms of gas quality requirements at the transmission level is, that "the main constraints identified by the French gas operators study[203] relate to sensitivity of specific industrial processes, as well as natural gas vehicles (NGV) charging station (2 % H_2 allowed) and end-users appliances on the consumption side."[204] The goal (formulated in the gas operators study[203]) is, to set a specification of 10 % blended hydrogen as a sector-wide target by 2030, the long term goal is to reach a 20 % H_2 blending level. Projects such as GRHYD and Jupiter 1000 and FenHYx[205] are testing the feasibility and impacts of injecting hydrogen into natural gas grids.

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[198] *Bouacida, I. (2023). France's Hydrogen Strategy: Focusing on Domestic Hydrogen Production to Decarbonise Industry and Mobility. Available at: https://publications.rifs-potsdam.de/rest/items/item_6002974_3/component/file_6002976/content*

[199] *France Hydrogene (2022). France Hydrogène Position Paper on the Hydrogen & Gas Package: Toward a global framework for the renewable and low-carbon hydrogen market. Available at: https://s3.production.france-hydrogene.org/uploads/sites/4/2022/04/France-Hydrogene-Position-Paper-on-Hydrogen-Gas-Package-April-2022.pdf*

[200] *Bouacida, I. (2023). France's Hydrogen Strategy: Focusing on Domestic Hydrogen Production to Decarbonise Industry and Mobility. Available at: https://publications.rifs-potsdam.de/rest/items/item_6002974_3/component/file_6002976/content*

[201] *GRTgaz (2018). Code Operationnel de Reseau Transmission. Available at: https://www.grtgaz.com/sites/default/files/2021-03/A2-2018-04-01-EN.pdf*

[202] *European Union Agency for the Cooperation of Energy Regulators (ACER) (2022). Opinion 08/2022 on the Review of Gas and Hydrogen National Network Development Plans to assess their consistency with the EU ten-year network development plan – Annex III: Hydrogen, Biomethane injections, and Related Network Adaptations. Available at: https://www.acer.europa.eu/sites/default/files/documents/Official_documents/Acts_of_the_Agency/Opinions/Opinions%20Annexes/ACER_Opinion_08-2022-Annex_III.pdf*

[203] *GRTgaz, GRDF et al. (2019). Technical and economic conditions for injecting hydrogen into natural gas networks. Available at: https://assets.ctfassets.net/ztehsn2qe34u/6KrAWmEKSUtLesr8W5RXx6/63b56813770ae2ed95ae743bb10dbe1a/Rapport_H2_EN.PDF*

[204] *European Union Agency for the Cooperation of Energy Regulators (ACER) (2022). Opinion 08/2022 on the Review of Gas and Hydrogen National Network Development Plans to assess their consistency with the EU ten-year network development plan – Annex III: Hydrogen, Biomethane injections, and Related Network Adaptations. Available at: https://www.acer.europa.eu/sites/default/files/documents/Official_documents/Acts_of_the_Agency/Opinions/Opinions%20Annexes/ACER_Opinion_08-2022-Annex_III.pdf*

[205] *GRTgaz (2021). Press release. Available at: https://www.grtgaz.com/sites/default/files/2021-11/PR-FenHYx-inauguration-23112021.pdf*

There are 100 % H_2 dedicated pipeline networks for industrial purposes in France in operation already[202], but not ran by DSO/TSO.

The primary legislative document regulating hydrogen in France is Ordinance No. 2021-167 of 17 February 2021[206], which categorizes hydrogen into renewable, low-carbon, and carbonaceous types and provides guidelines for its production, storage, and transport. However, there is no direct mention of detailed national standards for hydrogen purity within this ordinance.

Italy

- Infrastructure and Import Potential: Italy's existing and planned pipeline connections, particularly the SoutH2 Corridor, position it as a significant future importer of hydrogen within the EU.
- Regulatory Landscape: While specific hydrogen purity regulations are lacking, Italy is progressing with pilot projects
    - As Italy's main operator for natural gas transport, Snam is responsible for integrating hydrogen into the gas network
    - Snam's existing infrastructure is being upgraded to be hydrogen-ready, but the exact numbers seem to be not clear yet
    - The regulatory body overseeing the gas network, ARERA, is responsible for setting regulatory frameworks
- No publicly published preference for a specific hydrogen purity level found, although Italian stakeholders note that 98 % is likely to be preferred in Italy due to the expectation that end-use will not require high-quality hydrogen.

So far, in Italy the purity requirements for hydrogen are not explicitly defined and the regulations are still in their early development. However, Italy's main gas TSO Snam is actively involved in the European Hydrogen Backbone (EHB) initiative[207], which aims to create a pan-European hydrogen market with standardized quality measures to ensure safe and efficient cross-border hydrogen transportation.

Snam is Italy's primary operator for natural gas transport and dispatch, managing nearly all of the country's transport infrastructure. It operates 32,727 km of high and medium-pressure gas pipelines, covering approximately 94 % of Italy's total transport network. In the Network Code[208] for the existing pipeline system of the TSO Snam, the gas quality parameters Relative Density, Wobbe Index and CO_2 are determined, for gas chromatographs, in compliance with ISO 6976.

However, so far there is no 100 % H_2 dedicated pipeline in operation in Italy.[202] Also, in terms of regulation on hydrogen quality, there is no special law in place so far. In general, it is legally/regulatory possible to inject or allow H_2 volumes into the gas transmission network and the current maximum H_2 concentration accepted by the TSO in the natural gas transmission network is 2 % vol. The primary rationale for establishing a 2 % hydrogen limit in gas quality requirements at the transmission level is to preserve underground gas storage facilities and meet the acceptance limits of end-users. This precautionary value enables the immediate injection of hydrogen into existing gas networks while ensuring maximum safety for users, the public, and the environment.

Plans are underway to increase hydrogen acceptance into natural gas networks[202], with investments and adaptations outlined in the current National Development Plan (NDP) to enhance the TSO's capacity to accept hydrogen. Several studies and experiments are ongoing, some initiated with support from the Ministry of Ecological Transition. Notably, since April 2019, Snam, the main gas TSO, has been experimenting with blending 5 % hydrogen into existing natural gas pipelines to supply two

[206] *Légifrance (2021). Ordonnance n° 2021-167 du Février 2021 relative à l'hydrogène. Available at: https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000043148001/*

[207] *The European Hydrogen Backbone (EHB) initiative (2024). Website. Available at: https://www.ehb.eu/*

[208] *Snam (2016). Network Code. Available at: https://www.snam.it/en/our-businesses/transportation/network-code-tariffs-committee-area-and-consultations/network-code.html*

industries. Between 2019 and 2020, the same network was tested for blending 10 % hydrogen. Currently, pilot projects are being conducted[209] to test the direct injection of hydrogen produced from renewable sources, such as solar and Power-to-Gas (P2G) technologies. The latest Snam NDP presents a proposal for the development of an H_2 pipeline (almost 2 800 km) from North to South of Italy.

According to Snam[210], 70 % of its pipeline network is built with "hydrogen ready pipes". Also, Hydrogen Europe[211] states that priority is given to repurposing "most of the existing natural gas infrastructure" as a part of Snam's hydrogen network plans. Three pipeline axis with a total length of almost 2,800 km are planned, connecting mainly the south and the north of Italy.

Since no specific legislation governs hydrogen trade with other countries, it is subject to the same regulatory framework as natural gas[212] and the Italian Regulatory Authority for Energy Networks and Environment (ARERA) is responsible for the regulation of the gas network.

There are natural gas pipelines connecting northern Africa to southern Italy[213], making Italy a potential hydrogen importer in the EU.[212] For example, The SoutH2 Corridor project[214], a 3,300 km hydrogen pipeline that connects North Africa, Italy, Austria and Germany, is led by the TSOs Snam, TAG, GCA, and bayernets. Each submitted a Project of Common Interest (PCI) application under the EU Commission's TEN-E regulation in December 2022.

According to the National Hydrogen Strategy Preliminary Guidelines (Nov. 2020)[215], H_2 is going to account for 2 % of final energy consumption by 2030 and to 20 % by 2050.[216]

Poland

- Growing hydrogen demand in Poland predicted, more than 900 thousand tons in 2040
- Focus on Hydrogen Valleys in Poland's Hydrogen strategy
- Hydrogen pipelines as a future topic, not the focus right now
- TSO Gaz-System refers to ISO 6976 for natural gas pipelines, so far no specific regulations for hydrogen in place

According to a Report by Orlen[217] (an oil refinery), the demand for renewable hydrogen in Poland will amount to approximately 270 thousand tons (9 TWh_{LHV}) in 2030, 515 thousand tons (17 TWh_{LHV}) in 2035 and even 934 thousand tons (31 TWh_{LHV}) in 2040.

Poland adopted a Hydrogen Strategy in 2021[218] and aims to develop a Hydrogen Valley Innovation Ecosystem, "where each valley is to be a cluster of as many elements of the hydrogen economy value chain as possible in a specific location." Therefore, it seems to be not the main focus to develop a

[209] *Čučuk, A. (2024). Snam selects Baker Hughes' hydrogen-ready technology for its gas network. Available at: https://www.offshore-energy.biz/snam-picks-baker-hughes-hydrogen-ready-technology-for-its-gas-network/*

[210] *Snam (2023). Snam and Baker Hughes test world's first hydrogen blend turbine for gas networks. Available at: https://www.snam.it/en/media/news-and-press-releases/comunicati-stampa/2020/snam-and-baker-hughes-test-world-s-first-hydrogen-blend-turbine-for-gas-networks.html*

[211] *Hydrogen Europe (2023). Clean Hydrogen Monitor. Available at: https://hydrogeneurope.eu/wp-content/uploads/2023/10/Clean_Hydrogen_Monitor_11-2023_DIGITAL.pdf*

[212] *Ciminelli, M. (2021). Hydrogen Law, Regulations & Strategy in Italy. Available at: https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/italy*

[213] *The Oxford Institute for Energy Studies (2023). Italy and its North African gas interconnections: A potential Mediterranean gas 'hub'? Available at: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2023/03/Italy-and-its-North-African-gas-interconnections.pdf*

[214] *SoutH2Corridor (2024). The initiative. Available at: https://www.south2corridor.net/south2*

[215] *Ministero dello sviluppo economico (2020) Strategia Nazionale Idrogeno Linee Guida Preliminari. Available at: https://www.mimit.gov.it/images/stories/documenti/Strategia_Nazionale_Idrogeno_Linee_guida_preliminari_nov20.pdf*

[216] *Capra, M. (2021). Preliminary guidelines on the Italian Hydrogen Strategy. Available at: https://energy.ec.europa.eu/document/download/a4065933-9c3a-4b91-93c9-ae3b1d2de192_en?filename=7_-_m.capra_italy_hyenet_28052021.pdf&prefLang=da*

[217] *Orlen (2024). Hydrogen market in Poland and the Baltics until 2040. Available at: https://www.orlen.pl/content/dam/internet/orlen/pl/en/sustainable-development/transition-projects/hydrogen/Hydrogen-market-in-Poland-and-the-Baltics-until-2040.pdf*

[218] *Trade.gov.pl (2024). Poland's Hydrogen Strategy: A Green Future. Available at: https://www.trade.gov.pl/en/news/polands-hydrogen-strategy-a-green-future/*

pipeline infrastructure for hydrogen transportation. There are already pipeline networks for industrial purposes in Poland, that are 100 % hydrogen dedicated[202], but they are not operated by the TSO GAZ-system.

Currently, it is legally/regulatory not possible to inject or allow H_2 volumes into the gas transmission network.[202] However, according to objective 5 of the Polish Hydrogen Strategy, there is the goal that hydrogen can be transported through existing natural gas networks if they are adapted to accommodate hydrogen blends. In the initial years of market development, hydrogen will mainly be transported by road and rail. As demand increases, transportation can shift to existing gas infrastructure or dedicated hydrogen pipelines.[219]

Additionally, according to the European Union Agency for the Cooperation of Energy Regulators[202], the H_2 blending target of the TSO GAZ-system is 10 % vol. by 2030. H_2 networks are existing "mainly in large industrial plants in the steam reforming process of hydrocarbons, where hydrogen is used in industrial processes i.e. in reduction and hydrogenation processes, in refinery during hydrotreating, hydrocracking, reforming, in the food industry in hardening processes and in the metallurgical industry to iron ore reduction."

In Poland, there are no specific regulations for hydrogen purity in pipelines in place so far. The gas transmission system operator GAZ-system, however, refers to several natural gas standards in its Transmission network code[220]: among others, they refer to **PN-EN ISO 6976 Natural gas** for the calculation of calorific values, density, relative density and Wobbe index from composition.

Spain

- Main use of hydrogen in the industry
- The PD-01 protocol is applicable for hydrogen injection into the gas grid and refers to standard **UNE-EN 16726**
- Enagas is the Spanish TSO and a representative in the creation of ENNOH Aims to reach a H2 share of 60 % in their pipelines in Spain by 2030.
- Spanish stakeholders mention that 98 % hydrogen purity is used as a starting-off point when investigating the potential Spanish hydrogen market.

According to CMS[221], currently, most of the hydrogen in Spain is utilized in industry, primarily in refineries and chemical sectors, and is classified as 'grey' hydrogen. There is additional potential for decarbonization by integrating hydrogen into the gas grid. Regarding hydrogen injection into the gas grid, the PD-01 protocol[222] is applicable. This document outlines the technical specifications for gas within the grid and **references standard UNE-EN 16726**. The current maximum H_2 concentration accepted by the TSO in the natural gas transmission network is 5 %vol for 0 °C and 1 bar (not at normal conditions) and it is legally/regulatory possible to inject or allow H_2 volumes into the gas transmission Network and the same H2 blending limit applies for all gas transmission networks.[202] As a reason for the limit, safety concerns and technical network limits are named. Acer additionally noted that there are no 100 % H_2 dedicated pipeline networks for industrial purposes in Spain in operation in 2022.

Enagas[223], as a Transmission System Operator (TSO), has been appointed as the provisional hydrogen transmission network operator under the Royal Decree-Law 8/2023 dated December 27. The next

[219] *Ministry of Climate and Environment of Poland (2020). Polish Hydrogen Strategy until 2030 with an outlook until 2040. Available at: https://www.gov.pl/attachment/06213bb3-64d3-4ca8-afbe-2e50dadfa2dc*

[220] *GAZ-SYSTEM (2024): TRANSMISSION NETWORK CODE (TNC)*

[221] *Grangel, I. (2021). Hydrogen Law, Regulations & Strategy in Spain. Available at: https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/spain*

[222] *Enagas (2011). Detailed Protocols for the System Technical Management Rules. Available at: https://www.enagas.es/content/dam/enagas/en/files/gestion-tecnica-del-sistema/informacion-gestion-tecnica/normativa-y-procedimientos/PD_EN.pdf*

[223] *Enagas (2023). Towards a hydrogen infrastructure in Spain. Available at: https://www.enagas.es/content/dam/enagas/en/files/accionistas-e-inversores/comunicados-cnmv/otra-informacion-relevante/2024/PPT%20IIDiaH2_FINAL_EN.pdf*

steps regarding the development of hydrogen infrastructure will be established by the Ministry for Ecological Transition and the Demographic Challenge. Enagas owns 11,000km of gas pipelines in Spain and is an important point of entry for LNG in Europe.[224]

In April 2022, Enagás established the subsidiary Enagás Infraestructuras de Hidrógeno[225], thereby separating its role as the operator of natural gas infrastructures (TSO) from its management of hydrogen infrastructures.

As a future HTNO, Enagas also works as a representative in the creation of the European Network of Network Operators for Hydrogen (ENNOH) and developed a plan for the year 2030[226], where they aim to reach a hydrogen share of 60 % and an increase in the total amount of gases transported in Spain. Moreover, a new backbone H_2 network will be built on top of the current one, retrofitting existing gas pipelines. In March 2022, the Spanish government established a provisional legal regime for the operation of renewable gas pipelines[211], until EU's Hydrogen and Decarbonised Gas Market Package is adopted.

Additionally, several underground storage facilities are planned until the year 2030 and 30 projects on hydrogen production are planned, aiming to reach more than 1 GW electrolysis capacity in 2027. According to Hydrogen Europe[227], the total announced PtH hydrogen production capacity in Spain is almost 22 GW – the highest of all European countries. This further underlines the importance of infrastructure development in this region, making Spain a potential hydrogen exporter with domestic production being likely twice as high as the local demand in 2030.[228]

Sweden

- No specific hydrogen purity regulations in place so far
- The TSO Nordion Energi is part of projects for hydrogen infrastructure developments, together with TSOs of the neighboring countries (e.g. Gasgrid Finland)

In November 2021, the Swedish Energy Agency put forward a proposal for a national fossil-free hydrogen strategy.[229]. The proposal sets a target of total electrolyser capacity of 5 GW by 2030 and 15 GW by 2045. However, in addition to hydrogen production via electrolysis it is mentioned that chemical and refinery industries may have to rely primarily on other options such as the reforming of biogenic gases due to limited availability of electricity. In Sweden, biofuels and waste are the biggest source of energy (in 2022)[230] and therefore the usage of these resources for hydrogen production might be in the interest for a Swedish hydrogen strategy.

In the proposal, it is described that most of the hydrogen produced in Sweden is consumed near the production site. Smaller quantities are transported via trucks in tankers and Sweden's natural gas network is limited, primarily transporting natural gas from Denmark to industrial facilities in Skåne and along the west coast.

Hydrogen quality standards or regulations are not mentioned explicitly. The RIFS Potsdam sees a pressing need for a stronger alignment of Swedish hydrogen policies with the efforts of the EU and

[224] *ENTSOG (2023). ENTSOG Gas Quality workshop. Available at: https://www.entsog.eu/sites/default/files/2023-11/AllPresentations_GQWorkshop2023_FV%2BEC.pdf*
[225] *Enagas (2022). Una red de transporte para suministrar hidrógeno. Available at: https://www.enagas.es/es/transicion-energetica/red-gasista/infraestructuras-energeticas/transporte-hidrogeno/*
[226] *Enagas (2022). 2022-2030 Strategic Plan. Available at: https://www.enagas.es/content/dam/enagas/en/files/accionistas-e-inversores/informacion-economico-financiera/informes-resultados-presentaciones/informacion-publica-periodica/PPT_Enagas_PlanEstrategico_vDef_EN.pdf*
[227] *Hydrogen Europe (2023). Clean Hydrogen Monitor. Available at: https://hydrogeneurope.eu/wp-content/uploads/2023/10/Clean_Hydrogen_Monitor_11-2023_DIGITAL.pdf*
[228] *Polly, M. (2024). Spain to become major green hydrogen exporter to Europe, with domestic production double that of local demand by 2030. Available at: https://www.hydrogeninsight.com/production/spain-to-become-major-green-hydrogen-exporter-to-europe-with-domestic-production-double-that-of-local-demand-by-2030/2-1-1591337*
[229] *Swedish Energy Agency (2022). Proposal for a Swedish national strategy for hydrogen, electrofuels and ammonia.*
[230] *IEA (2022). Sweden. Available at: https://www.iea.org/countries/sweden/energy-mix*

other Member States.[231] Also, this paper states that the capacity targets of 5 GW by 2030 and 15 GW by 2045 have been formulated "largely based on the expressed intentions of business actors and without a direct link to EU strategic hydrogen targets."

The TSO in Sweden is Swedegas - Nordion Energi.[232] Nordion Energi is part of the European Hydrogen Backbone (EHB) initiative. In Sweden, **the TSO Nordion Energy follows the CEN recommendations** and rules regarding H_2 injection.[233] There are no 100 % H_2 dedicated pipeline networks for industrial purposes in Sweden in operation already but there are plans to develop such networks: The greenfield H_2 pipelines to facilitate decarbonization of energy-intense industries, are at an initial stage in northern Sweden. 100 % green H_2 produced with electrolysis from domestic electricity generation, primarily hydro and wind, will be transported in this pipeline.

There are two major initiatives/projects in Sweden:

- First: Nordion Energi's and Gasgrid Finland's joint initiative known as the Nordic Hydrogen Route (NHR)[234] is one of five identified hydrogen routes planned by the EHB to achieve the goals by 2030 and fulfil the supply and demand of hydrogen identified in the REPowerEU Plan.
- Second: The Baltic Sea Hydrogen Collector (BHC)[235] is a collaborative project between Nordion Energi, Gasgrid Finland, OX2 and Copenhagen Infrastructure Partners that connects offshore gas infrastructure between Sweden, Finland, Åland, Denmark and Germany, and can strengthen self-sufficiency in energy and guarantee access to an open, reliable and safe hydrogen market.

[231] *RIFS Potsdam (2023). Hydrogen Strategy of Sweden: Unpacking the Multiple Drivers and Barriers to Hydrogen Development. Available at: https://www.rifs-potsdam.de/en/output/publications/2023/hydrogen-strategy-sweden-unpacking-multiple-drivers-and-barriers-hydrogen*

[232] *Nordion Energy (2024). Swedegas. Available at: https://nordionenergi.se/engelska/nordion-energi/our-operations/gas-grid/swedegas*

[233] *European Union Agency for the Cooperation of Energy Regulators (ACER) (2022). Opinion 08/2022 on the Review of Gas and Hydrogen National Network Development Plans to assess their consistency with the EU ten-year network development plan – Annex III: Hydrogen, Biomethane injections, and Related Network Adaptations. Available at: https://www.acer.europa.eu/sites/default/files/documents/Official_documents/Acts_of_the_Agency/Opinions/Opinions%20Annexes/ACER_Opinion_08-2022-Annex_III.pdf*

[234] *Nordic Hydrogen Route (2024). Website. Available at: https://nordichydrogenroute.com/*

[235] *Baltic Sea Hydrogen Collector (2024). Website. Available at: https://balticseahydrogencollector.com/*

4. Stakeholder groups and perspectives

This section describes a stakeholder investigation performed by DNV and it builds on the literature review performed in the previous chapter. The following deliverables are the output of the current task:

- Key issues found between and within stakeholder groups with regard to hydrogen quality standardization, the purity level and contaminants are reported. The rationale as to why certain stakeholder groups desire a certain hydrogen purity level is explored.
- A list of requirements for new technical standards and changes to existing ones based on knowledge gaps which are identified during the stakeholder investigation is created.
- Recommendations are made on different options for the scope of the hydrogen quality standard in the European transport network based on three hydrogen purity levels. A discussion is included on which contaminants to include in the proposed specification and why they are important to certain stakeholders.
- Lastly, three example specifications are made based on stakeholder input and existing standards. These are required as input for cost analysis in chapter 5.

This chapter introduces the methodology of the stakeholder survey (Chapter 4.1), presents an overview of the overarching issues which were put forth by the stakeholders and highlights the key issues presented during this survey (Chapter 4.2). Lastly, the beforementioned changes to standards and three proposed hydrogen quality specifications are presented (Chapter 4.3).

Stakeholders are anonymized in this public report, but the list of participants is known to DG ENER. Sometimes, it is relevant to mention where a stakeholder is located in the EU. To preserve the anonymity of the respondents, the region where the stakeholder is from is indicated.

4.1. Methodology

4.1.1. Stakeholder selection and network representation

For a survey focusing on techno-economic topics, it is important to make a clear division between stakeholder groups to allow the survey documents to be technically specific enough to cover the entire scope. By doing so, precise technical questions can be asked, instead of generic questions. The following groups are introduced for this purpose:

- Producers: The producers stakeholder group includes any organization on the entry side of the hydrogen network. This group includes traditional producers of low-carbon or grey hydrogen such as operators of SMR facilities, companies (and associations of companies) who produce hydrogen as a byproduct of a chemical process, renewable hydrogen producers (via electrolyser) and importers of hydrogen in any form (ammonia, LOHC, LH_2).
- Transmission and distribution: This stakeholder group represents any direct stakeholder responsible for connecting producers, storages and end-users via their network. The group includes transmission system operators (TSO), distribution system operators (DSO), interconnectors between countries, and associations exclusive to these groups (e.g. ENTSOG, Ready4H2).
- Storage operators: This stakeholder groups represents companies and associations responsible for the storage of hydrogen gas. The group includes companies currently storing hydrogen, or stakeholder currently storing natural gas and who might intend to store hydrogen in the future. Subgroups are:

  - Salt cavern operators. Underground salt formations to store gas. Salt caverns can generally store gas at higher quality as discussed in the literature review, are chemically relatively inert and have quick fill/withdraw rates.
  - Depleted gas field operators. Gas fields where most of the natural gas has been extracted. To be stored gas is injected into porous structures. The cushion gas present in these fields often reduces the quality of injected gas as discussed in the literature review, and there can be microbiological activity depending on the location of the field.
  - Aquifer operators. Aquifers are underground natural water reservoirs. They are rarer than the other two storage types, but in some places in the EU they are present and should therefore be included. These facilities also use cushion gas.

- End-use: End-users represent the endpoint of the network, where the transported hydrogen is consumed. This stakeholder group includes both single stakeholders and associations (e.g. IFIEC, EUROMOT). End-users are highly diverse and have different requirements; therefore, subgroups are created:
  - Feedstock. Any stakeholder who uses hydrogen as a raw material as part of an industrial process. This includes refinery processes, desulphurization, the Haber-Bosch process etc.
  - Power and Heating. Any stakeholder who uses hydrogen to generate electricity or combined electricity and heat (CHP).
  - Process heat. Any stakeholder using hydrogen to provide energy for burners, ovens and kilns.
  - Mobility (Internal Combustion). Stakeholders representing the maritime, rail and road transport industries using hydrogen in internal combustion engines.
  - Mobility (Fuel Cell). Stakeholders representing users of hydrogen via fuel cells in cars, trucks and buses.
  - E-fuels. Stakeholders who use hydrogen to produce e-fuels such as green kerosine, methanol, ethanol or DME (green diesel).
- Associations: This stakeholder group has been created to represent organizations with members which would fall into multiple stakeholder groups. For example, many associations promoting hydrogen include producers, storages, TSO's and end-users. Many of these associations have members all over Europe and can therefore give an EU-wide perspective (e.g. GERG, ENTSOG, ENNOH).

To best represent the future hydrogen backbone, a network representation was created which can be seen in Figure 4-1.

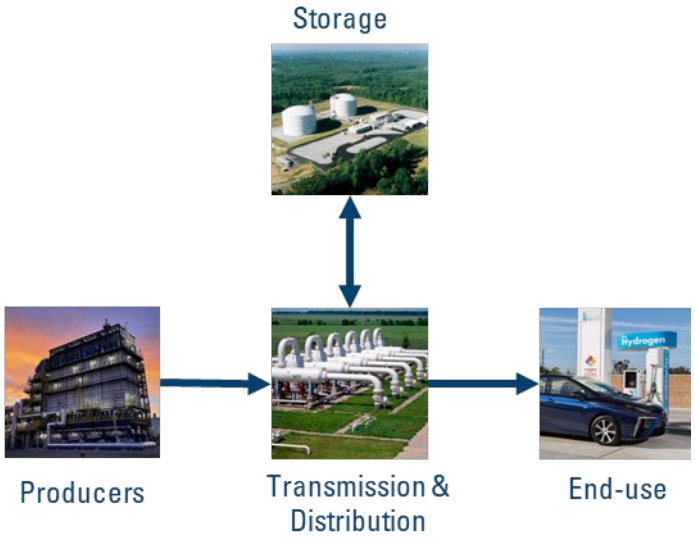

Figure 4-1: Network representation of the stakeholder groups used within the current work.

4.1.2. Stakeholder engagement process

Surveys

Based on discussions with the EU Commission (DG ENER), it was decided to prepare questionnaire documents specific to stakeholder groups for this survey. Questionnaires which are too generalized might include too many questions unrelated to specific stakeholders or the responses will end up not specified enough for valid analysis. However, general questions about the future of hydrogen in Europe give insight into the outlook these stakeholders have on the market and allowed the project team to compare different opinions between sectors/countries/stakeholder groups. The outlook stakeholders have can support DG ENER establishing future hydrogen market scenarios.

The questions are designed to get insight into the stakeholder's opinion about the current market, the future of the market and whether they desire a high- or low-quality specification. Furthermore, the questionnaires attempt to find what quality level and which contaminants are important to their stakeholder group. The surveys are composed of two sections:

- The first four questions are the same for every stakeholder group and include:
    - A question on opportunities and threats.
    - A question about which production techniques they expect to be dominant in the near future (2030).
    - A question about what end-use they expect to be dominant in the near future (2030).
    - A question on whether they expect the hydrogen standard for the hydrogen transmission network will be of high quality or low-quality.
- The second part of the questionnaire consists of 4-5 specific questions for their part in the hydrogen value chain with regards to hydrogen quality. Example topics include the expected microbiological activity for storages, and the limits on contaminants for end-users.
- Furthermore, every questionnaire has a question about which standards are missing/incomplete according to the stakeholder.

For the questionnaires the following stakeholders were approached initially:

- 26 associations were contacted through email of which 19 were hydrogen specific. This included the hydrogen associations of various countries such as NLHydrogen, DWV and Brintbranchen.
- 13 end-user associations were contacted through email of which 1 was hydrogen specific. Hydrogen specific end-user associations are relatively since hydrogen is already part of the 'traditional' value chain for many industrial processes, and therefore part of regular end-user associations.
- 10 TSO/DSO were approached directly. However, after initial contact, it was agreed that approaching them through higher-level TSO/DSO associations such as ENTSOG is preferred.
- 12 hydrogen-producing or hydrogen-import stakeholders were approached, including 6 electrolyser-related stakeholders.
- 11 storage companies were contacted, of which 3 were hydrogen specific, but all organizations had plans for hydrogen storage.

After word about the project spread, several stakeholders requested participation and were included in the results.

Workshop participation and in-depth interviews

In addition to the surveys, DNV organized several workshops between the start of the project in 2024 and the project delivery in 2025. The insights from workshops were used to verify the results found in the questionnaires, such as views on the future outlook of the hydrogen market and regional differences in hydrogen purity expectations.

Based on their response to the surveys, three stakeholders were interviewed. These were 1-hour TEAMS meetings where their response to the survey was discussed in-depth. The notes from these interviews will be used throughout this document in a qualitative manner.

4.1.3. Returned surveys distribution

Figure 4-2 shows the distribution of participating stakeholders in the European Union. As can be seen, organizations from 10 countries participated directly in the questionnaires, and other countries participated as a member of a European association.

For the overarching European/national associations, effort was made to include stakeholders who are hydrogen-specific (Ready4H2, HYTEP) and those from the natural gas focussed (e.g. ENTSOG, EASEE Gas). In total, 11 associations with members from all stakeholder groups participated, and 36 % of them were hydrogen specific.

After evaluation and revision of the returned documents, the input from 46 questionnaires was used in the current work. The statements made were integrated into a discussion of key issues within stakeholder groups, and between stakeholder groups in the form of an analysis. The names of the participants will not be included in the work. Of the returned questionnaires 11 stakeholders were

Figure 4-2: Distribution of surveyed stakeholders in the EU. Dark blue meant that organizations of these countries directly took part in the survey. Light blue nations are only represented as part of an association (e.g. ENTSOG).

identified as associations, 10 were end-users, 3 producers, 2 standardization bodies, 11 storage operators (mostly salt cavern) and 13 were transmission or distribution operators. Some questionnaires were not included because the answers were incomplete, others chose to do an interview instead.

4.1.4. Limitations

Stakeholder research is often limited by the amount of responses received and whether the body of responses is representative of the entire market. In the current work, although care was taken to get a good representative response, the response rate for hydrogen producers was significantly lower than that of transmission operators, end-users and storages. Although this can have a variety of reasons, the total number of hydrogen producers with practical experience in the EU is low due to the slow market ramp-up. Nevertheless, a questionnaire from the key player in hydrogen production in the EU was returned, and information from interviews and workshops was used to gain further insights from hydrogen producers.

4.2. Results and discussions - key issues identified

In this chapter, the key issues regarding hydrogen quality which have become clear in the process of the stakeholder investigation are reported. Opinions of stakeholders are presented 'ad verbum' as they are stated in the questionnaires to present an honest reflection of the stakeholder's intent. Where opinions differ between stakeholders, care is taken to represent both sides of the argument.

4.2.1. Market and volume

All stakeholders provided input on their expectations of the hydrogen market in the EU in the near future. They were asked to give their opinion on which production methods and what end-user segments they expected would be dominant in a future hydrogen market which is based on a European hydrogen transport backbone. The stakeholders' outlook on the future market is important to the topic of hydrogen quality, since the expected dominant production methods dictate the quality of the produced hydrogen and how much purification is required at network entry and exit.

Production

The primary expected method of hydrogen production for the backbone by stakeholders is electrolysis. 70.4 % of respondents mentioned electrolysis, 46.3 % of respondents mentioned import of hydrogen in the form of another energy carrier (LOHC/ammonia) or through pipelines, 40.7 % mentioned the production of hydrogen through traditional means (SMR/ATR) and 14.8 % mentioned gasification or pyrolysis.

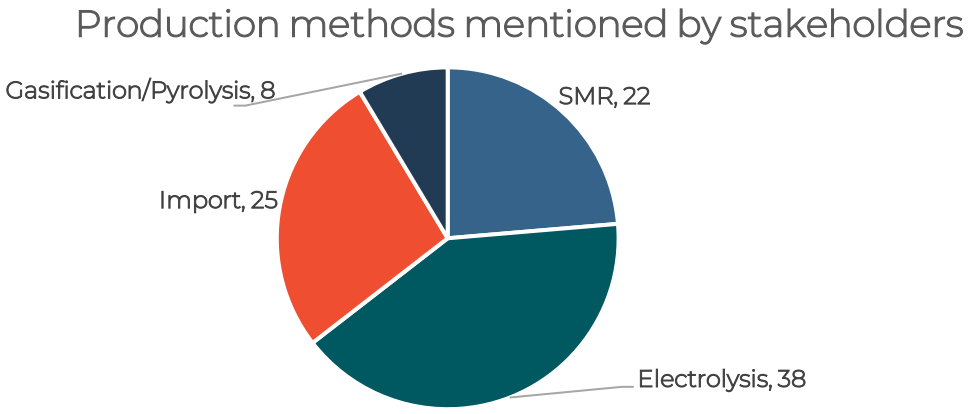

Figure 4-3: Illustration of how often stakeholders mention production methods. Niche production methods only mentioned once were not included. Import covers any hydrogen-based energy carrier. SMR includes other reforming processes such as autothermal reforming. N=46.

Figure 4-3 shows how often production methods were mentioned by stakeholders. Note that since stakeholders were allowed to mention multiple production methods, the numbers do not add to the total number of stakeholders.

Electrolysis is the most commonly mentioned production method, and some stakeholders specifically mention offshore wind and solar energy as power sources for electrolysis, meaning renewable hydrogen. A study cited by a stakeholder is the Pathway 2.0 study by the NSWPH[236] in which one of the findings was that 44 % of offshore wind will be converted into hydrogen. However, it is acknowledged by stakeholders that building a business case for hydrogen production through electrolysis in the European Union is difficult currently, due to other regions of the worlds having better access to affordable solar and wind energy. A major association for hydrogen stakeholders in Europe states:

> *"The cost of renewable electricity is one important cost driver of renewable hydrogen. Availability at an affordable price of large amounts of renewable electricity is paramount for renewable hydrogen production."*

Many stakeholders recognize that, at least in the early stages of the implementation of the EU hydrogen economy, the import of hydrogen into the EU will be crucial. Notably, countries with strong international connections, like Italy with its SouthH2 pipeline from North Africa, emphasize hydrogen imports more than less connected countries. The situation is different for landlocked countries, illustrated by this statement from a stakeholder from Eastern Europe

> *"We do not expect ammonia imports from third countries by 2030 in [name of landlocked eastern European country] Therefore, dominant production pathway[s] will still be [the] fossil fuels pathway and electrolysis."*

On the other side of the argument, a Spanish stakeholder states:

> *"Additionally, it is EU's goal to domestically produce 10 Mt of hydrogen and import another 10 Mt, therefore we would expect to see imports of hydrogen from other continents in the form of derivatives and hydrogen carriers."*

As can be seen, the expectation on how hydrogen will be acquired differs on the national level, even though most stakeholders agree that electrolysis and initial low carbon / blue hydrogen production through SMR should be the preferred strategy in the EU.

End-use segments

In addition to production methods, stakeholders were asked about what they think the dominant end-use market would be in the near future. They were not given specific options and were free to indicate the expected dominant end-use (see Figure 4-4).

Even though they could answer any specific end-use, 74.1 % of stakeholders mentioned the use of hydrogen as feedstock in the chemical industry as a dominant end-user market. Furthermore, this was often coupled with responses to the chemical use of hydrogen in the steel industry as part of a hydrogen direct reduction process (48.1 % of respondents). The use of hydrogen for power generation in gas turbine plants was mentioned by 42.6 % of respondents. After these three end-uses, heavy-duty mobility was mentioned by 37 % of respondents, where hydrogen or hydrogen derivatives are used in maritime, rail or truck transport applications through combustion engines.

[236] *The Pathway 2.0 Study, NSWPH is a 2024 study financed by Energinet, Gasunie, Tennet and the EU.* https://northseawindpowerhub.eu/files/media/document/2024.06.24_NSWPH%20Pathway%20Study%202.0.pdf

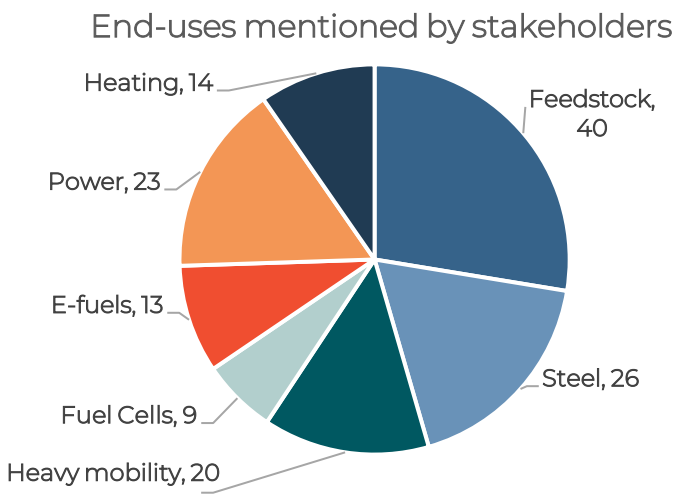

Figure 4-4: Illustration of how often stakeholders mention end-uses. Stakeholders were asked to present their expected dominant end-uses in the near future in an open question and were allowed to give multiple answers. N=46.

Industrial use of hydrogen as a source of heat in burners and ovens was mentioned by 25.9 % of respondents. However, countries with a significant portion of energy-intensive industry such as the Netherlands and Germany mentioned this more often and are relatively overrepresented in the survey. For example, Dutch stakeholders mention that congestion in the electricity network is a limiting force for electrification of Dutch industrial equipment in the heating industry. However, domestic heating was not mentioned as a potential avenue for hydrogen, with one stakeholder even stating:

"Heating for homes won't be [the] preferred decarbonization pathway unless we [...] start producing low-carbon hydrogen for 1 € per kilogram."

And another:

"In the short to medium term there is not a belief that residential heating will be driven by hydrogen."

Lastly e-fuels, which are hydrogen-derived fuels were mentioned by stakeholders, and some mentioned the use of hydrogen in fuel cells. In general, most stakeholders believe that the most immediate need for hydrogen will be the same as it is currently: as feedstock for processes such as steel refining and ammonia production. Furthermore, the excellent energetic and zero carbon qualities of hydrogen could be used in heat and electricity generating turbines, or in the transport sector when transformed into different fuels. A quote from a TSO from Northwestern Europe describes the general consensus well:

"Currently, the use of fuel cells for mobility seems to be limited to heavy duty applications. For the heating of homes, there are alternatives available so it is not expected that natural gas will be replaced by hydrogen on a large scale. Feedstock users and the chemical industry currently use already a lot of hydrogen. The manufacturing of steel is also expected to use a lot of hydrogen in future to reduce the emissions of carbon dioxide. (De)central power generation could also fill in part of their requirements with hydrogen."

It is notable that the number of stakeholders mentioning fuel-cells as a potential end-use is this low. This is likely due to them seeing electrification of small commercial and private vehicles being a more economic viable option than a hydrogen-based decarbonization method for this sector.

Supply and demand uncertainty

An often-mentioned topic by stakeholders is the 'chicken-and-egg' problem between hydrogen supply and hydrogen demand. Until a steady hydrogen demand has been established in the EU, potential producers are not incentivized to scale up. Conversely, without a steady supply of affordable renewable or low-carbon hydrogen, end-users are unwilling to convert machinery and infrastructure based on natural gas to hydrogen-ready ones. A hydrogen association states:

"...the uncertainty in the price and availability of low-carbon hydrogen from both producers and offtake sides is of importance. What we need at both MS and EU level is more integrated funding schemes to connect the producers and end-users with each other, with a guarantee system that infrastructure will be in place at the time of the implementation of the projects."

Additionally, stakeholders assess that without a steady hydrogen demand, the hydrogen system in the EU will become highly dynamic, increasing the dependency on gas storage to act as a buffer between a variable supply and demand. Putting hydrogen in and out of aquifers, depleted gas fields and salt caverns will introduce contaminants into the hydrogen which will have to be removed to fit the agreed upon hydrogen quality standard. Furthermore, pressurization will have to take place. Both these actions require energy, reducing the decarbonization potential of the hydrogen itself. This challenge was addressed by an association of storage operators:

"There is a need of structuring the hydrogen-delivery and -supply by flexible and large-scaled hydrogen-storages due to the volatile hydrogen-production (caused by production based on renewable electrical energy) and the expected hydrogen-import (caused by import based on derivates). Without underground storages, the structuring of the hydrogen supply, also including security of supply, cannot be managed by the (industrial) users on their own. Industrial users are expected to have a nearly constant demand, other end-users have fluctuating demand, from an intra-daily to a seasonal scale."

However, as this same organization notes, the concept of hydrogen storage in underground sites is still in the development phase, with challenges in output hydrogen quality and the required volume for relatively low-density hydrogen being significant:

"The timeline to bring hydrogen underground storages in operation is very ambitious. The demand of storage capacity cannot even approximately be met by adding up the capacities of storages reallocated from natural gas to hydrogen in the future plus the currently known planned projects of new storages (investment gap) without additional public funding. Underground storage facilities have not been proven yet to meet high purities of withdrawn hydrogen, with the first hydrogen storage facilities that will be set in operation, the possible purification results have to be evaluated."

As can be seen from the above quotes, stakeholders are generally in agreement that the supply and demand of hydrogen will be more dynamic than that of natural gas. This will increase the reliance on fast gas storage, which has not been comprehensively proven to be technically feasible to deliver high quality, is dependent on geography (salt caverns are restricted to certain areas of the EU) and might not have sufficient capacity.

There is strong stakeholder agreement on the expected initial end-use (feedstock) and the expected production methods (blue, green and imported hydrogen).

The end-use of using hydrogen in a residential setting is not supported by most stakeholders. For the mobility sector, the use of hydrogen in E-fuel production is mentioned far more often than the use of hydrogen in fuel cells.

There is a market expectation that the hydrogen backbone will be more dynamic than the natural gas network, and will require a significant volume of gas storage to compensate for fluctuating supply and demand.

Figure 4-5: Summary of stakeholders' perception on further market development

4.2.2. Stakeholder arguments for required purity levels in the standard

One of the key learnings which has come up from the returned questionnaires is a clear division between stakeholders in expectations of the hydrogen purity level in the proposed backbone (and thus in the standard). TSO and DSO are the most important stakeholders when it comes to the technical feasibility of being able to maintain and deliver a guaranteed hydrogen level. Therefore, their opinion is key on the hydrogen purity level in the future standard. Of 14 surveyed stakeholders (9 TSO, 2 DSO, 1 DSO association and 1 TSO association) half claimed a preferred hydrogen quality of >98 %, while the other half aligned with the >99.5 % quality standard Note that no stakeholders mentioned a 99.97 % quality level as a specification for the hydrogen networks . The cited reason for this is the technical uncertainty of guaranteeing this quality in repurposed networks. The division between 98 % and 99.5 % quality is not only found in the answers of transport operators, but is also found in the total stakeholder group, as can be seen in Figure 4-6. To verify that this decision was not caused by stakeholder selection bias, the problem was discussed in the workshops, and a similar division between desired purity levels was found here.

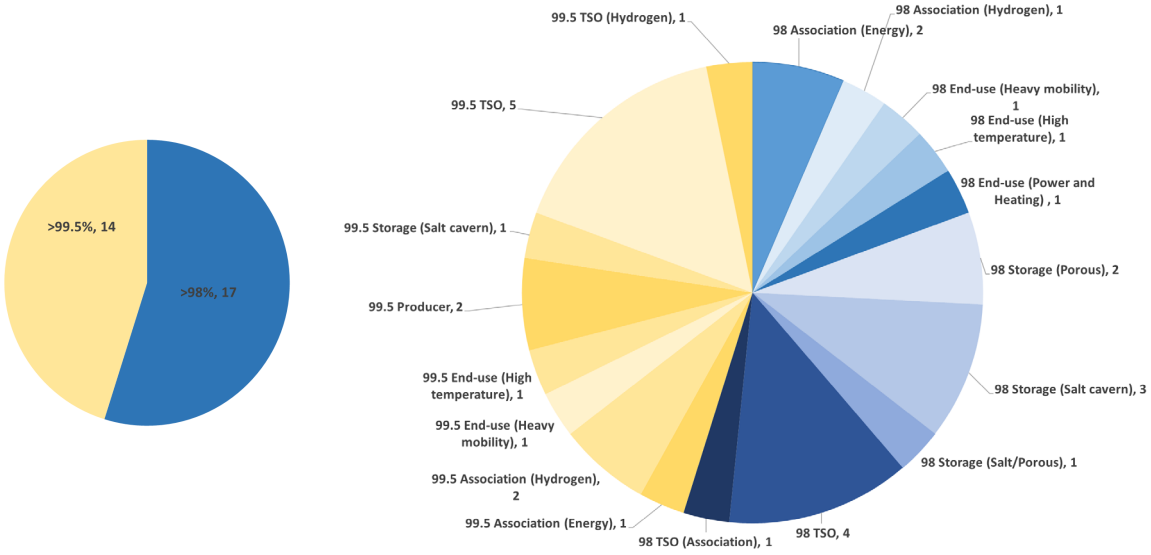

Figure 4-6: (left) Illustration of desired quality in the hydrogen backbone of stakeholders. Stakeholders who did not give a clear answer were excluded from the results. N=33. (right) Breakdown of the stakeholder categories for both purity levels, without 99.99%, as indicated by 2 feedstock end-users.

This division in the opinion of stakeholders on the ideal hydrogen purity in the network could lead to roadblocks for the standardization of the hydrogen quality in the EU. Furthermore, this division can lead to a request for two purity levels in the standard. Because of this, it is essential to explore the arguments stakeholders have for both levels in an in-depth way. When the division on this topic was discovered during the survey process, the questionnaires were adapted to further delve into the technical, political and economic rationales behind the desire to either have 98 % as a purity level or 99.5 %. The next section will explore arguments of both sides.

Arguments towards 98 % H_2

The following arguments are put forth by stakeholders as to why the quality standard should 98 %:

1. *End-users don't require high-quality hydrogen.*

   Multiple grid operators and their associated storage operators, have the opinion that a large proportion of hydrogen demand will require a rather low-quality hydrogen. One of the stakeholders provided a report by Guidehouse[237] on hydrogen purity. In this report, multiple arguments were presented towards a hydrogen quality of 98 %, including a calculated 'average demand' of 98.1 % purity based on volume. However, as will become clear in Section 4.2.3, end-user requirements can often be more complex than just a purity level.

   As an illustration for how this argument is presented, an association for transmission operators states:

   "...we expect that it is necessary to have one harmonized standard for a "high" hydrogen quality with ≥98 % purity and higher purity standards than those in the beginning of the hydrogen market phase are more a barrier than helpful in promoting the market integration. As only a few users need higher purity than ≥98 % (but the total costs are spread over all users, also those with lower needs!), the caused costs are unreasonable in comparison to the benefit."

   This view is aligned with some storage stakeholders, which also state that they expect that end-user requirements will be relatively low. This leads to the following argument by a large storage operator from Germany:

   "According to our findings [...], only small segments of the hydrogen end-use application have purity requirements greater than 98.0 mol%. The average purity requirement of the hydrogen end-user market is calculated to be 98.1 mol%."

   As can be seen from the above statements, market demand is an important factor for stakeholders. The results of the Guidehouse study which is being used here are not publicly available. Therefore, a market demand study with a strong technical basis, meaning that the required hydrogen purity level considers all contaminants, could be a useful tool to explore what the market demand is.

2. Some storages cannot economically store high-quality hydrogen.

   The argument that storages facilities cannot economically store high-quality hydrogen is an argument that is common among storage operators which do not operate salt caverns, but storage types such as depleted gas fields or aquifers. A stakeholder operating depleted gas field storage states:

   "For the time being to provide safe operation, 98 % purity as it is already currently in the

[237] *A value chain perspective on hydrogen gas quality in Europe. Guidehouse report for a stakeholder, 2024. Not referenced here to preserve the anonymity of the stakeholder.*

German DVGW G260 code this appears to be the best option. This is also based on our long-term experiences of the operation of former used crude oil caverns for natural gas. It is known that this already requires significant gas treatment, i.e. TSA. It cannot be guaranteed, that higher purities can be provided from underground hydrogen storage facilities on an efficient economical way."

This stakeholder argues that the purification costs are uneconomical but does provide further background on this. A Northwestern European storage operator illustrates the technical reasons for why high purity is not feasible:

"From today's point of view, we plan to reach a purity >98 %. For this target, already complex purification-units are needed within the withdrawal trains to handle the contaminations from the storage activities and microbiological processes within the storage-plants and caverns/porous rock. Since there are no salt cavern storages on an industrial scale for hydrogen in operation in Germany, some possible contaminations have been identified, but never verified. Test caverns will not deliver the same results due to different reasons, such as storage volume, storage time, connection to the reused natural gas grid and more."

And also, in Southern Europe the same arguments hold, with the addition of storage rates:

"[Storage operator] performed internal studies to determine this value. … a purity level of 98 % is the highest that can be guaranteed with the hypothesized purification systems. Achieving this level is already challenging, both technically and economically. Attaining a higher level of purity would necessitate additional purification steps, such as Pressure Swing Adsorption (PSA), which would be hardly compatible with the storage rates required by the system and would drastically increase the associated costs."

and another operator stating:

"For underground storages, which return stored hydrogen to the transport network as needed, discontinuously and with varying volume rates of > 1 million standard cubic meters per hour, a hydrogen quality standard >98.0 mol% means that the entire volume flow must be extensively purified, regardless of the quality requirements of the end-use application."

The above quotes sketch the stated challenge for dynamic storage in porous media storage quite well: microbiological activity and already-present contaminants in the storages will contaminate the hydrogen, and it is both uneconomical and not fast enough to purify the hydrogen when the hydrogen quality standard is too high. Since this is a major roadblock for higher purity levels in the standard, these technical arguments will be further explored upon in Section 4.2.4

Arguments towards 99.5 % H_2

On the other side of the argument, some stakeholders are convinced that >99.5 % hydrogen purity is critical to the European hydrogen backbone. The following arguments are presented:

1. Stakeholders believe repurposed networks can technically transport 99.5 % hydrogen.

   The first barrier towards the use of repurposed pipelines for hydrogen is the technical feasibility of guaranteeing an exit quality of 99.5 % by cleaning up the pipelines. It is critical for transmission operators to ensure that the hydrogen gas leaves their system at the promised quality, regardless of the length of the pipeline, and be consistent in delivering that quality. In practice, natural gas components have adsorbed into the wall of the pipeline over years of use and can contaminate the hydrogen after the pipeline has been repurposed, reducing the quality of the hydrogen at system exit. Before a pure gas like hydrogen is introduced, the pipelines will have to be purged (typically, with nitrogen) and cleaned of solid deposits (with a

cleaning pig).

To the knowledge of DNV, only a few studies have been performed on the topic of hydrogen in repurposed systems. The 2022 DNV study '*Conversion of a natural gas pipeline to hydrogen transport and the effects of impurities on the hydrogen quality*'[238] is cited multiple times by stakeholders in returned questionnaires. This document describes the conversion of a 12km long natural gas pipeline in the Netherlands to hydrogen service and the appropriate cleaning procedure. The study found that the transport of 99.5 % pure hydrogen through this pipeline is technically feasible, and that over time the negative influence of the natural gas history of the pipeline will diminish through depletion of contaminants within the pipeline.

In the survey document, all TSO's were specifically asked if they had performed any practical research themselves on this topic, but none had done so publicly, or was willing to divulge this information to DNV at this time. A number of stakeholders acknowledged that internal work is being conducted but were not willing to share this work for the purposes of the survey before the work was completed. Combined with the findings in the first part of this report on available literature, it can be concluded that the research on the technical feasibility of hydrogen transport in repurposed pipelines is limited to only a few practical studies including the 2022 DNV study, and practical work by OGE and others. A Northwestern European TSO states:

"[Stakeholder name] trusts that it can maintain a purity level of 99,5 % H_2 through its Hydrogen transmission network with new and rededicated pipelines."

However, this technical confidence is mostly found at the TSO level: a final critical argument for a relatively high quality is the expected degradation in distribution networks. Distribution piping, especially polymer pipes, are vulnerable to leak-in of atmospheric gases including oxygen and nitrogen. Furthermore, the DSO network can contain more contaminants adsorbed into the piping walls due to odorization practices. These effects are worsened in low-demand periods since the hydrogen will be static (not moving due to flow created by demand) in the piping system. Therefore, it is the expectation of some stakeholders that hydrogen quality will degrade over time after entering the DSO network. Having a higher starting purity will increase the exit quality for DSOs after contamination by their network, since the starting-off point before contamination is higher, e.g. 98 % purity hydrogen will be of lower quality after 2 days of being static within a pipeline than 99.5 % purity hydrogen [239].

For dedicated pipelines, no significant problems are expected since high quality hydrogen (>99.97%) is currently being transported by industry as common practice in Europe and elsewhere, as confirmed to DNV by industrial stakeholders.

2. Some storages can guarantee 99.5 % hydrogen delivery.

Some storage operators are confident in their ability to produce 99.5 % pure hydrogen from their storage. These are exclusively salt cavern operators. In the survey, two storage operators, both salt cavern operators from Northwestern Europe, indicated that 99.5 % was not an issue for them, technically. One stated:

"From technical perspective we have no real preference, we expect to be able to

[238] *Top, H. (DNV) (2022): Conversion of a natural gas pipeline to hydrogen transport and the effects of impurities on the hydrogen quality. Presentation at ENTSOG GAS QUALITY & HYDORGEN WORKSHOP, 11/07/2022. Available online: https://www.entsog.eu/sites/default/files/2022-11/4.2%20Conversion%20of%20a%20natural%20gas%20pipeline%20to%20H2%20and%20effects%20of%20impurities%20-%20Henk%20Top%20%28DNV%29.pdf*

[239] *Van Essen, M., Knijp, J., Turkstra, J.W., Vermeltfoort, N., van Greuningen, S. (2024) HyDelta 3 WP1a – Asset Management – Quality assurance for local hydrogen purity specification (exit and entry).*

handle up to 99.5 mol% and we do not see reason to go lower than 98 mol%. Moreover, not only the level of purity but the accepted impurity level for various components shall be defined."

TSO's aligned with these storage operators will therefore be more inclined to a 99.5 % hydrogen purity in the network.

3. Hydrogen will be produced at a high quality, and injecting pure hydrogen in a low purity network would be a waste.

Since many stakeholders believe that electrolysis and import of hydrogen will be the primary production methods, and the assumptions that producers of high-quality hydrogen would not want to dilute their product in a low-quality network, the expectation is that producers would drive the hydrogen quality upwards. An association states:

"Additionally, a lower hydrogen purity standard for the transport network would be illogical with the future production methods in mind. Electrolytic hydrogen will, after purification (drying), net high purity hydrogen (99.99 % mol). Contaminating the high purity hydrogen with lower purity levels is inefficient."

Although the producers which were interviewed for this report did not state this, the number of participating hydrogen producers was low, and limited in terms of electrolyser stakeholders. Therefore, it is recommended that this particular question be explored further.

4. >99.5 % is an economic optimum in terms of socializing purification costs, according to some studies.

Several proponents of higher quality state that the chosen hydrogen quality should be based on the economic optimum: the most cost-efficient placement of the hydrogen quality level in terms of purification costs for all stakeholders. If the entry specification of the network is very high, purification would have to take place on the producer side, if the exit specification of the network is low, the burden of purification would fall on the end-user. To further complicate this, storage operators would be responsible for their own entry and exit purification. Because storages, producers and end-users have different requirements, an economic optimum with the lowest purification costs exists at a specified percentage, which would theoretically be the best solution for all stakeholders if the purification costs were socialized. A Northwestern European TSO states:

"It is in our interest to provide a single gas quality in our infrastructure. So, the challenge is to find a compromise covering most end-user requirements while still being aware that not all user's requirements will be fulfilled. In the context of 99.5 % hydrogen gas quality draft, that acceptance will be much wider than in case of 98 % (see CEN SF JTF "Hydrogen quality needs for industrial end uses")."

A Western European TSO references the DNV/Kiwa study '*A follow-up study into the hydrogen quality requirements*' published in November 2023[240], which assesses the economic optimum in the Netherlands. However, before making any conclusions they await the EASEE gas study[241] which extrapolates the optimum in the Netherlands to the context of the European union. This study is expected to be published Q2 2025.

[240] *DNV and Kiwa (2023). A follow-up study into the hydrogen quality requirements. Available at: https://www.eerstekamer.nl/overig/20231009/rapport_kiwa_dnv/document*

[241] *Van Wesenbeeck, P. (2024) Optimum hydrogen purity in Europe. Presented at the ENTSOG hydrogen quality workshop. Available at: https://www.entsog.eu/sites/default/files/2024-12/Presentations_GQWorkshop2024.pdf*

These studies indicate an optimum which lies above 98 %, closer to the 99.5 % quality level. However, it should be noted that these studies have so far been simplified models of gas quality. Several assumptions are made in terms of purification complexity (e.g. covering all contaminants), economics of scale and topography (centralized versus decentralized purification). On this topic, an association of end-users-states:

"In our view, …, a high standard (e.g., 99.5 – 99.99 mol%) offers the lowest societal costs, if not immediately, then certainly over time. This is due to the challenges with ex post purification, the economies of scale from centralized purification, the elimination of marginal purification costs, and the avoidance of value loss from expensive green RFNBO hydrogen."

As can be seen above, some stakeholders consider economies of scale and centralized versus decentralized purification critical. Therefore, the 2025 EASEE-gas study and further work should be awaited[242], since this study includes more variables such as tail gas loss and topology of purification sites. Furthermore, DBI's section of this report will further explore the abovementioned problem.

5. Pricing methods will drive the hydrogen quality up.

A common topic of discussion in hydrogen gas quality standardization and regulations is the matter of trade units. For hydrogen to be priced for sale, purchase or custody transfer, the amount and quality of hydrogen must first be determined. Considerations include the measurement of weight versus volume, and whether contaminants should be included in the calculation or not. For example, in natural gas it is common to calculate the price of the gas based on the combined calorific value of all components, although no harmonized agreement exists over the entire EU. Because of the inherent differences between hydrogen and natural gas explored in Section 2.1, this could be different for hydrogen.

In 2023, EASEE-gas published a common business practice[243] on the topic of hydrogen units in market processes. In this document, it is argued that since hydrogen is most commonly used as a feedstock, and chemical processes are only benefitted by actual hydrogen, that only the hydrogen molecules should contribute to the cost of the gas. This means that any trace components contributing to the calorific value such as methane and propane have no value when sold as a component of 'hydrogen gas'. Stakeholders feel that this will drive the quality of hydrogen towards and beyond 99.5 % since producers are incentivized to deliver the purest gas possible without (possibly valuable) trace components. A Northwestern European stakeholder states:

"In the recent years, we consulted many potential producers who also confirm they can deliver the 99,5 % H_2 purity level without significant cost increase, especially considering the CBP of EASEE Gas on Hydrogen Units, which foresees that only the energy content of the H_2 will be accounted in the energy calculation of the hydrogen stream (energy content of the impurities like CH_4 will not be considered)."

And a Northwestern European TSO stakeholder:

"The way the hydrogen is traded (inter)nationally is also influencing the hydrogen quality. Trading hydrogen on an energy basis but only taking into account the contribution

[242] *This publication is expected in the first half of 2025.*
[243] *EASEE-gas: Common Business Practice 2022 – 001/01 (CBP)*

of the hydrogen molecules as proposed in the EASEE-gas CBP results in a higher hydrogen quality when converting hydrocarbons since the non-converted hydrocarbons present in the hydrogen don't have a commercial value."

It can be clearly understood from the above quotes that the EASEE-gas document has been impactful on the opinion of transmission operators on hydrogen quality units. In the document, EASEE-gas puts forth the unit *kWh* ($H_{2, HHV}$) as a measure of the energy quantity of hydrogen, derived from the amount of hydrogen and the determined calorific value at a set temperature and the hydrogen purity of this amount. Although this could lead to clumsy units such as *kWh/h* for transmission capacity, it is felt that this unit aligns most with current market communication. Furthermore, the use of *kWh* aligns with the electricity market, which is argued to be closely coupled to the future hydrogen market because of the use of electrolyser units for hydrogen production.

As for regional considerations: transmission and distribution operators from Northwestern Europe generally agree on 99.5 % quality, Central European operators are split between 99.5 % and 98 % and Mediterranean/Southern European operators stated 98 % would be preferable in the near future.

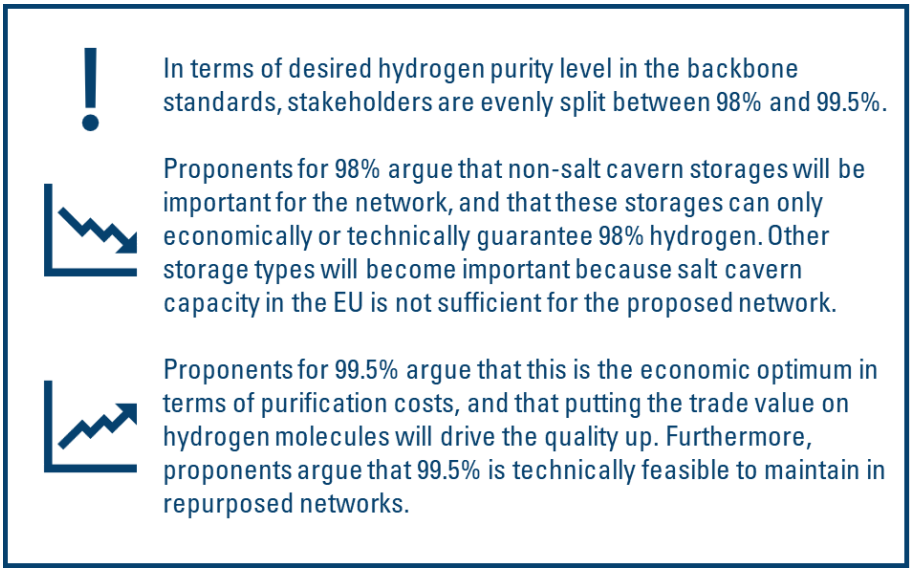

Figure 4-7: Summary of stakeholders' positions on certain purity level in standards

4.2.3. Key issues for end-use stakeholders

One of the key findings about hydrogen quality is that most end-users do not have specific requirements on the hydrogen purity level, but rather on trace components. This is because end-users are concerned with contaminants that could damage their equipment or slow down their processes. A major association for feedstock and fuel cell end-users in Europe summarizes end-user demands well:

"In conclusion, both higher than 98 % and 99.9 % (mol%) hydrogen purity levels have merits depending on consumer needs and specific applications. However, focusing on possible impurities is often more critical than merely looking at hydrogen purity in terms of mole percentage. This highlights the need for automated, real-time systems to monitor both hydrogen purity and impurities. Additionally, hydrogen should ideally be priced according to its mole percentage rather than its energy value to ensure more accurate billing and cost distribution."

Stakeholders state that the difference between fuel cell users and feedstock users is that feedstock processes are vulnerable to some contaminants due to catalyst deactivation, but fuel cells are

vulnerable to many contaminants and therefore require even higher quality standards. Typical hydrogen processes which use catalysts are[244]:

- Ammonia production (iron catalysts), 55 % of global hydrogen demand.
- Methanol production (copper, zinc oxide catalysts), 10 % of global hydrogen demand.
- Refining (various catalysts), 25 % of global hydrogen demand.

As can be seen above, the market share for current hydrogen demand is dominated by processes that use catalysts. Therefore, limiting contaminants which deactivate catalysts is an essential requirement for the end-use stakeholder group. In other works, the hydrogen purity requirement for feedstock is sometimes stated as being 99.5 %, but stakeholders state that it should be made clear that this 99.5 % number is conditional on the limitation of certain contaminants.

Stakeholders using hydrogen for combustion do not have specific demands on purity, but on the stability of this purity over time and the reduction NO_x emissions. An association of industrial end-users states:

"The members [the association] will use hydrogen for different applications with varying specifications for quality. Chemical processes generally require strict quality specifications due to toxicity to catalyzers, while combustion processes generally allow for a more lenient bandwidth but are at risk of nitrogen emissions."

An association for producers of internal combustion engines states:

"The WI range should be maintained between 42 and 46 MJ/m³. I.e. a maximum delta WI should be 4 MJ/m³ (variation range). This range would enable the safe and efficient operation of equipment. Regarding the maximum change of speed in hydrogen quality, the limit should be 0.5 - 1.0 MJ/m3 per minute (15/15 °C)."

Other end-users of hydrogen also state that the hydrogen purity is of secondary importance compared to which trace components are present, which affect chemical processes and calorific value. Furthermore, the stability and predictability is important to end-users to optimise industrial processes. Lastly, the cost of hydrogen is critical to end-users, especially in the energy generation sector.

Because a higher quality allows for less 'space' for contaminants which could poison catalysts, industrial end-users for feedstock processes tend to desire a very high quality (99.99 %), which is beyond the expected capabilities of rededicated networks. End-users operating burners and ovens prefer 98-99.5 % stating:

"A maximum bandwidth of 0.5 % accompanying gas substances has a significantly lower influence on the combustion parameters."

However, another stakeholder notes that cost is more important in some cases than stability:

"The high temperature industry doesn't have an ideal percentage of hydrogen purity, but mainly look [sic] at the commodity price. Less purity combined with lower commodity price would have preference."

From the above considerations it becomes clear that an abstract hydrogen purity number is not of primary concern to most end-users. End-users have requirements which differ significantly for each sector. For example, stakeholders were asked whether they preferred a single hydrogen quality standard in the network or multiple. Notably, whereas some end-users desire a single standard, others would prefer the addition of lower-quality standards to reduce the price of hydrogen. No other stakeholder groups were split on this topic, and they all wanted harmonization to a single hydrogen transport quality standard.

[244] *Vos, M., van den Noort, A. (2019) HyQuality: Hydrogen Quality Compatibility*

Purity level is of secondary importance, the primary requirement is that specific trace components do not poison/inhibit/disturb industrial processes.

For end-users in the high-temperature, electricity and heat generation sectors, lower cost can have preference above high purity.

In general, industrial end-users demand consistent quality. For some, consistency is more important than quality.

Figure 4-8: Summary of key issues for end-use stakeholders

4.2.4. Mismatch between hydrogen storage and end-use purity levels

As discussed in Section 4.2.2, the purity level mismatch between storage, the network and end-use would be significant if the purity level in the specification is chosen too high. Figure 4-9 is an illustration of the acceptable purity levels for various stakeholders, compared to their expected volume in the EU market, as stated by stakeholders. Note that this is a simplification, since as mentioned in the previous section, end-user requirements are not driven by purity level specifically.

As depicted in Figure 4-9, porous media storage (i.e. depleted gas fields and aquifers) represents the majority of available gas storage space in the EU, especially when considering the lack of salt cavern storage in many member states. These storage operators almost universally state it is uneconomical to clean up their exit gas to a purity level above 98 %. Opposite to that, the steel industry (through combustion and DRI) and the feedstock industry are the expected largest end-user groups. These end-users often want the highest quality possible with few contaminants, especially sulphur contaminants. This gap in purity level will be problematic for the future European gas infrastructure and needs to be addressed, if storage is required in the future network.

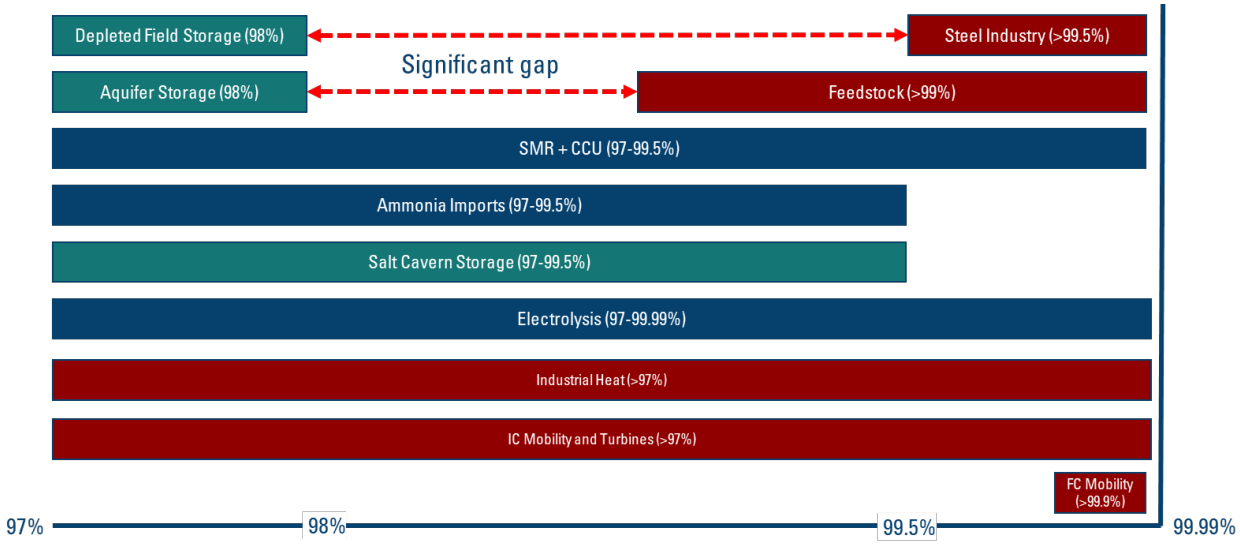

Figure 4-9: Simplified model of the acceptable ranges of hydrogen quality for various stakeholder groups compared to their expected volume. Note that the hydrogen purity requirements are approximations, since in reality, end-user requirements are mostly based on contaminant limits.

Therefore, it is critical to analyse the underlying reasons for this gap. As became clear from the stakeholder questionnaires, workshops, the literature survey and interviews, the major issues driving down the quality of hydrogen which can be guaranteed from porous media-type storages are (i) microbiological activity, (ii) remaining natural gas in storage, and (iii) space for purification infrastructure + permitting. Note that some salt cavern storage operators from Denmark and the Netherlands surveyed were confident that they could deliver higher quality hydrogen; the below sections explain the rationale most storage operators use to explain their lower desired purity level in the EU hydrogen infrastructure.

(i) Microbiological activity

Although highly site-specific, many stakeholders mention microbiological activity as a cause for concern when hydrogen is stored. Microorganisms consume hydrogen and create waste products which are typically hydrogen sulphite (H_2S) or methane. For porous media operators, methane and hydrogen sulphite formation are mentioned to be site-specific:

"Additional impurities that may be released from storage are site-specific and could be generated only under particular conditions. Specifically, methane and traces of H_2S may be present due to microbiological activity."

Similar statements were made by other porous media storage stakeholders. Additionally, microbiological activity is not only present in porous media storage types, with a Northwestern European salt cavern operator stating:

"Microbial and/or geochemical reactions might lead to possible pollution (H_2S) of stored hydrogen."

However, salt cavern operators are divided on this topic. A Northwestern/Central European storage operator who has done practical research on the topic states that:

"... influences e.g. on microbacteriological activities in salt cavern reservoirs, which can lead to a deterioration of the storage material, are to be regarded as unlikely on the basis of our experience and there are technical solutions.... We do not currently assume that H_2S purification will be necessary, because of the very low production of H_2S If at all) due to microbiological processes in a salt cavern environment."

This means, that at least in the case for this particular salt cavern, the problem of contaminant formation through microbiological activity in salt caverns is manageable, based on practical experience. However, stakeholders state that this is highly site-specific, even for salt caverns. Furthermore, stakeholders describe the process of H_2S removal as being less difficult than methane removal in general, and that desulphurization systems can be used which are already typical for natural gas processes. Furthermore, to limit microbiological activity, stringent limits to oxygen and carbon oxides can be set for the entry specification into the storages.

(ii) Remaining (buffer) natural gas

When gas storages are repurposed, it will most likely not be possible to completely remove all natural gas. Therefore, at least initially, natural gas components will be present in the hydrogen which leaves the storage. Natural gas components which could be present are sulphur, sulphur compounds, long and short chain hydrocarbons. In the survey, storage stakeholders generally try to communicate the difficulty of purifying hydrogen which comes from storage, especially in porous media storages:

"Today it is not yet possible to extract short-chain hydrocarbons (especially methane) from the hydrogen due to external restrictions (permitting, use-cases for tail-gas, etc.). Also, purification from methane would lead to high amount of hydrogen-losses – and due to this to uneconomic behavior – because of the need to clean-up high flows."

And:

"... For the time being, to provide safe operation, 98 % purity [...] appears to be the best option. It is known that this already requires significant gas treatment. It cannot be guaranteed, that higher purities can be provided from underground hydrogen storage facilities."

The above quotes illustrate practical limitations to separating hydrogen from methane. Because of the small size of methane molecules, H_2/CH_4 separation leads to a high fraction of hydrogen in the tail gas in separation processes. This tail-gas is considered too valuable to dispose of without a direct local use for it. To flare the tail gas would be a major waste of renewable gases. Furthermore, stakeholders are concerned with permitting and regulations with regards to emissions and disposal of the tail gas. A storage operator from Germany operating both porous media and salt cavern storages investigated the required treatment for a hydrogen storage facility with a withdrawal rate of 1 million m^3/hr. They proposed a water separation, PSA and desulphurization process line. However, regarding methane removal they noted:

"We currently consider contamination by methane a particular challenge, for which no treatment technology has yet been identified. If necessary, blending different gas streams may be employed to achieve a quality level >98 mol%."

Although blending in entry gas into the exit of a gas storage may increase exit quality, it can also increase the complexity of the local infrastructure. Another German salt cavern operator confirms that methane is the most difficult to remove component from hydrogen:

"In contrast to natural gas, we are paying more attention to short-acting hydrocarbons, as these are more difficult to remove using established purification processes."

Therefore, most porous media storage operators, for whom remaining natural gas is a significant problem, desire a lower hydrogen quality standard to reduce the amount of required purification and increase the economic efficiency of their operation.

(iii) Infrastructure at facilities and permitting

As discussed in previous sections, the purification processes required for hydrogen storage will most likely be more complex than those required for natural gas storage. For natural gas storage, removal of any higher hydrocarbons, gas drying and desulphurization steps are typical. For hydrogen storage, multi-step PSA/TSA processes can be required to separate methane from hydrogen. Furthermore, to make the process more economical, recirculation lines are included to extract hydrogen from the tail gas of separation processes. Lastly, if a use case is found for the tail-gas, infrastructure will need to be created for this purpose. The increased complexity of all these processes can lead to concerns about available space for process equipment at storage facilities:

"Generally, to achieve high hydrogen purities is a matter of cost, limited physical space and amounts of tail gases (as emissions/losses from purification processes) not usable for the market that also require handling."

Additionally, besides physical space, emission regulations and permitting are of concern to storage operators:

"Purification at this level stays challenging and costly: Limited areal space; legal environmental obligations; technical constraints; high energy consuming and related emissions"

Implications for end-use

As discussed above, the primary contaminants from storage facilities are sulphur compounds, short-chain hydrocarbons and moisture. For end-use, it has been put forth by stakeholders that a consistent quality level, affordability and a lack of catalyst poisons are essential.

The removal of water should not be a major problem; gas drying facilities are nearly always installed at gas storages and no stakeholders mentioned methane as being a catalyst poison. However, of the three primary storage contaminants, sulphur compounds such as SO_2 and H_2S could be catalyst poisons. Sulphur can poison the exhaust catalysts in mobility applications, reduce the efficiency of fuel cells, damage turbine and motor components and poison catalysts used to accelerate chemical interactions in the process industry. In contrast to gas drying equipment, desulphurization equipment may or may not be present at a natural gas storage which could be repurposed for hydrogen use.

This means that including a stringent sulphur limit in the network hydrogen specification will require additional infrastructure development at gas storage sites for desulphurization equipment which requires additional space. Choosing a more relaxed sulphur limit will shift this equipment to the end-user side, where more space could be available for the equipment. However, it is unlikely that transmission and distribution operators will tolerate a sulphur limit higher than 5-13 ppm, as stated by transmission operators in their survey responses. Therefore, it is assumed that desulphurization equipment will be required in storages with high levels of sulphur-creating microbiological activity.

As for short-chain hydrocarbons from remaining natural gas in storages, a high fraction of methane up to 2 vol% would still be allowable by the DVGW G260 group A transport standard, which has a purity level of 98 %. From the stakeholder feedback, it has become clear that many storage operators currently use this German transport as a guideline for the level of required purification. Little feedback was received on the allowable amount of methane in hydrogen from end-users, with the exception of an internal combustion manufacturer wanting to limit the methane fraction to 20.000 ppm (2 vol%), which is already aligned with DVGW G260 group A.

As discussed, for other industrial end-uses consistency and affordability are critical when detrimental components have been removed. Although a low purity level at 98 % might increase the affordability of the hydrogen because of the reduced purification costs for storages reducing network costs, it will decrease the consistency of the gas quality due to the large amount of wiggle room in the specification. On the other hand, if storages were tasked to remove the methane to a large extent, they claim the operation would become uneconomical. Therefore, research is required on the purification of hydrogen from storage facilities with a focus on particular contaminants, economy of scale, and the technical/regulatory feasibility of removing methane locally at storage sites.

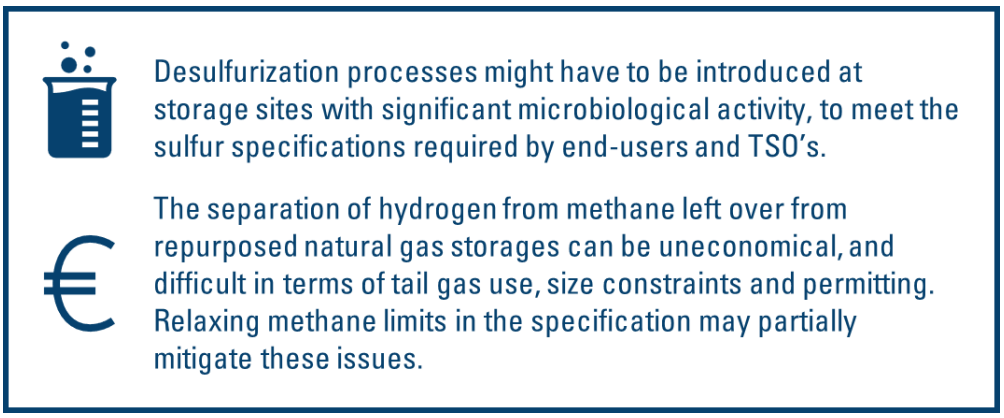

Figure 4-10: Summary of stakeholder insight on the mismatch between storages and end-users.

4.2.5. Other topics

Some topics are relevant to the topic of hydrogen quality and were brought up by stakeholders, but not directly related to supporting the specification. Nevertheless, this information can be vital input for follow-up projects such as HyQual. These are listed in this section.

Metering, measuring and equations of state

An often mentioned topic by TSO and DSO is how hydrogen is measured in the context of fiscal metering, flow measurement and custody transfer, and how this relates to the hydrogen composition. There are still technical questions on these topics which relate to hydrogen quality itself. For example, in hydrogen flow metering, equations of state are used to transform measured values such as m^3/s into other, more usable units such as kWh/h as proposed by the EASEE CPB[245]. The current equations used for natural gas such as GERG-2008[246] and AGA-8[247] are not designed to accommodate relatively pure hydrogen Since the mixture models were not designed for hydrogen mixtures, the lower the quality specification, such as <98 % H_2, the higher calculation error ranges will occur when contaminants are introduced. Calculation error ranges are problematic for DSO, TSO and storage operators since it is critical that correct fiscal measurements are made in custody transfer or billing of the gas. A final concern is the ability of devices such as gas chromatographs to measure the composition of hydrogen due to, for example, carrier gas incompatibility.

Perspectives on the Seveso III directive

Several end-users commented on the relationship between the Seveso III directive[248] and the use of hydrogen from the EU hydrogen infrastructure. Most have to do with relaxing regulations set in the Seveso directive for storing hydrogen on-site, for example:

"Local hydrogen storage standards are critical for our members, especially the Seveso storage limit of max. 5 ton / site. Higher limits or an exception to the Seveso limit for different onsite and above ground storage technologies would be welcomed."

This problem is common among mobility stakeholders, since hydrogen fuelling stations are the most relevant use-case for storing large quantities of hydrogen temporarily. An association for European engine manufacturers states:

"Safety constraints: The size of the hydrogen storage may legislatively present a constraint. From 5 tonnes the SEVESO guidelines are applicable. Below that there is no uniform legislation as of yet, although several initiatives have and are being executed to deal with this"

The above quote reveals a regulatory gap below the Seveso 5-ton limit, which is applicable to smaller fuelling station locations, or facilities where hydrogen has to be temporarily stored in a buffer. Just like the first quote in this section, the second stakeholder also requests relaxation of Seveso regulations regarding hydrogen storage, stating:

"... In the future, as knowledge improves, hydrogen storage will become more common and safer. Then, if possible, the regulation should be revised."

In general, a discussion with mobility end-users regarding Seveso III and hydrogen storage could be useful.

[245] *EASEE-gas: Common Business Practice 2022 – 001/01 (CBP)*
[246] *ISO Standard (ISO 20765-2), GERG-2008 Equation of State for Natural Gases and Similar Mixtures.*
[247] *AGA Report No. 8, Thermodynamic Properties of Natural Gas and Related Gases GERG–2008 Equation of State, 2017.*
[248] *Directive 2012/18/EU of the European Parliament. The SEVESO III Directive aims to prevent major industrial accidents involving hazardous substances and to limit their consequences for human health and the environment.*

Perspectives on odorization

Multiple stakeholders indicate that odorization practices for hydrogen are a significant technical knowledge gap. Three primary points are brought up in the questionnaires:

- It is unclear what odorization practices should be used for hydrogen. While most stakeholders agree that harmonized odorization practices are preferred, there is no consensus on what kind of molecules should be used. Although sulphur-based odorants are currently common, they might not be suitable for hydrogen since they are damaging to catalysts and fuel cell applications.
- It is unclear at what point odorants should be injected into the network, or only be injected on DSO level, since many EU member states currently use varying methods.
- There is still a technical knowledge gap on the influence historical odorization practices have on the ability of a natural gas pipeline to be repurposed for hydrogen use. An association for transmission operators in the EU states:

> *"Yes, we see a regional variability [in the ability to repurpose pipelines] due to the fact that odorization could cause different preconditions in regards to repurposed pipelines, namely the component nitrogen could play a bigger role then and cause higher necessary efforts."*

Based on the above points, it is clear that the knowledge gaps related to odorization practices are primarily technical knowledge gaps. Therefore, applied research on the effect new and existing odorants have on hydrogen-typical end-user equipment should be performed, before complete regulation can be made.

DSO concerns on entry and exit specifications

From discussions with a DSO, it was revealed that there are some concerns regarding in-leak of oxygen and other gases in polymer hydrogen pipelines. 'In-leak' means that other gases permeate or otherwise enter the piping system and contaminate the hydrogen contained within.

Distribution systems often make use of PVC and (HD)PE polymer pipelines. These materials are generally more permeable to hydrogen and other gases. Furthermore, the flow rates in distribution pipelines can be very low or completely stopped in certain cases. This increases the in-leak of contaminants into hydrogen, since the hydrogen is not constantly 'refreshed' with clean hydrogen when the flow is slow or stopped.

Especially oxygen/air is a concern for DSOs since hydrogen is combustible with oxygen at very low levels, due to the low flammability limit of H_2/O_2. Therefore, oxygen in the entry specification should be lowered. Furthermore, it may be more difficult to guarantee a good exit specification for DSOs due to in-leak.

Often-mentioned topics out of scope

Some topics which are often mentioned by stakeholders are completely outside of the scope of this study on support for hydrogen quality standardization or follow up projects supporting the standard. However, because they were seen as important by the stakeholders themselves, they are listed here:

- Many stakeholders have opinions on the Renewable Energy Directive III (RED III) agreement.
- The development of CCU(S) infrastructure, equations of state, regulations, metering and pricing. Some stakeholders state that low-carbon hydrogen will be a dominant production technology and therefore the problems of hydrogen and carbon dioxide transport are connected.
- Some stakeholders would like changes in the definition of RFNBO-hydrogen, to allow more gases to be classified as renewable fuels, or at least more clarity in the definition.

- The lack of clarity regarding the regulatory framework for hydrogen guarantees of origin (GOs) and proofs of sustainability (PoS) for cross-border trade.
- A unified EU hydrogen pipeline standard like the American ASME B31.12[249].
- The lack of standards for non-conventional hydrogen storage, e.g. LOHC or metal hydride storage.

4.3. Recommendations

4.3.1. Contaminant requirements

Stakeholders were asked to state the technical limits they would like included in the network specification from their point of view, and the technical reasons why these limits should be included. This section compiles all limitations mentioned by stakeholders, to be used as input for the creation of the hydrogen quality specification.

Table 4-1: Overview of statements stakeholders have given on specific contaminant requirements. Limits are given as provided in the questionnaire. Reference temperatures are 15/15, unless stated indicated otherwise. Stakeholders did not always specify whether they used higher (gross) or lower (net) calorific values.

Property	Considerations from Stakeholders
Wobbe Index [MJ/m³], 15/15	• **Associations:** Suggested limits include **43.56-45.89** for 99.5 %, **40.09-44.4** for <98 %, **45.99-48.35 [25/0]** for 99.5 % and **42-46.** • **End-use:** Stakeholders from the automotive industry would like to use the lower calorific value, since this is what they use, and for hydrogen the difference between the lower and higher calorific value is significant. • **End-use:** Stakeholders from the automotive and turbine industries would like to limit the change in Wobbe to **ΔW < 0.5MJ/m³·minute**. Another automotive industry stakeholder stated **ΔW < 0.5-1 MJ/m³·minute**. • **End-use:** A stakeholder from the ceramics industry stated that only the Wobbe index is of concern to them, and no contaminant is relevant for their purpose. • **End-use:** IC and burner end-user stakeholders suggest limiting the Wobbe index band 4 MJ/m³ [15/15].
Water (Dewpoint)	• **DSO:** A DSO has warned about the difficulty of keeping the purity level of hydrogen high in polymer distribution pipelines . Water can permeate these pipes relatively easy, and they are difficult to be cleaned (not-piggable). • **End-use:** For the automotive industry, **250 ppm** at **10 bar** is recommended as a limit since liquid accumulation in the supply line sinks are destructive for the engine. Another automotive stakeholder mentions **2 g/kg** which is about **223 ppm** by volume. • **End-use:** A stakeholder from the turbine industry had special consideration regarding water limits. The summed-up $H_2O+N_2+O_2$+Ar content limit **of 1.9 %mol in ISO 14687 is considered too high**. A water content of 1.9 %mol in hydrogen would mean e.g. a water dew point of 94°C at 45 bar, problematic for start-up and not preheated hydrogen gas. A specific (low) limit for water content as specified in **DVGW G260 is preferred.** • **Storage:** A storage operator mentions **50 ppm** as a limit. • **TSO:** Many operators cite CEN/TS 17977 **60 ppm** limit. • **TSO:** CEN/TS 17977 allows water content of 60 ppm however ASME B31.12 which some TSO's expect to utilize as the primary design and construction code, does not apply if the water content is above **20 ppm.**
Methane	• **End-use:** An internal combustion end-user suggested limiting methane to **<20.000 ppm,** but only if there are no higher hydrocarbons. • **End-use:** For the production of hydrogen peroxide, methane should be limited to <**10 ppm**. • **Storage:** Storage stakeholders state that total hydrocarbons should be limited to **<20 ppm** as an entry specification. • **Storage:** Porous media storage stakeholders state that their exit specification of methane is significantly above the 20-ppm entry specification. This is due to microbiological processes and repurposing natural gas storage. They also state that methane is significantly more difficult to clean from hydrogen than higher hydrocarbons.

[249] *B31.12 - Hydrogen Piping and Pipelines*. This standard describes how hydrogen pipeline systems should be designed.

Property	Considerations from Stakeholders
Higher hydrocarbons	• **End-use:** An automotive stakeholder specifically mentions propylene and propane as ideally being limited to **<1000 ppm**.
Oxygen	• **Associations:** Hydrogen associations state that oxygen should never exceed **10,000 ppm.** • **DSO:** Oxygen can permeate polymer pipes relatively easy, and they are difficult to be cleaned (not-piggable). • **End-use:** Certain catalysts can be poisoned by oxygen and therefore oxygen should be limited to **<5-10 ppm**. • **End-use:** An IC end-user suggested targeting oxygen at **~500 ppm** to prevent hydrogen embrittlement processes. • **End-use:** Most chemical industry stakeholders wants to limit oxygen, stating that oxygen leads to higher process costs due to loss of efficiency. • **End-Use:** For ammonia production specifically, oxygen should be reduced to <30 ppm to prevent catalyst deactivation. • **Storage:** Porous media storage operators want to limit oxygen to **<10 ppm**. • **TSO:** Transmission operators state that a low ppm of oxygen, **100-1000 ppm** can help prevent hydrogen embrittlement processes in pipeline steels. • **TSO:** Transmission operators often cite the **<1000 ppm** oxygen limit as set in TS 17977. • **TSO:** A transmission operator mentioned that high oxygen percentages can lead to corrosion problems.
CO and CO_2	• **End-use:** The burner industry states that CO_2 must be carefully controlled because of its significant impact on the Wobbe index. • **End-use:** CO and CO_2 are considered catalyst deactivators for the ammonia and methanol-producing industries and should be limited **as low as possible.** • **End-use:** Engine operators want to limit CO to **<1000 ppm** and CO2 to **<20,000 ppm** if the Wobbe does not drop below 42 MJ/m^3 (15/15). • **Storage:** Both porous media and salt cavern storage operators want to limit oxygen to **<20 ppm** each. • **TSO:** Carbon oxides can cause corrosion in pipeline systems, but also offer some protection against hydrogen embrittlement.
Ammonia	• **Association:** A hydrogen association recommends limiting ammonia to **0.5 ppm** due to the deactivation of certain catalysts. • **End-use:** A stakeholder from the automotive industry wants to limit the ammonia to **3 mg/ kWh,** which is about **11 ppm** to prevent corrosion in the supply system. However, the engine itself should have no problems with ammonia. • **End-use:** The steel industry wants to limit ammonia to **0.5 ppm**. It should be noted that these low levels can be difficult to measure. • **TSO:** An operator mentions <10 ppm as a limit to ammonia because of corrosion.
Inert Gases	• **Associations:** Hydrogen stakeholders want to limit to **<5000 ppm** to maintain operational efficiency. • **DSO:** Oxygen can permeate polymer pipes relatively easy, and they are difficult to be cleaned (not-piggable). • **End-use:** A stakeholder from the automotive industry wants to limit the sum of inert gases including carbon dioxide to **below <20000 ppm**.
Halogenated Compounds	• **End-use:** In the automotive industry, halogenated compounds are not really seen as a problem unless emission limits are exceeded. • **End-use:** Fluor and chlorine compounds are strong catalyst poisons for the ammonia and methanol-producing industries and should be limited as **low as possible.** • **TSO:** An operator mentions **<10 ppm** as a limit to halogenated compounds to prevent corrosion.
Formaldehyde	• **End-use:** In the automotive industry, formaldehyde is not really seen as a problem unless emission limits are exceeded.
Fuel-Bound Nitrogen (FBN)	• **End-use:** The turbine industry states that FBN, such as ammonia but other nitrogen-containing contaminants as well should be limited. To maintain low NOx emission, **0 % FBN content** in fuel gas is preferred, in the opinion of turbine operators.
Dust and Particulates	• **End-use:** Engine manufacturers warn that solid particles can cause cylinder overload. • **End-use:** Turbine operators have offered comprehensive guidance on the topic of dust and particulates. Solid particles should be limited to prevent erosion, deposition, and plugging of the fuel gas nozzles and gas turbine hot gas-path. Solid particles in the fuel gas as fed to the nozzles of the combustion system should be limited to a maximum concentration of **30 ppm** by weight with up **to 5 µm size**. And the size of all solid particles should not exceed **5 µm**. For this requirement 99.5 %wt of all particles and 100 % of all particles larger than 5 µm should be removed before delivery to the gas turbine. • **TSO:** A Northwestern European TSO limits dust to **<5 µm**.
Total Sulphur	• Various stakeholders define their sulphur limits either as including hydrogen sulphide as included or separate from their total sulphur limit.

Property	Considerations from Stakeholders
	• **End-use**: A stakeholder from the automotive industry wants to limit the total sulphur to **<5 ppm** due to corrosion and catalyst deactivation issues in the three-way catalyst of vehicles. • **End-use:** Turbine stakeholders have offered guidance on their sulphur limits. The total sulphur in the fuel (from hydrogen sulphide plus other sulphur compounds) should be limited **to 0.5 %wt (0.2 %vol as hydrogen sulphide)** maximum to avoid corrosion of the turbine hot section parts. Total sulphur is recommended to limit **0.01 %wt (60 ppmv as H_2S)** maximum due to the detrimental effects of sulphur to the fuel system. • **End-use:** Sulphur is a catalyst poison for both the ammonia and methanol-producing industries and should be limited **as low as possible.** • **TSO:** An operator mentions **<10 ppm** as a limit total S with hydrogen sulphide being limited to **<3.5 ppm**. Another operator mentions **<13 ppm.**
Oils	• **End-use:** The chemical industry requires limits on oils used in compressors because they are problematic contaminants in chemical processes.
Hydroxides	• **Associations:** Hydrogen associations state that KOH/NaOH should be limited to <**2 ppm** • **End-use:** The chemical industry requires limits KOH and NaOH which are contaminants from electrolysers because they are problematic contaminants in chemical processes. • **Producers:** KOH and NaOH can be in hydrogen when alkaline electrolysis is used.
Amines	• **End-use:** The chemical industry requires limits on amines used in gas cleaning including MEA, DEA, and MDEA because they can poison catalysts.
Heavy Metals	• **End-use:** The turbine industry stated: Sodium + Potassium (Na+K) max. **0.4 ppm wt**, Calcium + Magnesium (Ca+Mg) max. **4.0 ppm wt**, Vanadium (V) max. **1.0 ppm wt,** Lead + Zinc (Pb+Zn) **max. 1.0 ppm wt**, Nickel (Ni) **max. 2.0 ppm wt**, total heavy metals (V+Ni+Pb+Zn) **max. 2.0 ppm wt**. These metals can cause high temperature corrosion to the gas turbine hot parts.
Others	• **Associations:** Arsine, a chemical used in the semiconductor industry, should be included in some way according to hydrogen stakeholders

4.3.2. Recommendations for new standards and revisions to existing standards

Stakeholders were asked for recommendations on new and existing standards with regards to hydrogen quality in the proposed hydrogen backbone. These are compiled in this section.

Table 4-2: Recommendations from stakeholders for the creation of new standards, or the revision of existing standards – aspects related to hydrogen quality.

New or Existing	Urgency	Topic	Gap Description	Responsible Organisation
New	**High**	Odorization	Nearly every stakeholder mentions the **lack of a hydrogen odorization standard**. Furthermore, they note the need for an odorant not based on sulphur.	ISO/TC 197 (or 193), CEN/TC 234
Existing	**High**	Gas Analysis	Hydrogen is not always able to be analysed by standard process gas analysers. For quality control and fiscal purposes, **guidelines and standards surrounding the analysis of trace components in hydrogen** should be created. This includes sampling procedures, in-line determination of the hydrogen purity and contaminant analysis down to the lowest ppm level as specified in the new, harmonized standard.	ISO/TC 193
New	**High**	Traceability	For metrological purposes such as flow measurement, there is a **lack of traceability standards for hydrogen gas.** Traceability is the ability of a measured result to be correlated to a recognized standard through an unbroken list of calibrations. This tracks the amount of uncertainty which is added to the result at each step. There is a lack of calibration facilities for pure (>98 %) hydrogen specifically, which must be addressed.	ISO/TC 30
New	**High**	Trade Units	Two things are mentioned about trade units: first, the **method of quantification of hydrogen** should be established (i.e. mass-based, volume-based, etc), and secondly, the **connection to cost per unit and its relation to hydrogen quality should** be clearly defined. For example, agreements need to be made about the difference in cost between 98 % pure hydrogen with	ACER, EASEE

New or Existing	Urgency	Topic	Gap Description	Responsible Organisation
			2 % CO_2 as a trace component and with 2 % methane as a trace component. Should there be a difference or none, and should only the hydrogen molecules be used in the cost calculation?	
New/Existing	Medium	Hydrogen Quality in Dedicated Networks	Although CEN/TS 17977:2023 is often mentioned by transmission stakeholders, an identified standardization gap is **a standard for dedicated (not repurposed) networks**. In areas like Scandinavia, significant investment could be done in new pipeline systems, which currently do not have a standard for hydrogen quality. This standard could be based on experience commercial companies have with existing hydrogen networks in Europe and the United States. The standard could be integrated with CEN/TS 17977:2023 to form a comprehensive hydrogen transport quality standard.	ISO/TC 197 (or 193), CEN/TC 234
New	Medium	Hydrogen Purification	**Standards for processes** such as pressure swing adsorption and gas drying on **hydrogen purificatio**n are required because of the scale of upgrading processes which will be needed when a hydrogen backbone is implemented.	Unknown
New	Medium	Repurposing Guidelines	Although DNV has published methodology on repurposing of pipelines[238], more work is needed to **create guidelines to ensure the highest quality of hydrogen possible in repurposed networks.**	Unknown
New	Medium	Unified Pipeline Standard	A **hydrogen-specific pipeline standard for (>98 %)** such as the comprehensive American standard ASME B31.12 would be useful in Europe.	CEN/TC 234
Existing	High	Material Compatibility	Although some standards such as ISO 11114 offer guidance on material selection in hydrogen service, this guidance is very limited. More research and guidance is needed on material computability, including the **prevention of hydrogen embrittlement of metals and the prevention of blistering and permeation of polymers by hydrogen and the interaction contaminants might have**. The interaction between contaminants and hydrogen embrittlement is a significant topic in literature, with some being HE inhibitors and others being HE facilitators.	ISO/TC 58
Existing	Medium	TSO/DSO Interconnection	Many storage operators are connected to the DSO instead of the TSO network. **Quality requirements of DSO networks should be harmonized with TSO networks** for this purpose. Rules which are currently in place for natural gas storage could be expanded.	Unknown
Existing	High	Equations of State	**Equations of state for the computations of gas variables such as density and compressibility** should be adapted for use with pure hydrogen. Models such as GERG-2008 and AGA-8 DETAIL currently are not designed for this purpose.	ISO/TC 197 (or 193), CEN/TC 234

Table 4-3: Recommendations from stakeholders for the creation of new standards, or the revision of existing standards – further topics.

New or Existing	Urgency	Topic	Gap Description	Responsible Organisation
Existing	Medium	Seveso III	End-use mobility stakeholders would like **relaxation of Seveso III directives regarding storage at fuelling stations**. Furthermore, they would like the directive to cover hydrogen storage below 5 tonnes.	EU Council

New or Existing	Urgency	Topic	Gap Description	Responsible Organisation
Existing	Medium	Guarantees of Origin and Proof of Sustainability	Stakeholders would like more **clarity on GOs, and PoS definitions**, and require input from organizations such as CertifHY. The NGC could be extended to more member states. Furthermore, for the time being, **some** stakeholders would like to extend the **definition of renewable hydrogen** somewhat to kick-start the hydrogen economy.	CertifHy
New	Medium	Absorbed Hydrogen Storage	There is a **complete lack of standardization for alternative hydrogen storage solutions** such as liquid (in)organic hydrogen carriers, formic acid, iron oxide, glass adsorption etc. Standardization on the topic should be introduced as these technologies develop to market maturity.	Unknown
New	Medium	Tank Storage	For **gaseous and liquid (tank) storage**, several knowledge gaps exist. These include standards for gas transfer, non-industrial classification/permitting, uniform approach to hazardous areas.	ISO/TC 197
New	**High**	CO_2	Standardization on the topic of **carbon dioxide including trade units**, metrology, traceability and quality is required since CCU is an important aspect of blue hydrogen production. Without guidelines on CO_2, the production of blue hydrogen will be hampered.	Unknown

4.3.3. Example specifications based on stakeholder input for the cost analysis

Introduction

In the next chapter of this report, a cost analysis for three different hydrogen grid purity levels is performed. In essence, these represent three cases or scenarios where a hydrogen purity level has been harmonized across the network. Besides the purity level, a detailed specification of contaminants is required for the calculations. In this subchapter, three example specifications are detailed with a hydrogen purity level of 98%, 99.5% and 99.97%. To build these specifications the following steps are taken:

1) An existing standard is taken as reference with a matching purity level.
2) The standard is adapted to better match general stakeholder requirements:
    a. Calorific value calculations (Wobbe, density and calorific value) are aligned with ISO 6976:2016 and harmonized with other ISO/EN hydrogen quality standards, including EN-ISO 13443:2005. This means that the reference temperatures chosen (base/combustion temperature) are 15/15 °C.
    b. Even though some stakeholders might argue for using the net Wobbe Index, the higher (gross) Wobbe Index is used since it is industry standard and indicated in ISO 6976:2016 as being 'in common usage'.
    c. The list of contaminants is standardized. Formaldehyde, formic acid and hydroxides (KOH, NaOH) are included. Formaldehyde is included since they are introduced in the Hynetwork and DVGW G260 specifications. Formic acid is included since it was highlighted by an industrial stakeholder with practical experience with hydrogen transport networks. Lastly, hydroxides are included. These contaminants can be found in hydrogen when it is produced through alkaline electrolysis and can be harmful to certain end-uses, as indicated by stakeholders.

d. The limit to dust and particulates limit is harmonized across all specifications to 1 mg/kg to align with DVGW G260 and ISO 14687.

3) Specific stakeholder requirements for each purity level are introduced. These will be discussed in each subchapter.

98 % Example H_2 specification

This specification represents the lowest proposed hydrogen purity level, as lower purity levels were not in the scope of the task set by the DG ENER commission. The 98 % case would fulfil the requirements of underground storage manufacturers because it would significantly reduce the amount of purification required at storage exit. Producers, especially those of high-quality hydrogen such as electrolysers, would have increased wastage, since their high-quality product would be diluted in the lower quality transport network. End-users requiring high quality hydrogen would require purification before use. In a 98 % purity example specification, it would still be useful to limit contaminants which can cause problems for end-users and storages.

In contrast to DVGW G260 and ISO ISO/DIS 14687:2024, the levels of carbon oxides and oxygen are limited to the ppm level for the proposed stakeholder specification. This choice was made because both oxygen and carbon oxides are detrimental to storages and some industry employing hydrogen as feedstock, even though higher levels of oxygen might offer some protection against hydrogen embrittlement processes in pipelines, as stated by stakeholders. Furthermore, limiting the amount of CO and CO_2 allows for less variation in the Wobbe index. The remaining contaminants were aligned with DVGW G260, the Hynetwork proposed specification and available ISO standards.

As discussed before, even though some stakeholders recommend to calculate the Wobbe Index based on the lower calorific values of the components in a gas, the higher calorific value is used to align with ISO standards and common usage. This value is then divided by the square root of the sum of the specific gravities of the gas components:

$$W_s = \frac{H_s}{\sqrt{\frac{\rho_{gas}}{\rho_{air}}}}$$

As can be seen in the equation above, gases with a higher specific gravity will have a lower Wobbe index if the calorific value remains constant. This means that 'inert' contaminants without calorific value in hydrogen can have significant impact on the Wobbe index.

In Figure 4-11 different calculated Wobbe index ranges are represented, as an illustration of how subcomponents impact the Wobbe index, even at relatively high hydrogen purity. Note that these are not realistic pipeline gas compositions (2% Argon by volume would not be found in hydrogen). The gas compositions indicated in red have a significant variation in the Wobbe index, from 38 MJ/m³ with carbon dioxide as a 2 % subcomponent, to nearly 45 MJ/m³ when the 2 % contaminants allowed in hydrogen are solely CH_4. This is a ~15% difference, which is a significant variation.

Most end-user equipment (e.g. burners, boilers, furnaces) is not designed for this wide range of Wobbe indices. Therefore, a lower limit to the Wobbe index should be set in the 98 % specification. Based on discussion with stakeholders from the energy-intensive industry, this minimum limit is set at 41.89 MJ/m³ while the maximum is set at 45.89 MJ/m³, reducing the Wobbe index bandwidth to 4 MJ/m³. The Wobbe variation for the 99.5 % specification (green bars) is far less pronounced. Based on CEN TS17977, an exemplary specification was developed taking stakeholders feedback into account (see Table 4-4). The speed at which the Wobbe index can change is also limited to accommodate turbine, engine and burner end-users.

Lastly, the limit water content is derived from TS 17977:2023 as requested by TSO stakeholders and an association of TSO's.

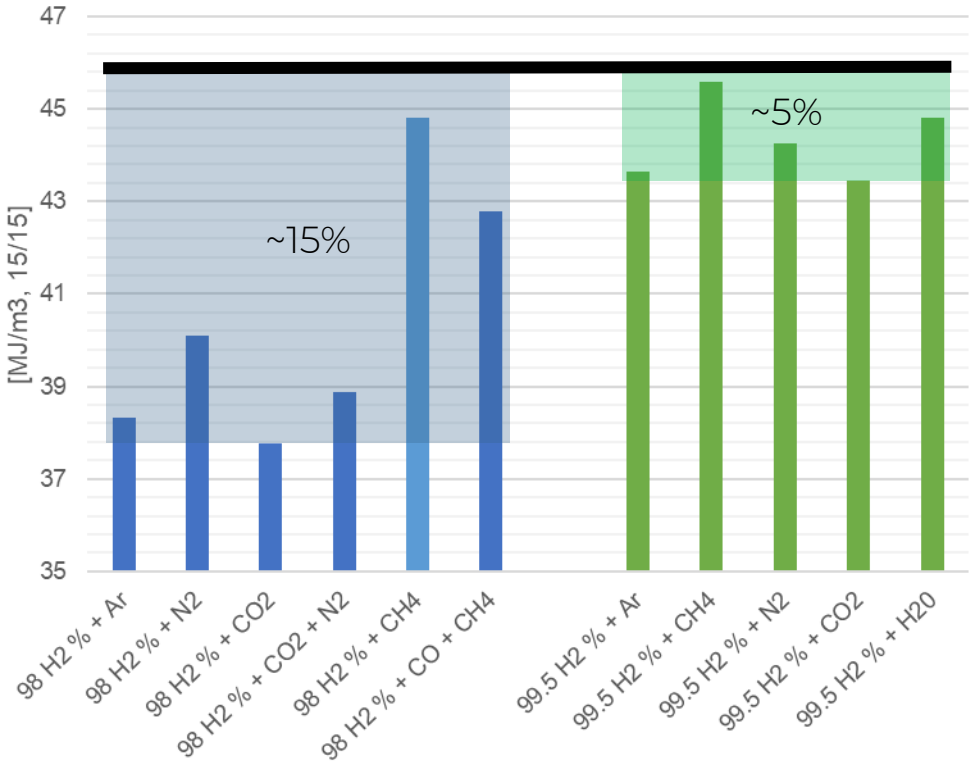

Figure 4-11: Illustration of the effect contaminants in hydrogen can have on the Wobbe index (H_s) at reference temperature 15/15 and standard pressure. The black line indicates the Wobbe Index of 100% hydrogen (45.89). Note that the compositions depicted above are not real pipeline gases, they are merely used to illustrate the theoretical variability.

Table 4-4: Overview of the example >98 % specification (derived from CEN TS17977:2023[157])

	Example >98% specification
Wobbe Index	41.89– 45.89 MJ/m³ (15 °C/15 °C)[250]
ΔWobbe index	<0.5 MJ/m3·minute
Water	<250 ppm at <10 bar <60 ppm at >10 bar
Water Dewpoint	<-8 at 70 bar
Hydrocarbons	<20,000 ppm
Oxygen	<10 ppm
CO and CO_2	<40 ppm (20 ppm each)
Ammonia	<10 ppm
Inert Gases	<20,000 ppm
Halogenated Compounds	<0.05 ppm
Dust and Particulates	<1 mg/kg
Total Sulphur	<7 ppm
Formaldehyde	<10 ppm
Formic acid	<0.2 ppm
Hydroxides (KOH, NaOH)	<2 ppm

[250] *Lower bound would be 38.33 MJ/m3 (98% H_2 + Ar) but limited by the 4 MJ/m3 bandwidth limit in this case.*

99.5 Example % H_2 specification

The 99.5 % specification proposal is primarily based on the requirements and proposals of transmission system operators. Therefore, the opinions of TSOs and the Hynetwork specification as proposed by Dutch Ministry of [KGG] are integrated. The Wobbe index limitation is relaxed in this specification and the reference temperatures are aligned to (15 °C/15 °C).

Limitations to hydrocarbons and inert gases are set from 20,000 ppm to 5,000 ppm to realign with the allowable contaminant bandwidth and the total sulphur limit is reduced to align with the HNS specification. 99.5 % hydrogen quality is chosen since it is the highest percentage which some TSO's indicate can be guaranteed from repurposed networks. As can be seen in Table 4-5, the input from stakeholders was mostly aligned with the HN specification. Some changes included:

- A limit to the change rate of the Wobbe Index. There is still enough variation in the bandwidth at 99.5% to limit the change rate.
- The water content limit is adopted from TS 17977.

Table 4-5: Overview of the example >99.5 % specification compared to the proposed indicative Hynetwork specification[142].

H_2	Proposed	Indicative Hynetwork Specification
Wobbe Index	43.65-45.89 MJ/m³ (15 °C/15 °C)[251]	43.65-45.89 MJ/m³ (15 °C/15 °C)[252]
ΔWobbe index	<0.5 MJ/m3·minute	-
Water	<250 ppm at <10 bar <60 ppm at >10 bar	-
Water Dewpoint	<-8 at 70 bar	<-8 at 70 bar
Hydrocarbons	<5,000 ppm	<5,000 ppm
Oxygen	<10 ppm	<10 ppm
CO and CO_2	< 40 ppm (20 ppm each)	< 40 ppm (20 ppm each)
Ammonia	<10 ppm	<10 ppm
Inert Gases	<5,000 ppm	<5000 ppm
Halogenated Compounds	<0.05 ppm	<0.05 ppm
Dust and Particulates	<1 mg/kg	-
Total Sulphur	<3 ppm	<3 ppm
Formaldehyde	<10 ppm	<10 ppm
Formic acid	<0.2 ppm	<10 ppm
Hydroxides (KOH, NaOH)	<2 ppm	-

99.97 % Example H_2 specification

The 99.97 % H_2 example specification is based on an industrial network specification provided by a stakeholder. Since catalytic processes and fuel cells require high purity hydrogen with low concentration of contaminants, this specification could also meet the requirements of these end-users. However, although stakeholders state this purity level can be transported in dedicated industrial transport pipelines, it is unclear whether this specification is technically feasible for repurposed networks. This means, TSOs could be responsible for purification at network exit. No publicly available transport specification for 99.97 % pure hydrogen exists at this time to our knowledge, and therefore no comparison is made.

[251] *99.5% hydrogen + 0.5% Argon by volume.*

[252] *The original Hynetwork specification "Indicative quality and temperature specification" provided the Wobbe Index using 25/0 reference temperatures. Since the composition of the lower bound was not precisely specified, this translation to 15/15 is a best estimate using the allowable total sum of inert gases (Argon).*

Overview

Table 4-6 presents the example specifications, and further considerations for all three quality levels are presented.

Table 4-6: Example specifications for all three grid purity specifications based on stakeholder input

Property	Example Specifications			Notes
H_2	>98 %	>99.5 %	>99.97 %	
Wobbe Index	41.89– 45.89 MJ/m³, (15 °C/15 °C)	43.45-45.89 MJ/m³, (15 °C/15 °C)	n/a	The 98 % specifications require a lower limit to the Wobbe index to prevent significant variation.
ΔWobbe index	<0.5 MJ/m³ minute		n/a	Derived from automotive, turbine and burner end-users.
Water	<250 ppm at <10 bar <60 ppm at >10 bar		<5 ppm	Aligned with TS 17977and DVGW G260.
Water Dewpoint	<-8 °C at 70 bar			Aligned with Hynetwork indicative specification.
Hydrocarbons	<20,000 ppm	<5,000 ppm	< 2 ppm	Aligned with ISO standards and DVGW G260. Expected to be mostly methane.
Oxygen	<10 ppm			A higher oxygen level is preferred by some stakeholders for 98/99.5 % quality, however, stakeholders from the feedstock industry and storages want to limit oxygen as much as possible.
CO and CO_2	<40 ppm (20 ppm each)		<2 ppm (total)	CO and CO_2 levels are limited for the 98 % scenario for gas storage and to reduce Wobbe index fluctuations. At 99.97%, the specification is aligned with ISO standards.
Ammonia	<10 ppm		<0.1 ppm	Aligned with HNS specification, industrial specification provided by a stakeholder and DVWG G260.
Inert Gases	<20,000 ppm	<5,000 ppm	< 300 ppm	He + Ar + N_2. Although some stakeholders want to reduce fuel-bound nitrogen, nitrogen is notoriously difficult to remove using PSA, and relatively inert for other end-uses. Therefore, limits are aligned with ISO standards and DVGW G260 and will be mostly limited by the Wobbe requirements.
Halogenated Compounds	<0.05 ppm			Aligned with ISO standards.
Dust and Particulates	<1 mg/kg			Common particulate limit among standards, combined with size limit of stakeholders.
Total Sulphur	<7 ppm	<3 ppm	<0.05 ppm	Derived from ISO, HNS and G260 respectively. This specification might have to be changed after the odorization practice has been agreed upon.
Formaldehyde	<10 ppm		<0.01 ppm	Derived from HNS and G260 respectively. Can be harmful to end-users. 99.97 % limit is aligned with industrial specification provided by a stakeholder.
Formic acid	<0.2 ppm			Limit is aligned with industrial specification provided by a stakeholder.
Hydroxides (KOH, NaOH)	<2 ppm			Derived from end-user stakeholder input. These contaminants can be released by alkaline electrolysis and can be harmful to end-users.

5. Cost analysis for different hydrogen grid quality levels

The study includes an analysis of the purification efforts and costs that are related with applying the hydrogen specifications derived in the previous chapter (see Table 4-6) as a grid standard for the European hydrogen grid. The analysis is done considering both, the purification costs for individual supply chain elements as well as along the overall supply chain (i.e. transport pipelines, underground storage and different end-user groups with deviating quality requirements).

In order to introduce a harmonised nomenclature, some key terms are defined as followed.

Case: A case describes a specific hydrogen specification that is determined for the overall grid. In the analysis, three different cases with differing grid specifications (based on example specifications provided in the previous chapter, i.e. 98 mol%, 99.5 mol% and 99.97 mol%) are analysed.

Configuration: The term (grid) configuration is referring to a certain composition of the hydrogen infrastructure in terms of pipeline (new vs. repurposed) or underground storage sites (salt caverns vs. porous media storages). Here, two extreme configurations with different impact on the gas quality are distinguished: best-case and worst-case configuration.

Scenario: With scenarios, different developments of the hydrogen market or different country characteristics are taken into account. Here, a certain set-up of infrastructure, storages and end-user demand compositions are assumed, including the hydrogen volumes that are considered in the infrastructure.

Chapter 5.1 summarized key assumptions for the different analysis and purification technologies needed to remove contaminants from the hydrogen gas. In Chapter 5.2, the different extreme grid configurations are described and the hydrogen specific purification costs compared for the removal of different contaminants. The chapter also includes a so-called sensitivity analysis, where variations in the configuration of the infrastructure and end-users' composition are applied. This allows for assessing the impact of a best- vs. a worst-case grid configuration and potential combinations of both on the purification costs. In a second step, the modular set-up of the cost tool is applied to perform a detailed cost assessment along the overall supply chain by considering individual scenarios on future market development (Chapter 5.3). In both cases, the cost data is presented as specific purification costs in € per kg hydrogen. Finally, Chapter 5.4 discusses uncertainties of limitations of the methodology.

5.1. Assumptions and methodology for cost estimation

5.1.1. Quality requirements ("cases")

Basis assumptions

Three infrastructure quality cases are considered in the analysis below. The respective specifications are in line with the recommendations given in chapter 4.3.3:

- 98 mol%
- 99.5 mol%
- 99.97 mol%

These qualities are used as entry and exit specifications for the different supply chain steps, i.e.

- hydrogen producers
- grid operators (transport and distribution grids)
- storage operators and
- end-user groups (with different quality requirements)

Transfer points or points of possible gas treatment exist between

- producers and grid operators
- grid operators to storage operators
- storage operator to grid operator
- grid operators and users

In addition to that, the following assumptions are taken: direct connections between H_2 producers and users are not considered. Storage system operators are only connected to the high-pressure transmission level. Purification could theoretically also exist between TSOs and DSOs, but this is not considered, as a harmonised quality is assumed for TSO and DSO systems. The only exception is the aspect of odorization, which, in some countries for natural gas, only occurs on DSO level.

In any case, the majority (around 70 %) of existing underground gas storage facilities in Europe are porous structures, i.e. aquifers and former oil & gas reservoirs and will have to use extensive gas treatment for a certain period of time. This is essential for the facility conversion from natural gas to hydrogen storage and is independent of the H_2 quality in the gas network. It is expected that this processing is required at the affected UGS for around 5 - 10 years. As the conversion of storage facilities in Europe will take at least 20 years, these gas treatment processes will be necessary for a very long time across Europe.

In the 98 % case, it is furthermore assumed that the gas composition is constant, so that no additional stabilisation of the gas quality is necessary, e.g. in order to have no variations in the calorific value or Wobbe index of the gas (see discussion in Figure 4-11).

The transport network will have many different feed-in points. These feed-in points vary both in the method of hydrogen production and in the composition of accompanying and trace substances / contaminants. These differences apply to all three discussed quality levels. Since the composition of accompanying and trace substances can vary greatly depending on the feed-in point, it becomes more challenging for network operators to organize centralized gas processing. Standardized processing is made more difficult because the chemical and physical properties of the injected hydrogen are not uniform.

In the following, the different assumed quality specifications defined in chapter 4.3.3 (= cases) and the respective purification needs along the hydrogen supply chain are described.

Case 1: Minimum hydrogen grid quality of 98 mol%

Producers can feed into a gas infrastructure with a lower quality specification than what the output quality of the production technology is. In this case, a dilution will occur. It should, however, be noted that consequently a mix of different H_2 qualities within the grid is conceivable.[253] Reasons for those variations are, e.g.

- Accompanying gases such as nitrogen (N_2) or methane (CH_4), which can be present in varying amounts and therefore require different treatment processes.

[253] *This situation is already observed today in the natural gas grid, where gases from different sources (e.g. North Sea vs. LNG gas) or biomethane are mixed resulting in challenges regarding the correct billing (based on the energy content) occur.*

- Differences in production methods: Electrolytically produced hydrogen has a different quality than hydrogen generated through processes such as steam methane reforming (SMR, grey hydrogen) or ammonia cracking.

Gas treatment may be necessary prior to storage to ensure that no contaminants (e.g. water, N_2, CH_4, O_2, CO, CO_2 and sulphur compounds) are introduced into the underground storage facility. Caverns should be protected in order to reduce the costs of gas treatment in the long term. The gas treatment of a salt cavern will therefore differ from the gas treatment of a porous storage facility.

In the case targeting a hydrogen purity of 98 mol% H_2 as shown in Figure 5-1, the hydrogen stream undergoes comprehensive gas treatment. The process includes Pressure Swing Adsorption (PSA) and optionally odorization with non-sulphur-containing substances to meet specific safety and purity requirements.

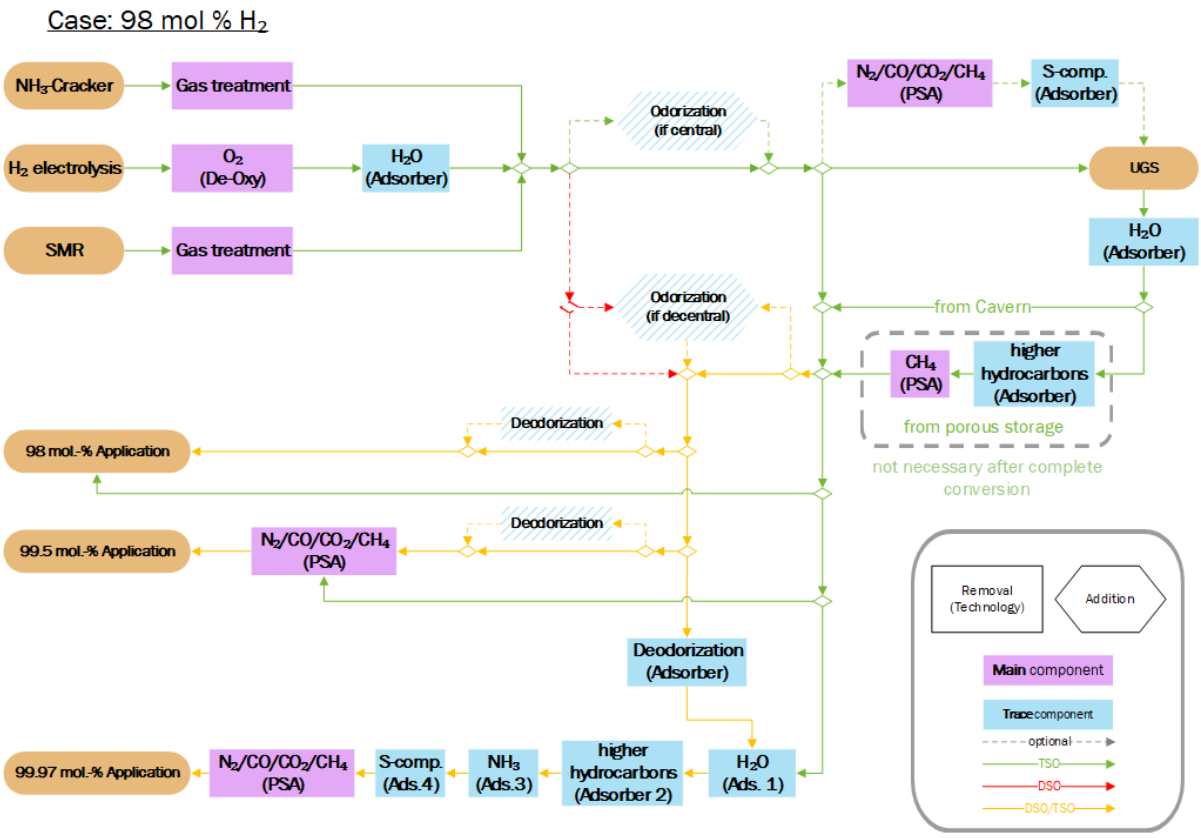

Figure 5-1: Gas purification steps in the 98 mol% hydrogen grid purity case (Source: DBI, own representation)

The following statements can be summarised:

- Hydrogen sources:
  - H_2 electrolysis, NH_3 crackers, and Steam Methane Reforming (SMR) serve as the primary sources of hydrogen.
- Gas treatment:
  - Oxygen removal: Oxygen is eliminated via (catalytic) de-oxy adsorption to prevent oxidation processes and ensure gas quality.
  - Moisture reduction: H_2O adsorption using TSA or other adsorption processes is employed to significantly reduce moisture content, stabilizing the gas quality.

  - **PSA technology:** Pressure Swing Adsorption removes nitrogen (N_2), carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4), ensuring that the target purity of 98 mol% is achieved. In addition, H_2S is removed after storages (if needed).
  - **Sulphur and hydrocarbon removal:** Adsorptive processes with tailored molecular sieves are applied to remove sulphur compounds (e.g., H_2S, COS) and higher hydrocarbons (e.g., C_2^+). Advanced systems combine different molecular sieves within a single adsorber to simultaneously address these impurities, enhancing efficiency and reducing operational complexity.
  - **Odorization:** Optionally, the hydrogen stream can be odorized with non-sulphur-containing substances to enhance safety during distribution without adverse chemical effects on subsequent processes.
  - **Deodorization:** For applications requiring odourless hydrogen, the odorants are removed through the process of adsorption.
- End-uses:
  - **98 mol% application (= low sensitive customers):** Hydrogen is directly supplied for industrial applications with moderate purity requirements, such most combustion processes.
  - **99.5 mol% application**: A partial stream can be further processed (see description in Case 2) to meet the needs of more demanding applications.
  - **99.97 mol% application (= highly sensitive customers):** For ultra-high purity applications, the hydrogen stream can undergo additional treatment as outlined in Case 3.

Case 2: Minimum hydrogen grid quality of 99.5 mol%

The injection of hydrogen with a purity of 99.5 mol-% by producers has significant implications for downstream processes and infrastructure components of the hydrogen network.

In this case the treatment of hydrogen in underground gas storage (UGS) facilities requires less processing, as the injected purity already meets high standards. As a result, pressure swing adsorption (PSA), typically used at the entrance of UGS facilities to remove impurities, is no longer necessary. This reduction in processing steps not only leads to operational cost savings but also simplifies the configuration of the facilities.

However, the need to further treat hydrogen for sensitive end-users with particularly high purity requirements remains. Such consumers might include applications in the mobility (fuel cell) but also electronics or pharmaceutical industries, where ultra-high purity hydrogen (e.g., 99.97 mol-%) is essential.

In this case, the treatment steps from Case 1 are expanded to achieve a hydrogen purity of 99.5 mol-%, which is essential for demanding industrial applications. The steps are as follows:

- Gas treatment and PSA:
  - Similar to Case 1, the raw hydrogen stream is initially **treated to remove oxygen (O_2) and water (H_2O)** and undergoes pressure swing adsorption (PSA) to effectively reduce the primary impurities before injection.
  - **Advanced adsorption:** Targeted removal of sulphur compounds (S-Comp), which pose risks as potential corrosion agents and catalyst poisons in downstream processes.
  - **Odorization:** Hydrogen is odorized using non-sulphur-containing substances to meet safety requirements without compromising the chemical purity of the hydrogen.
  - **Deodorization:** For applications requiring odourless hydrogen, the odorization agents are removed to maintain the required purity standard.
- End-uses
  - **98 mol% application:** A portion of the hydrogen stream can be provided for applications with lower purity requirements, such as industrial heating processes.

- **99.5 mol% application:** This level of purity is suitable for chemical processes, the production of synthetic fuels, and the operation of fuel cells with moderate requirements.
- **99.97 mol% application:** For applications requiring nearly pure hydrogen, such as highly specialized chemical syntheses or fuel cells with the highest demands, the hydrogen stream can undergo additional treatment steps from Case 3.

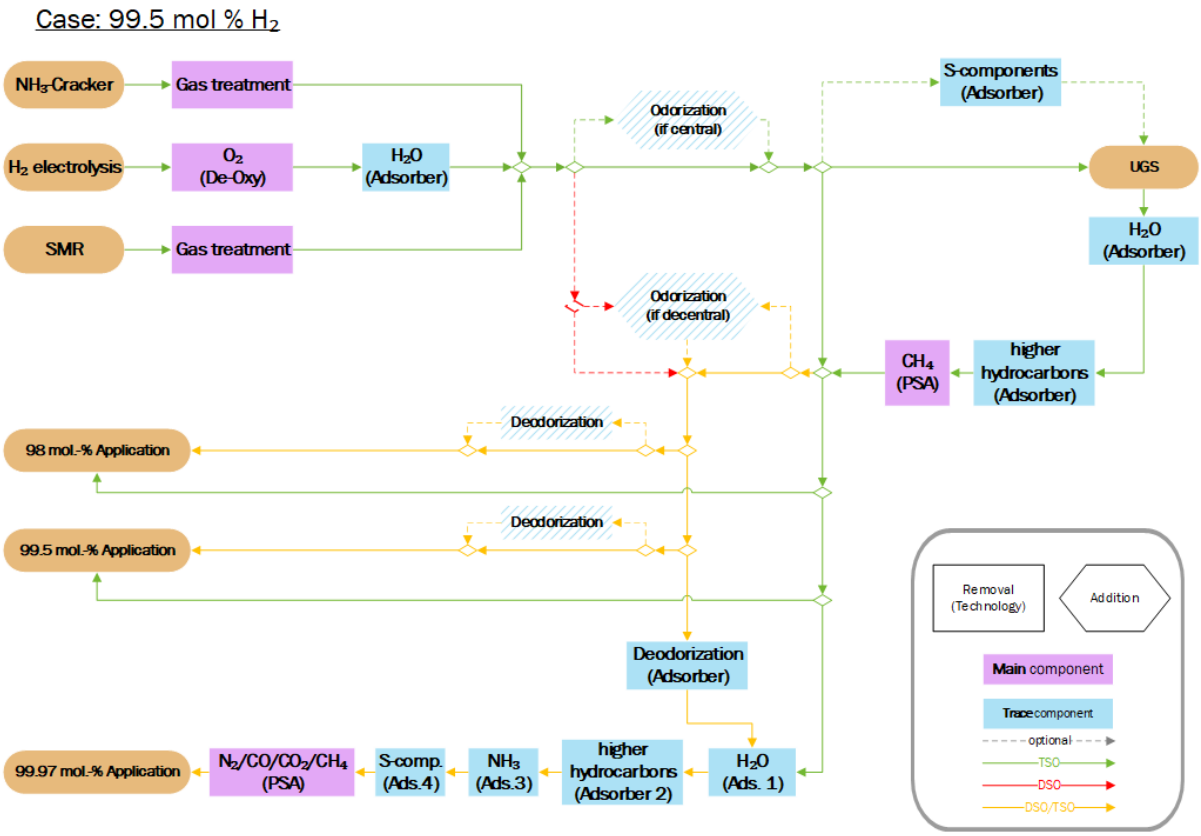

Figure 5-2: Gas purification steps in the 99.5 mol% grid hydrogen purity case (Source: DBI, own representation)

Case 3: Minimum hydrogen grid quality of 99.97 mol%

Hydrogen producers supply hydrogen of exceptionally high purity. However, during storage in underground gas reservoirs and transport through the gas network, the hydrogen becomes contaminated by various factors. The primary sources of contamination include water, microbiologically induced sulphur formation, and residues of oils that can originate from the operation of storage and network components.

This case represents the most technologically advanced process, achieving nearly complete hydrogen purity. The process builds on the steps described in Case 2 and expands them with additional adsorption stages (at injection points) to remove even trace impurities. Simultaneously, it addresses the optimization of purification strategies considering the quality at entry points and the origin of impurities from infrastructure.

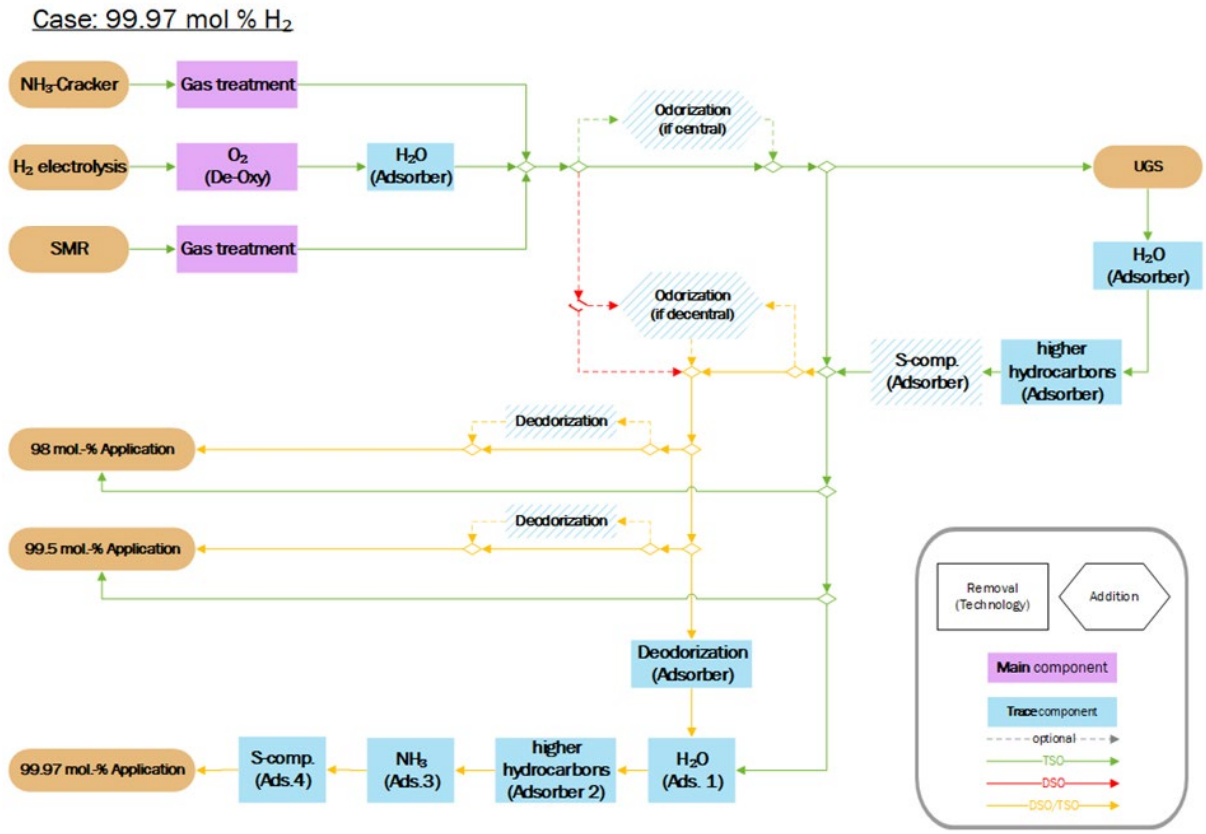

Figure 5-3: Gas purification points in the 99.95 mol% hydrogen grid purity case (Source: DBI, own representation)

Key characteristics and aspects are:

- Gas Treatment:
  - **Pressure Swing Adsorption (PSA)** remains a key step for removing N_2, CO, CO_2, and CH_4, establishing the basis for increased purity.
  - **NH_3 adsorption:** Ammonia is removed using specialized adsorbers, as even trace amounts can significantly impact hydrogen purity and quality.
  - **Higher hydrocarbons:** Specialized adsorbers eliminate longer-chain hydrocarbons, which could pose issues in applications requiring extremely high purity.
  - **H_2O adsorption:** A final dehydration step ensures the removal of residual moisture, achieving maximum purity.
- Solution Approach:
  - **Odorization:** Non-sulphur-containing substances can optionally be added to meet safety requirements without compromising high hydrogen quality.
  - **Deodorization:** This step is essential for applications requiring the highest purity standards, as no odorants can be tolerated.
- Application Areas:
  - **98 mol% Application**: A portion of the hydrogen stream can be diverted before the final purification stages to serve applications with moderate purity requirements.
  - **99.5 mol% Application**: Hydrogen after advanced PSA steps is suitable for applications with medium to high purity demands.

- **99.97 mol% Application**: Fully purified hydrogen meets the requirements of highly specialized applications, such as in the electronics industry, advanced fuel cells, or research and medical sectors.

As the share of high-purity hydrogen from electrolysis and improved infrastructure (cleaner grids and storages) increases, such adsorption stages could be centralized by grid operators or at UGS to reduce costs and complexity.

Regardless of future infrastructure developments, certain purification steps represent **"no-regret" investments**, as they are essential for ensuring hydrogen quality across the value chain. In particular, purification is always required after production, especially for SMR and ATR processes, where CO, CH_4, and sulphur compounds must be removed via PSA. Likewise, hydrogen transported through repurposed natural gas pipelines will inevitably require membrane separation or PSA to eliminate residual CH_4 and CO_2. The most critical purification needs arise after storage in porous underground formations, where contamination with CH_4, CO_2, and H_2S is unavoidable, necessitating a combination of PSA and cryogenic separation. These purification steps are indispensable for maintaining network compatibility, ensuring efficient end-use applications, and meeting regulatory standards, making them fundamental investments in any hydrogen infrastructure grid quality specified.

5.1.2. Cleaning and purification requirements along the hydrogen value chain

Throughout the entire hydrogen value chain, specific requirements for gas purification exist to meet the infrastructure quality standards.

In the **production phase**, primarily Pressure Swing Adsorption systems (PSA) or so-called de-oxo units are used. These technologies effectively remove impurities such as carbon monoxide (CO), carbon dioxide (CO_2), and oxygen. Another important method for removing sulphur compounds and hydrocarbons is adsorption, where impurities bind to a solid surface. This often involves the use of activated carbon or metal oxide adsorbents, which are particularly effective in removing hydrogen sulphide (H_2S) and other organic sulphur compounds. These processes are especially necessary during steam reforming (SMR) and ammonia splitting to protect the high sensitivity of catalysts in subsequent processes.

During **transportation**, especially when repurposed natural gas pipelines are used, cleaning measures are necessary to remove residues like methane and sulphur compounds that may have accumulated due to the prior use of the pipelines. Regular cleaning operations, such as pigging, are essential to ensure the purity of the transported hydrogen. Additionally, adsorption is often employed to eliminate residual sulphur traces in repurposed pipelines.

In **underground storage**, specific challenges arise as contact with water, methane, and sulphur compounds can deteriorate hydrogen quality. To counter these impurities, drying processes as well as PSA and adsorption technologies are required. Adsorption, in particular, is used to remove water and sulphur compounds like mercaptans, which can form through microbial processes in porous storage media. For instance, analyses of storage facilities in Germany and the USA show that using metal oxide adsorbents can increase purity to over 98 %, even when sulphur compounds were previously highly concentrated.

At the point of **end-use**, especially in PEM fuel cells, highly specific filter units are required. These systems target and remove critical impurities such as ammonia and sulphur compounds, which could impair the functionality and efficiency of the fuel cells. Adsorption plays a crucial role here, particularly in removing sulphur compounds, whose precise control is essential as concentrations below 0.004 µmol/mol can already impact catalyst performance.

A key aspect of cleaning requirements along the hydrogen value chain is the **potential use of existing purification technologies and assets** from the natural gas and hydrogen infrastructure. The following aspects may be considered in this regard:

- While established technologies such as amine scrubbing for CO_2 and H_2S removal and molecular sieves for dehydration are widely used in natural gas processing, the potential for their direct repurposing for hydrogen purification is often limited. Amine scrubbing is not optimized for hydrogen-specific processes, and molecular sieves would need to be adapted to the different gas compositions.
- In industrial hydrogen production, PSA (Pressure Swing Adsorption) systems are already used to remove CO, CO_2, CH_4, and N_2, as seen in SMR plants operated by Linde or Air Liquide. These technologies could theoretically be utilized in a future hydrogen infrastructure, but they are currently designed for localized high-purity hydrogen production rather than large-scale network purification. Membrane separation processes, which are applied in refineries and ammonia production, could also play a role in specific grid configurations but have not yet been established for large-scale hydrogen networks.
- The repurposing of existing purification systems at storage sites presents a particular challenge. Natural gas treatment facilities designed for CO_2 and H_2S removal would require fundamental modifications to effectively handle hydrogen-specific impurities. On the other hand, integrating existing PSA systems from industrial hydrogen production may be a more feasible option, provided they can be adjusted to the varying gas compositions at injection and withdrawal points. Consequently, directly reusing existing natural gas purification technologies for hydrogen is often possible only with significant adaptations.

Identifying the exact cleaning requirements along the hydrogen value chain requires a detailed technical and economic assessment to determine the most efficient solutions for large-scale purification in a future hydrogen network. The challenges associated with post-transport purification in repurposed gas pipelines and after storage in underground formations should be further investigated.

5.1.3. Cost assessment of cleaning processes and description of the cost framework

The developed cost framework for estimating purification costs along the hydrogen value chain is based on four central methodological approaches, which are described below:

1) Literature and market research
   The foundation of the framework is a comprehensive analysis of scientific publications, technical reports, and market studies. Additionally, price data from German suppliers over the past 15 years were evaluated to obtain practical data on capital expenditures (CapEx) and operational expenditures (OpEx). These sources provide a solid basis for reflecting the economic and technological framework in the European context. The results are summarised in Table 5-1.

2) Definition of the hydrogen supply chain
   The supply chain was divided into four main stages: production, processing, transportation and storage, and end-use. Each stage was analyzed in terms of its specific process requirements and cost drivers. For example, the production stage primarily includes electrolysis and steam reforming, while processing is dominated by technologies such as pressure swing adsorption (PSA) and membrane processes. This systematic structure allows for a targeted analysis of costs at each point in the value chain.

3) Identification of cost parameters
Relevant cost parameters were defined for each stage of the value chain. These include capital costs for infrastructure and equipment, operating costs such as energy and maintenance, and planning and approval costs. Additionally, risks and uncertainties caused by market volatility and regulatory changes were factored into the calculations.

4) Cost estimation model (Excel-based calculation)
Instead of a complex parametric system optimization model, a simplified Excel-based calculation was used to estimate the (specific) cost ranges (in €/kg hydrogen) based on the points outlined above. This calculation differentiates between various facility sizes due to the initialized data foundation, considers potential regional differences, and allows for the differentiation of technological options.

The advantage of this approach is that not only the hydrogen purity level is analysed, but also the required purification steps for the removal of other contaminants can be taken considered. Considering these wide set of parameters in an optimization model would have required the creation of extensive datasets, the implementation of advanced simulation methods, and detailed validation. This would have significantly exceeded the study's scope in terms of both available time and cost. Examples from other studies on finding the cost-optimal purity level from a system perspective show that these challenges require a reduction in complexity in terms of neglecting any contaminants.

In contrast, the Excel-based solution enables a pragmatic yet well-founded analysis of cost structures. It meets the study's requirements by providing an indicative evaluation of specific costs without disproportionately expanding the study's scope. This approach ensures that the study's results can be delivered without omitting essential insights.

5.2. Cost assessment of cleaning processes ("Inventory")

The costs for purification vary depending on the desired hydrogen purity level.

The transition from natural gas to hydrogen as an energy carrier requires a detailed evaluation of the existing and new infrastructure. This chapter analyses the technical characteristics of two grid configurations: an optimized best-case configuration, where newly developed grid components exclusively designed for hydrogen applications are utilized, and a worst-case configuration, where existing infrastructures, originally used for natural gas transport and storage, are repurposed for hydrogen. For both configurations it is assumed that peripheral components such as seals and valves are compatible with hydrogen.

By calculation the cost estimate for both grid configurations, a cost range is determined for each of the three quality cases described above.

5.2.1. Best-case cost estimation: new dedicated pipeline and salt cavern

Pipeline

In the best-case (=upper bound) configuration, the pipeline is specifically designed for hydrogen transport and is constructed from high-strength, hydrogen-resistant materials such as high-alloy steels or composite materials. These materials ensure high structural integrity and prevent hydrogen embrittlement. The pipeline is designed to operate at pressures of up to 100 bar and features smooth internal surfaces to minimize pressure losses and reduce energy requirements for transport.

State-of-the-art monitoring systems are integrated into the pipeline. These systems continuously measure operational parameters such as pressure, temperature, and flow rate. Sensors for leak detection and corrosion monitoring enable proactive maintenance and ensure high operational safety.

Underground storage

The underground storage in the best-case configuration is a purpose-built salt cavern for hydrogen storage. It is equipped with hydrogen-resistant coatings to minimize permeation losses. The design allows for operating pressures of up to 200 bar, ensuring a high storage capacity.

Comprehensive sensor technology is installed in the cavern to monitor real-time pressure, temperature, and gas concentrations. Automated control systems enable efficient loading and unloading processes and ensure a quick response to fluctuating demand.

Gas pipeline infrastructure

The transmission and distribution system is fully optimized for hydrogen. All connection points, including valves and compressors, are designed for maximum tightness and durability. Transport occurs with minimal losses, supported by redundant structures that ensure high infrastructure availability, even during maintenance activities.

5.2.2. Worst-case cost estimation: repurposed natural gas pipeline and storage

Pipeline

In the worst-case (lower bound) configuration, an existing pipeline, originally designed for natural gas transport, is utilized. The pipeline is constructed from materials capable of withstanding the mechanical stresses of hydrogen transport and is hydrogen compatible. However, its physical properties, such as internal surface roughness, are suboptimal, leading to higher pressure losses.

Although the pipeline is equipped with hydrogen-compatible seals and valves, modern monitoring and control systems are lacking. This limits the ability to continuously monitor the pipeline's operational condition, reducing efficiency and safety.

The age of the pipeline could significantly impact conversion costs. Older pipelines with material fatigue or residual contaminants may require more extensive refurbishments, whereas newer ones with advanced coatings could allow for a more cost-effective transition. Interestingly, contaminants in repurposed pipelines may diminish over time, though the exact duration of this process remains unclear.

Underground gas storage

The cavern was originally built for natural gas storage and later retrofitted for hydrogen use. While its basic structure meets pressure requirements, its previous use for natural gas storage means it is not optimized to minimize permeation losses.

Thanks to the installation of hydrogen-compatible seals and valves, basic safety standards are met. However, advanced sensor technology and control systems are absent, limiting operational monitoring. The lower cycle durability of the old structure further restricts the cavern's flexibility.

Gas pipeline infrastructure

The transmission and distribution system consists of existing connection points that have been adapted for hydrogen use. Peripheral components, such as valves and seals, are hydrogen compatible. However, the suboptimal design of the existing infrastructure results in higher pressure losses and reduced energy efficiency compared to the best-case configuration. The lack of redundancy in the system increases the risk of supply interruptions during maintenance or failures.

The technical analysis highlights that the best-case configuration ensures maximum efficiency and operational safety through infrastructure specifically developed for hydrogen. The new pipeline and cavern storage provide optimal conditions for low-loss transport and storage of hydrogen. In contrast, the worst-case configuration faces limitations due to the use of existing structures and the absence of

modern monitoring systems. Despite the retrofitting of hydrogen-compatible peripheral components, the operation remains less efficient and more prone to losses and disruptions.

5.2.3. Hydrogen purification costs

The estimation of hydrogen purification costs is based on feed-in hydrogen quality, the required output purity, and the configuration of the infrastructure used. The impact of these factors, as well as the differences between the best-case and worst-case configurations, are outlined below.

Table 5-1 below, derived from Chapter 5.1.3, summarizes findings from literature and market research regarding the costs of removing various impurities during hydrogen purification. The graphical representation of this data is shown in Figure 5-4. It categorizes these costs into capital expenditure (CapEx) and operating expenditure (OpEx), illustrating the variability in complexity and operational requirements across different purification processes.

Each contaminant—such as N_2, CO, CO_2, CH_4, H_2O, hydrocarbons (HC), sulphur compounds (S), odorants, O_2, and NH_3—has a specific cost range for CapEx and OpEx, highlighting the economic implications of their removal. The purification of oxygen (O_2) presents the highest costs (CapEx_max: 0.41 €/kg; OpEx_max: 0.92 €/kg), indicating the complexity and resource intensity of the process. In contrast, the removal of odorants and water (H_2O) shows significantly lower costs, reflecting the relative simplicity of these purification steps.

Table 5-1: Cost Overview for the Removal of Impurities in Hydrogen Processing

Components to be removed	CapEx_min / €/kg	CapEx_max / €/kg	OpEx_min / €/kg	OpEx_max / €/kg	Sum_min / €/kg	Sum_max / €/kg
N_2, CO, CO_2, CH_4 [1,4]	0.11	0.26	0.44	0.53	**0.56**	**0.79**
H_2O [2,4]	0.08	0.13	0.06	0.09	**0.14**	**0.22**
HC, S [3,4]	0.07	0.17	0.07	0.18	**0.14**	**0.35**
Odor [4]	0.05	0.13	0.05	0.12	**0.09**	**0.25**
O_2 [1]	0.21	0.41	0.57	0.92	**0.78**	**1.33**
NH_3 [1]	0.07	0.17	0.07	0.18	**0.14**	**0.35**

[1] *2008, Urban, W. et. Al., Technologien und Kosten der Biogasaufbereitung und Einspeisung in das Erdgasnetz. Ergebnisse der Markterhebung 2007-2008*
[2] *2022, Lubenau, U. et. Al., H_2-Rein - H_2-Kurzstudie: Wasserstoffqualität in einem gesamtdeutschen Wasserstoffnetz*
[3] *2024, Lubenau, U., BIOSTAR2c - Removing Technical Barriers to Biomethane Standardisation Phase 2c - WP5*
[4] Evaluation of DBI available offer

The OpEx values presented in the table include electricity costs, which are a significant factor in the operational expenses of hydrogen purification processes. However, the specific electricity price assumptions used in the referenced sources are not explicitly stated. As energy consumption varies depending on the purification method and system efficiency, the actual impact of electricity costs may differ across scenarios. This uncertainty highlights the need for sensitivity analyses, particularly when evaluating the economic viability of different hydrogen purification strategies.

These cost variations provide a valuable basis for assessing the economic feasibility of different purification strategies while ensuring compliance with hydrogen purity standards. Given the uncertainty surrounding the development of future hydrogen infrastructure, a comprehensive cost analysis must account for different potential grid configuration. The following chapter explores how assumptions regarding purification requirements, infrastructure configurations, and sensitivity analyses influence the overall economic outlook for hydrogen purification.

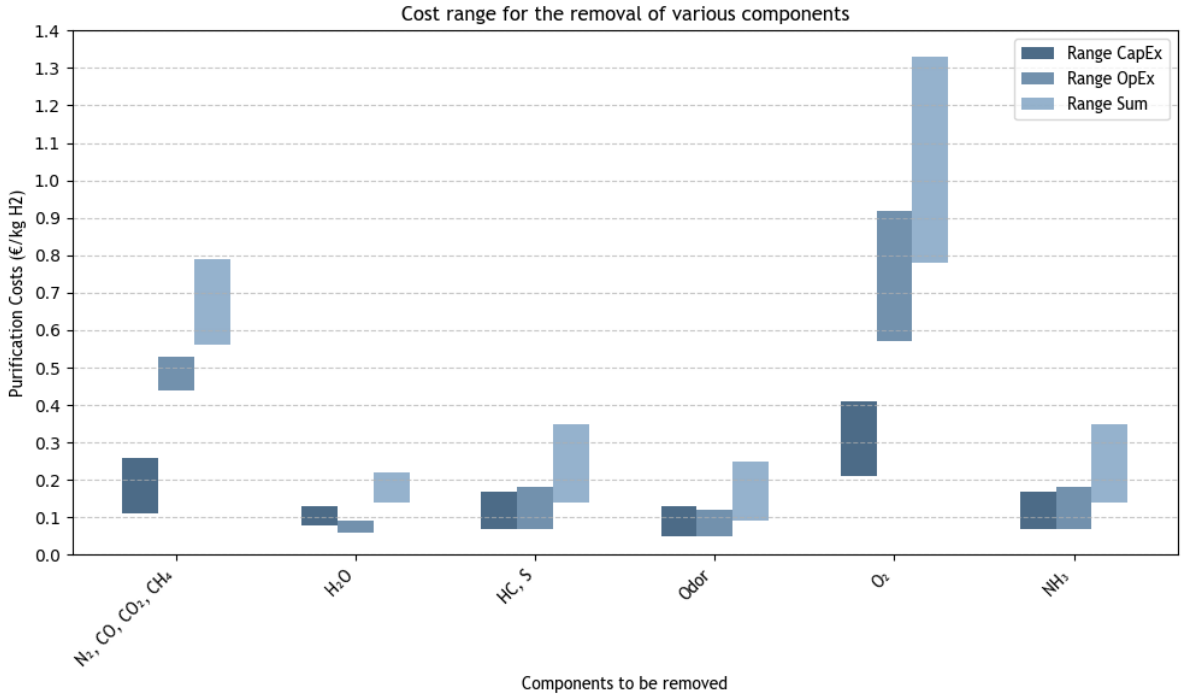

Figure 5-4: CapEx and OpEx ranges for the removal of specific gas components from hydrogen

The cost of hydrogen purification depends largely on the infrastructure used and the required purity level. Two contrasting grid configurations illustrate the possible cost ranges:

- In the **best-case configuration**, hydrogen purification is carried out in dedicated infrastructure, consisting of newly built pipelines and salt caverns optimized specifically for hydrogen. These systems minimize energy losses and enable efficient purification at relatively low costs. Despite increasing requirements for higher purity levels, the additional purification costs remain moderate as the entire value chain is designed for hydrogen.
- In the **worst-case configuration**, retrofitted natural gas infrastructure is used. Although seals and valves have been adapted, the suboptimal material properties of pipelines and storage facilities result in higher pressure losses and contamination, particularly due to storage in former natural gas reservoirs. This necessitates additional purification steps after withdrawal, significantly increasing costs for high-purity hydrogen.

The actual development of a future hydrogen infrastructure is difficult to predict, as it depends on regulatory, economic, and technical factors. Therefore, a reliable cost estimation can only be achieved through assumptions about potential infrastructure pathways and sensitivity analyses of individual cost components. The following chapter examines how different weightings of individual purification costs influence the overall economic viability of hydrogen supply.

5.2.4. Cost drivers and sensitivities for individual supply chain elements

The previous sections of this chapter have analyzed the costs associated with the purification and processing of hydrogen along the value chain. Two extreme grid configuration were considered: the best-case configuration, where a fully new infrastructure is implemented, including dedicated hydrogen pipelines, newly constructed cavern storage facilities, and an optimized distribution system for end-users, thereby minimizing the need for additional purification steps; and the worst-case configuration, where existing natural gas infrastructure is repurposed for hydrogen transport and storage, leading to increased purification efforts, potential quality losses, and higher operational costs.

In reality, the hydrogen infrastructure will likely develop somewhere between these two extremes. The actual costs will depend largely on how the infrastructure is composed. A central question is the extent to which new hydrogen pipelines will be constructed or existing natural gas pipelines will be repurposed. While new pipelines present a lower risk of contamination and allow for high hydrogen purity, repurposed pipelines are more cost-efficient but pose contamination risks from prior use, necessitating additional purification efforts.

Similarly, hydrogen storage involves different technical options with significant cost variations. Newly constructed cavern storage facilities provide high gas quality and are well-suited for hydrogen, whereas porous storage facilities, such as former natural gas reservoirs, can act as potential contamination sources and thus require additional gas processing/purification. The choice of storage technology affects not only hydrogen quality but also the associated operational costs across the entire value chain.

Another critical aspect is the distribution of hydrogen to end-users. Depending on the required purity levels for industrial applications, mobility, or energy production, additional purification steps may be necessary. Decentralized distribution models with on-site purification at end-user facilities may be more economically viable than centralized purification before network injection. At the same time, the question arises as to what extent contamination along the infrastructure can be controlled and selectively removed to avoid unnecessary processing costs for end-users.

To systematically evaluate these complex dependencies, a sensitivity analysis is performed. It examines the impact of infrastructure decisions—including pipeline selection, storage technology, and distribution concept—on the overall specific purification costs and identifies the key cost drivers along the supply chain. This analysis explores how different combinations of new and repurposed pipelines, various storage technologies, and centralized versus decentralized distribution concepts influence the economic viability of the hydrogen value chain.

The goal of this analysis is to enable a realistic cost estimation by quantifying the interactions between infrastructure components and identifying uncertainties in cost development. The results serve as a basis for informed investment decisions and strategic planning that takes into account both the economic and technical aspects of hydrogen infrastructure.

Impact of new pipeline share on purification costs

The following graph illustrates the relationship between the share of newly built hydrogen pipelines and the specific purification costs of hydrogen distribution. The x-axis represents the percentage of new pipelines, while the y-axis shows the resulting specific purification costs needed for hydrogen transport in euros per kilogram of hydrogen. A key factor in this analysis is the purity of the assumed hydrogen grid specification, represented in the legend by three different cases: (i) lower grid specifications with 98 mol% hydrogen purity, (ii) medium grid specification of 99.5 mol% hydrogen purity and (iii) high-purity hydrogen grid specification with 99.97 mol%.

The graph clearly shows that specific purification costs decrease as the share of new hydrogen pipelines increases. This effect is particularly pronounced for a high grid purity level of 99.97 mol%, as repurposed natural gas pipelines can be a potential source of contamination. In these cases, additional costly purification steps are required to ensure the necessary purity after transport, significantly increasing operational costs of the pipeline. In contrast to that, the cost difference for grid specifications of 98 and 99.5 mol% is limited, due to the lower purification efforts needed.

The key cost driver in this analysis, hence, are the technical and operational challenges in transporting hydrogen via repurposed natural gas pipelines. Existing pipelines often contain traces of moisture, hydrocarbons, and sulphur compounds, which dissolve in the gas stream and affect hydrogen purity. Particularly in case of high grid specifications, additional post-transport purification is necessary.

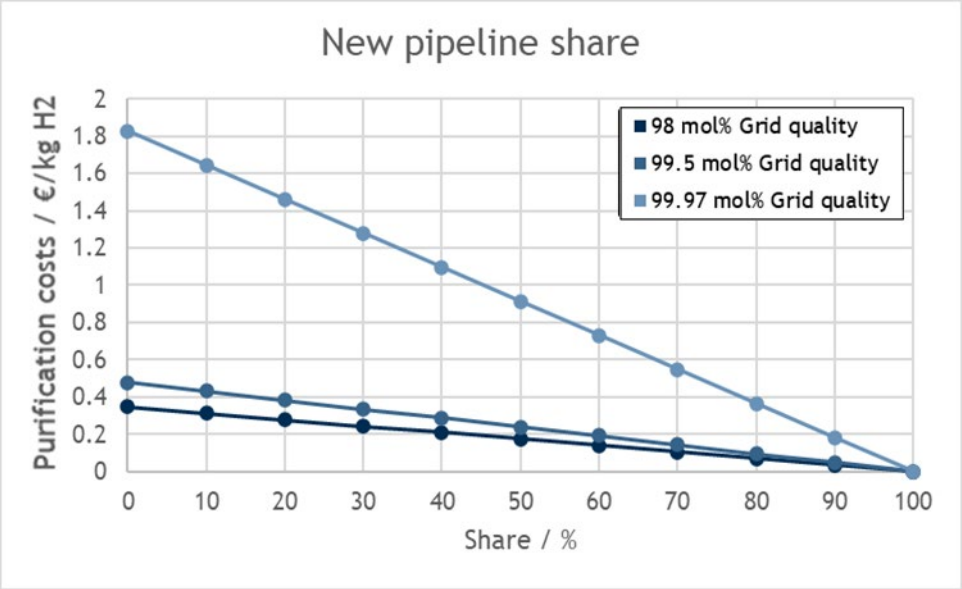

Figure 5-5: Relationship between the share of newly built hydrogen pipelines (x-axis) and the specific purification costs required for hydrogen transport at different hydrogen grid purity levels.

In addition to these purification costs, also **further costs** for hydrogen transport in repurposed pipeline need to be considered: older steel pipes are more susceptible to hydrogen embrittlement, increasing the need for regular inspections and maintenance. Compared to current natural gas use, also the fact of a lower density of hydrogen result in either higher operating pressures or larger volume flows that are required to transport the same energy content. This results in additional capital expenditures for compression and monitoring, which are reflected in operational costs of gas transport.

In contrast, new hydrogen pipelines are specifically designed for the transport of high-purity hydrogen and minimize the risk of contamination. Since no residues from previous usage are present, a significant portion of the necessary purification steps is eliminated. This explains why the specific purification costs decreases to zero as the share of new infrastructure assets in the grid reaches 100 %. This fact needs also to be taken into account, when comparing the overall infrastructure costs in both cases: While the initial capital costs for new pipelines are significantly higher than for repurposed pipelines, this difference is (at least partly) offset in the long run as the operational costs (driven also by purification efforts) need to be taken into account.

In summary, this sensitivity analysis demonstrates that the share of new hydrogen pipelines is a decisive cost factor for transport. The higher the share of new infrastructure, the lower specific purification costs and hence, the long-term operational costs. This effect is pronounced in the case of a high purity grid specification of 99.97 mol%. In the overall cost analysis, these savings must, however, also be weighed against the (significantly) higher initial investments required for new pipelines. A flexible infrastructure strategy that considers both economic and technical factors offers the greatest potential for a sustainable and cost-efficient hydrogen distribution system.

Impact of the share of new cavern storage on purification costs

The following graph (Figure 5-6) illustrates the relationship between the share of newly built cavern storage facilities and the purification costs at the hydrogen storage element within the supply chain. The x-axis represents the percentage of new cavern storage facilities (vs. the share of storage in porous reservoirs), while the y-axis indicates the resulting **specific purification costs** in euros per kilogram of hydrogen. The assumed overall grid specification significantly impacts the cost structure, as shown for the three different cases in the graph, representing the cases of 98 mol%, the 99.5 mol% and the 99.97 mol%, respectively.

The graph demonstrates that the specific purification costs tend to decrease slightly as the share of new cavern storage increases in the overall system and the share of storage in porous reservoir decreases. In summary, this effect is, however, less pronounced than for the pipeline infrastructure in the previous section. The reason for the decreasing trend is that salt cavern storage facilities generally have a lower tendency for contamination compared to porous storage, ensuring relatively high gas quality (this is in general also the case for repurposed salt caverns, after the methane has been removed from the storage reservoir). When hydrogen storage is mainly performed in porous media, in the contrary, additional purification steps become necessary. Although a similar trend can be observed for all grid quality levels, a difference of up to 0.5 €/kg can be observed between the 98 mol% and the 99.97 mol% case.

A key factor influencing this cost development is the interaction between storage technology and hydrogen quality. New cavern storage facilities are specifically designed for hydrogen storage and minimize the risk of contamination from residuals of prior use. In contrast, repurposed storage facilities, particularly former natural gas porous storage, may contain traces of hydrocarbons, moisture, and other gases that can mix with the hydrogen stream and necessitate additional purification. These effects are particularly relevant for high-purity hydrogen grid specifications, whereas for lower purity grid specifications, the impact resulting specific purification costs are lower.

The differences between the three cases indicate that hydrogen with a lower initial contamination level requires fewer additional purification efforts before reinjection. This suggests that the choice of storage technology plays a crucial role, especially for applications with stringent purity requirements.

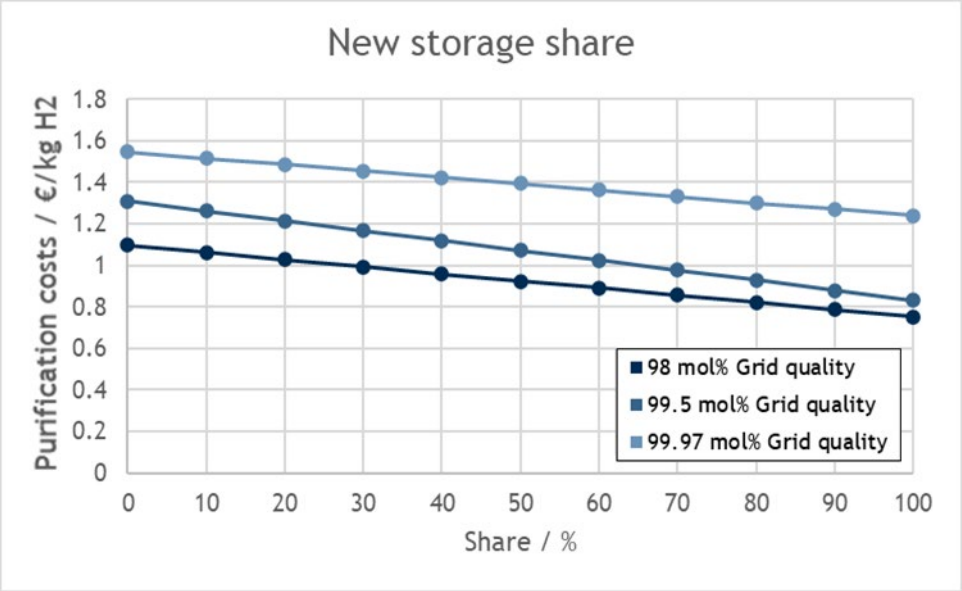

Figure 5-6: Relationship between the share of newly built salt caverns (x-axis) and the specific purification costs required for hydrogen storage at different hydrogen grid purity.

Another influencing factor on overall costs is the technical adaptation of existing storage facilities for hydrogen use. Repurposing requires structural modifications, such as the implementation of specialized sealing systems to minimize hydrogen losses due to permeation. Additionally, extensive flushing and purification procedures are necessary to remove contamination from previous storage operations. These additional measures increase operational costs (in addition to purification efforts described above), making repurposed storage facilities economically less attractive, particularly for high-purity applications. Hence, the overall economic evaluation suggests that while a high share of repurposed storage can reduce initial investment costs, it leads to increasing operational costs due to frequent purification and quality assurance efforts. A fully new cavern storage infrastructure minimizes long-term purification costs but requires significant upfront capital expenditures. In practice, a hybrid

strategy is emerging, in which new cavern storage is prioritized for high-purity applications, while repurposed storage is utilized for less demanding use cases.

In summary, this sensitivity analysis reveals that the share of new cavern storage is an important but less dominant cost driver compared to pipeline infrastructure. Also in the (hypothetical) scenario, where 100 % of storage facilities in operation are newly built salt caverns, the specific purification costs still will be considerable high (0.8-1.2 €/kg hydrogen). In this context it is, however, important to conder that only a minor share of the overall hydrogen transported in the gas grid will be injected into the storage (probably around 10-20 %). Hence, only a share of the costs described above will be added to the overall purification costs along the supply chain.

Impact of end-user requirements on purification costs

Hydrogen demand is distributed among various end-users, each with different requirements for gas purity. The following analysis focuses on specific end-users' group that requires a certain hydrogen quality (i) 98 mol%, (ii) 99.5 mol% and (iii) 99.97 mol%.

In each of the analyses, the focus is laid upon one end-user group, whose share in the overall market demand is varied from zero to 100 %. The demand of the other two end-user groups is then assumed to be equal to each other. This means, for example, that in a scenario where 50 % of the hydrogen demand by the group requiring a lower hydrogen quality (i.e. 98 mol%), the remaining 50 % is evenly split between the other two groups requiring 99.5 mol% and 99.97 mol%, resulting in 25 % of the overall demand, each.

This sensitivity analysis assesses how the distribution of hydrogen demand among end-users groups affects the specific purification costs per kilogram of hydrogen at the end-users site.

Variations in hydrogen demand: focus on the end-user group with 98 mol% purity requirements

In this first step, the role of the end-user group requiring a rather low hydrogen purity level of 98 mol% is increased and the impact on specific purification costs at end-users site (calculated over all end-user groups) is assessed. The data in Figure 5-7 show the specific purification costs over all end-user groups are the highest in case of a low grid quality specification (dark blue line). In contrast, in case a high grid specification of 99.97 mol% is chosen, no additional purification efforts are required for all end-user groups.

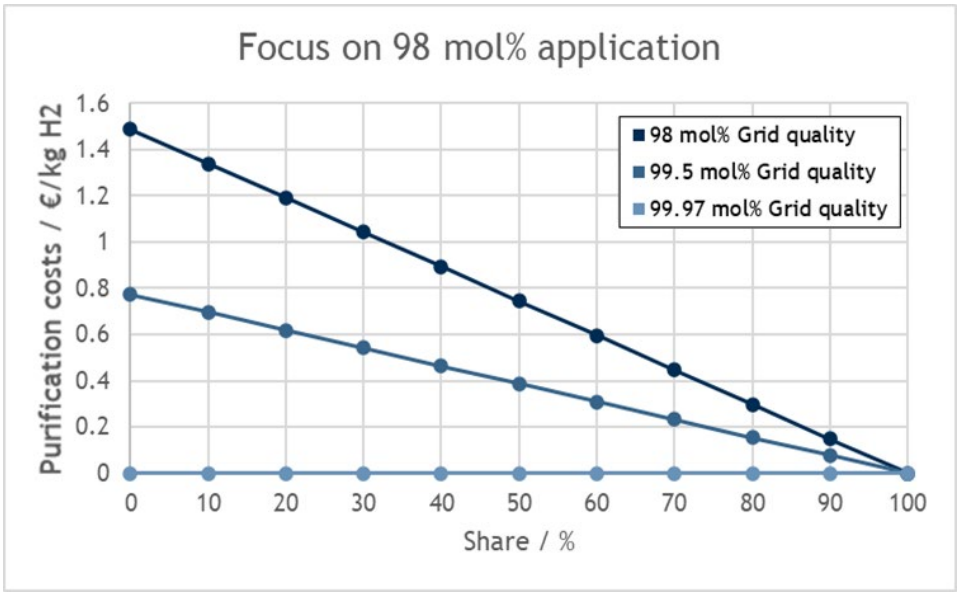

Figure 5-7: Specific purification costs at end-users' sites for varying demand composition. X-axis: variation in share of end-user group requiring 98 mol% hydrogen (with equal split among the other two end-user groups). The lines represent different cases of grid quality specifications.

In case, 50 % of all end-users require a hydrogen quality of 98 mol% and the other 50 % have higher quality requirements (i.e. 25 % require 99.5 mol% and 99.97 mol% each), the overall specific purification cost at end-users sites are around 0.75 €/kg (in case of a grid quality of 98 mol%), 0.40 €/kg (in case of a grid quality of 99.5 mol%) and 0.00 €/kg (in case of a grid quality of 99.97 mol%).

Variations in hydrogen demand: focus on the end-user group with 99.5 mol% purity requirements

In a second step, the role of the end-user group requiring a medium hydrogen purity level of 99.5 mol% is continuously increased and the impact on specific purification costs at end-users site (calculated over all end-user groups) is assessed. The data in Figure 5-8 show the specific purification costs over all end-user groups are the highest in case of a low grid quality specification (dark blue line).

In case, 50 % of all end-users require a hydrogen quality of 99.5 mol% and the other 50 % have other quality requirements (i.e. 25 % require 98 mol% and 99.97 mol% each), the overall specific purification cost at end-users sites are around 0.90 €/kg (in case of a grid quality of 98 mol%), 0.40 €/kg (in case of a grid quality of 99.5 mol%) and 0.00 €/kg (in case of a grid quality of 99.97 mol%).

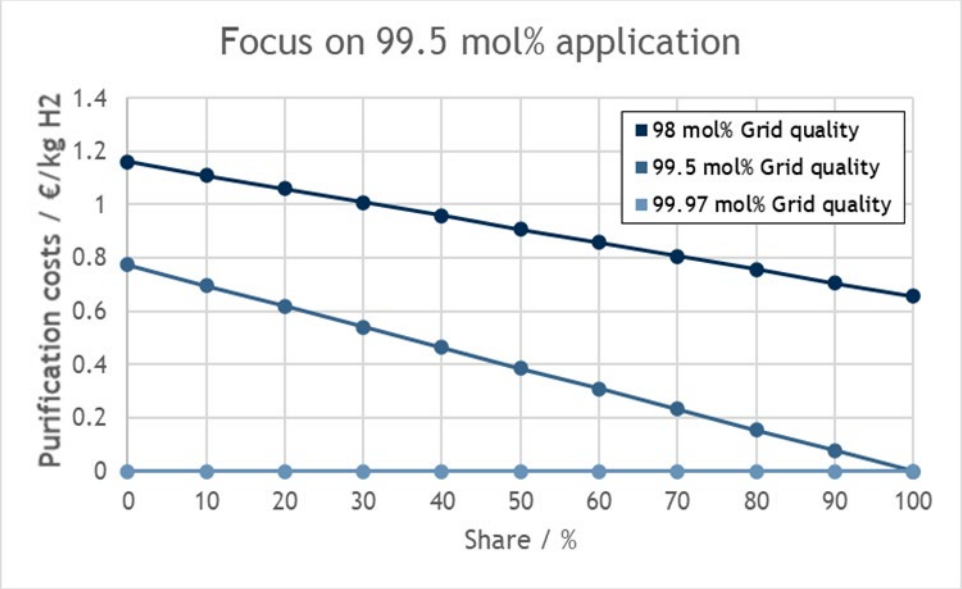

Figure 5-8: Specific purification costs at end-users' sites for varying demand composition. X-axis: variation in share of end-user group requiring 99.5 mol% hydrogen (with equal split among the other two end-user groups). The lines represent different cases of grid quality specifications.

Variations in hydrogen demand: focus on the end-user group with 99.97 mol% purity requirements

The third scenario focuses on end-users that require ultra-high-purity hydrogen at 99.97 mol% (e.g. fuel cell applications) Also here, the data in Figure 5-9 show the specific purification costs over all end-user groups are the highest in case of a low grid quality specification (dark blue line). However, in contrast to the other analysis, the costs significantly increase with a higher share of these sensitive customers in case the grid quality is lower that what this group requires, as additional purification steps are needed.

In case, 50 % of all end-users require a hydrogen quality of 99.97 mol% and the other 50 % have other quality requirements (i.e. 25 % require 98 mol% and 99.5 mol% each), the overall specific purification cost at end-users sites are around 1.30 €/kg (in case of a grid quality of 98 mol%), 0.80 €/kg (in case of a grid quality of 99.5 mol%) and 0.00 €/kg (in case of a grid quality of 99.97 mol%).

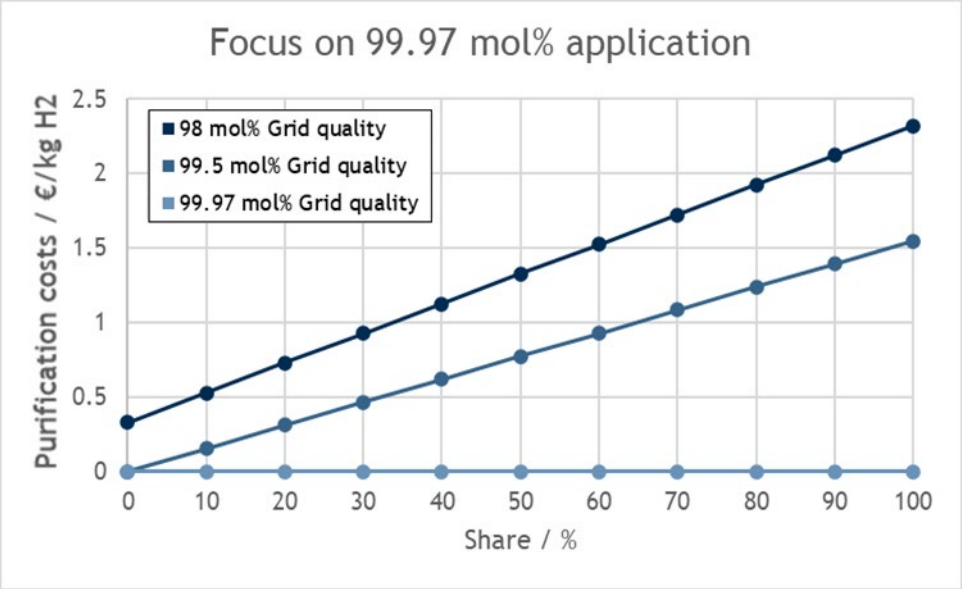

Figure 5-9: Specific purification costs at end-users' sites for varying demand composition. X-axis: variation in share of end-user group requiring 99.97 mol% hydrogen (with equal split among the other two end-user groups).

Comparison among the three cases:

Based on the calculations above, the specific hydrogen purification costs are compared for specific compositions of the end-user demand in Table 5-2 under the assumption of the different grid specifications. The results show that, from a purely end-user perspective, a high grid quality is advantageous. In contrast to that, a medium grid purity of 99.5 mol% could provide an interesting compromise between upstream (see sections above on pipeline and storage) and downstream purification efforts.

Table 5-2: Estimated specific purification costs over all end-user groups

Grid quality	Share end-user groups (98 / 99.5 / 99.97 mol% purity requirement) in %		
	50 %/25 %/25 %[1]	25 %/50 %/25 %	25 %/25 %/50 %
98 mol%	0.75 €/kg	0.90 €/kg	1.30 €/kg
99.5 mol%	0.40 €/kg	0.40 €/kg	0.80 €/kg
99.97 mol%	0.00 €/kg	0.00 €/kg	0.00 €/kg

[1] Meaning 50 % of end-users require hydrogen with a purity of at least 98 mol%, while 25 % require higher purity levels of at least 99.5 mol% and 99.97 mol%, respectively.

This analysis demonstrates that the distribution of hydrogen purity levels among end-users significantly affects overall specific purification costs at end-user sites. While a homogeneous distribution of purity levels generally leads to a balanced cost structure, extreme concentrations of either low or high purity result in inefficient cost distribution. This is particularly evident when there is a low hydrogen quality in the grid (dark blue lines) and the role of the end-user group requiring higher purities than 98 mol% becomes significant.

An optimal end-user mix should therefore take advantage of economies of scale in purification and ensure that the infrastructure is efficiently aligned with the required purity levels.

Overall Assessment of Cost Drivers and Sensitivities

The conducted sensitivity analysis clearly illustrates that the costs associated with hydrogen purification and distribution are primarily driven by infrastructure choices and specific end-user purity requirements. Three key factors were analyzed: the share of new hydrogen pipelines, the share of new cavern storage, and the distribution of hydrogen purity levels among end-users.

The analysis of pipeline infrastructure has shown that a high share of new hydrogen pipelines is the most cost-efficient solution in the long term, especially in scenarios with high purity requirements. While repurposing existing natural gas pipelines may reduce short-term investment costs, it leads to increased operational costs due to additional purification and technical constraints. This highlights the need for a balanced strategy, where new pipelines are preferred for high-purity applications, while selective repurposing of existing infrastructure remains economically viable for less demanding scenarios.

A similar trend is observed in the evaluation of storage infrastructure. New cavern storage offers advantages in terms of purity and long-term operational reliability but requires significant upfront capital investment. Repurposed porous storage may be a cost-effective alternative but necessitates additional measures to ensure hydrogen quality. The analysis has demonstrated that a higher share of new cavern storage is particularly necessary for high-purity applications, while a flexible mix of new and existing storage solutions is economically viable for applications with lower purity requirements.

The analysis of end-user purity requirements has revealed that the distribution of hydrogen purity levels significantly affects total costs. A balanced distribution of end-users with different purity requirements allows for better utilization of economies of scale in purification and distribution. In contrast, a strong focus on a single purity level results in either high costs due to additional purification or inefficient operational expenses when less pure hydrogen streams are integrated into an over-engineered high-purity infrastructure. Particularly critical are scenarios where a full focus on high-purity hydrogen is implemented, as this leads to excessive costs for applications that do not require such stringent purity levels.

Overall, the sensitivity analysis indicates that a differentiated infrastructure strategy is required to optimize the economic feasibility of hydrogen distribution. A combination of targeted new infrastructure investments and repurposed infrastructure offers the best balance between capital and operational expenditures. Additionally, the distribution of hydrogen purity levels should be aligned with existing infrastructure to leverage synergy effects in purification and distribution. The results of this analysis provide a solid foundation for strategic investment decisions and highlight the factors with the most significant influence on the long-term economic viability of the hydrogen value chain.

5.3. Scenario-based purification cost estimation for the hydrogen value chain

The conducted sensitivity analyses enable the definition of various scenarios for the hydrogen value chain and provide a structured cost estimation based on the identified relationships. The choice between new or repurposed pipelines, the decision to use cavern storage or porous storage, and the distribution of end-user requirements significantly impact the long-term economic viability of the hydrogen system. These parameters influence each other and must therefore be considered in a holistic approach to derive realistic cost forecasts for future hydrogen infrastructure.

Infrastructure represents one of the most critical factors affecting overall purification costs. New hydrogen pipelines ensure an uninterrupted transport flow with minimal contamination risk but come with high capital investment requirements. Repurposed natural gas pipelines may be economically advantageous in certain scenarios but pose risks due to residual contaminants, increasing the need for purification. The sensitivity analysis shows that an increasing share of new pipelines is particularly beneficial for high-purity applications, as it significantly reduces the costs associated with additional

purification and quality control. In scenarios with lower purity requirements or significant use of decentralized purification units, repurposed natural gas pipelines can be a viable option.

Storage technology choice is another major cost determinant. New cavern storage is technically optimized for hydrogen storage, providing long-term cost advantages while minimizing contamination risks. However, high initial investments are required, making them more suitable for scenarios with stringent purity requirements. Repurposed porous storage from former natural gas use is a more cost-effective alternative but requires continuous efforts to remove hydrocarbons and other contaminants, increasing purification efforts along the value chain. In scenarios with a balanced mix of end-users requiring both high-purity and lower-purity hydrogen, a combination of storage technologies can be an economically viable solution.

End-user structure is another decisive factor for the purification costs. Scenarios where a majority of end-users require hydrogen with a purity of 98 mol% benefit from lower purification efforts but may lead to increased overall costs when combined with high-purity applications that require downstream purification. A more balanced mix with a grid quality of 99.5 mol% purity proves to be an interesting solution in many scenarios with different demand composition. Scenarios with very high demand for 99.97 mol% purity, however, lead to disproportionately high purification costs in case the grid quality is lower than this value. In addition, the implementation of new pipelines and cavern storage may be required to limit overall purification efforts along the supply chain.

To further illustrate the practical application of the sensitivity analysis, the **following exemplary distribution of hydrogen across different infrastructure** components and end-use applications is considered ("reference scenario").

- 40 % of the hydrogen is transported via newly built pipelines, while 60 % flows through repurposed natural gas pipelines.[254]
- 90 % of the hydrogen is supplied directly to end-users, while 10 % is injected into underground storage facilities. These stored 10 %[255] are then equally split between new and repurposed storage infrastructures, with 5 % allocated to each.

The hydrogen distributed for direct end-use applications follows different purity requirements: 50 % is allocated to applications requiring a minimum purity of 98 mol% H_2, 25 % requires 99.5 mol% H_2, and 25 % must meet the highest standard of 99.97 mol% H_2.

For this specific example distribution, the resulting final specific purification costs along the overall supply chain are

- 1.05 €/kg in case of a grid quality of 98 mol% purity,
- 0.78 €/kg in case of a grid quality of 99.5 mol% purity and
- 1.24 €/kg in case of a grid quality of 99.97 mol% purity.

In order to interpret these numbers: these are the costs that need to be added for purification along the supply chain on top of the levelized cost of hydrogen production per kilo hydrogen. A grid quality of 99.5 mol% shows the lowest additional purification costs among the three qualities analysed here.

These costs already account for the entire value chain, including transport, storage, and necessary purification steps. The analysis highlights that both the use of existing infrastructure and the required purity level significantly impact the final purification costs. In particular, storage in repurposed facilities introduces additional purification requirements, leading to higher costs in these cases.

[254] *Based on assumptions of European Hydrogen Backbone for 2040, see https://ehb.eu/newsitem/european-hydrogen-backbone-grows-to-meet-repowereu-s-2030-hydrogen-targets.*

[255] *Based on assumption in Duda, U. (Uniper) (2024): Hydrogen purity Requirements – The SSO Perspective, Presentation at the ENTSOG Gas Quality Workshop, Brussels, 27. November 2024, Available at: https://www.entsog.eu/sites/default/files/2024-12/Presentations_GQWorkshop2024.pdf referring to an analysis by Guidehouse for Germany.*

On the basis of this cost calculation, it is possible to determine and compare the impact on purification costs when different demand volumes are considered for the three end-user groups. In each analysis described below, the share in overall demand of the largest end-user group is assumed to be 50 %, while the share for the other two groups is fixed to 25 %. This leads to the following distribution of hydrogen demand among end-users:

Table 5-3: Variation in demand distribution of different end-user groups for the following analysis

Minimum quality requirement of end-user group	Share in overall demand		
	"Focus on low quality"	*"Focus on medium quality"*	*"Focus on high quality"*
98 mol%	50 %	25 %	25 %
99.5 mol%	25 %	50 %	25 %
99.97 mol%	25 %	25 %	50 %

The effect of these variation in end-user demand shares on overall additional purification costs along the supply chain (i.e. transport, storage and end-users) is shown in Figure 5-10. On the x-axis, the three different scenarios are shown, where the focus of end-users' demand in either on the group with a low (98 mol%), medium (99.5 mol%), or high (99.97 mol%) minimum hydrogen purity requirements. The y-axis indicates the specific costs purification in euros per kilogram of hydrogen. The colours of the different bars represent the different grid qualities assumed for the overall grid, with dark blue representing 98 mol%, medium blue 99.5 mol%, and light blue 99.97 mol%.

These cost analysis shows that specific purification costs for different purity levels are strongly influenced by the chosen demand considerations and grid quality levels.

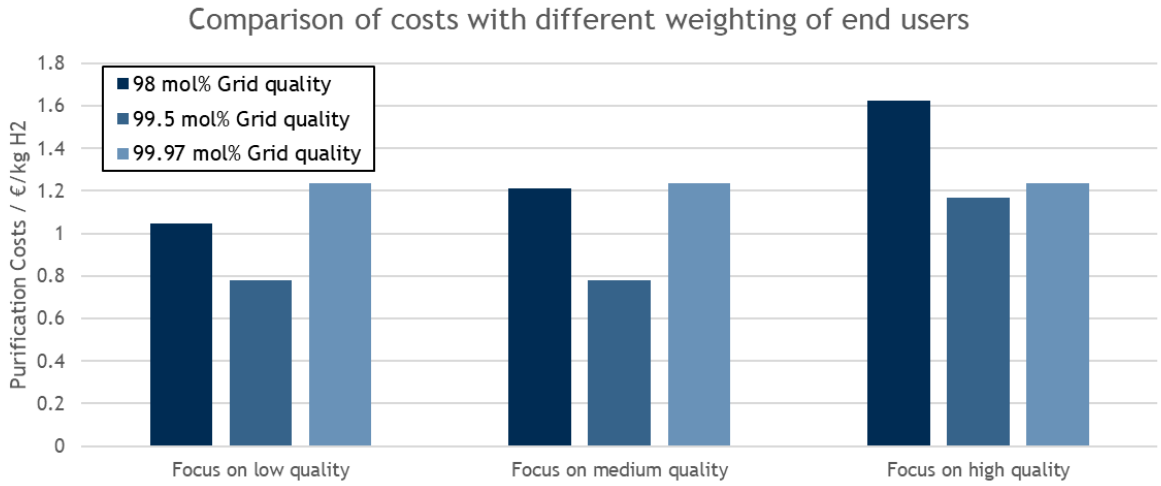

Figure 5-10: Comparison of overall purification costs along the supply chain (transport, storage and demand) under the assumptions of the reference scenario with variations in end-users' composition as indicated in Table 5-3.

The overall results of the cost analysis indicate that – independently of the assumed composition of end-users' demand – the lowest additional purification costs along the supply chain are observed for the cases with a grid quality of 99.5 mol% (medium blue bars). In addition, it can be observed that costs for this grid quality remain exemptional low (around 0.8 €/kg) for both scenarios with a focus on end-users with low and medium quality requirements. In contrast to that, for an assumed grid quality of 98 mol% (dark blue bars) purification costs significantly increase from 1.05 €/kg to up to 1.60 €/kg – when a significant share of end-users requires high hydrogen quality of above 99.97 mol% and, hence, need to implement additional on-site purification facilities. This cost even surpasses the additional

purification costs that are estimated, in case a grid quality of 99.97 mol% is assumed (around 1.24 €/kg (light blue bars). These costs are estimated to be the same – independent of end-users' composition – as no additional purification is assumed at end-users site – anyway.

For all these analyses it must be noted that the potentially required purification efforts at producers' side (i.e. before injection into the grid) are not considered here.

The results highlight that the identification of the most cost-efficient solution from a grid perspective strongly depend on the assumptions taken. For the reference scenario defined above, a grid quality of 99.5 mol% seems to represent a robust solution – representing the lowest additional purification costs along the supply chain for different distributions of end-user's demand. Whether this is also the case for different scenario set-ups need to be basis of further analysis.

This example calculation with the assumptions of the reference scenario, however, demonstrates how the sensitivity analysis in Chapter 5.2.4 can be applied to determine overall purification costs under various infrastructure configurations. By using this methodology, total costs for any given scenario regarding infrastructure configuration or end-users can be quantified, enabling an informed economic assessment of different hydrogen supply and utilization strategies. The ability to adjust infrastructure configurations and directly derive their impact on purification costs provides a valuable decision-making tool for planning future hydrogen networks.

The ability to model different scenarios is particularly relevant for investment decisions and policy measures aimed at promoting the hydrogen economy. The results of the sensitivity analyses in Chapter 5.2.4 indicate that a one-sided infrastructure strategy—either fully relying on new systems or exclusively repurposing existing infrastructure—is not the most economically viable long-term solution. Instead, a cost-effective hydrogen value chain requires a flexible combination of various technical and infrastructural elements that can be adapted to specific regional conditions and market demands. A scenario with a strategically balanced mix of new and repurposed pipelines, diverse storage technologies, and an optimized distribution of purity requirements allows for a sustainable hydrogen infrastructure with optimized investment and operational costs.

The conducted cost analyses in this chapter provide a solid foundation for such scenario modelling. By deriving cost functions for transport, storage, and purification, a rough estimation of total purification costs for any given hydrogen value chain scenario can be performed. This not only allows for economic evaluation of individual infrastructure decisions but also supports strategic planning for a long-term, sustainable, and adaptable hydrogen supply. The findings emphasize that investment decisions should not be made in isolation but rather in the context of the entire value chain, ensuring that economies of scale are utilized and cost-driving interactions between infrastructure elements are minimized.

5.4. Uncertainties and limitations in (purification) cost analysis for hydrogen processing plants

The cost analysis across the hydrogen supply chain reveals several uncertainties, encompassing both technical and economic aspects. These primarily concern storage technologies, purification technologies, contamination and operating conditions, as well as demand and infrastructure development.

Storage technologies

Storage technologies such as salt caverns and porous media are essential components of the hydrogen infrastructure but come with specific challenges:

- Salt caverns: contamination from brine, microbial activity, and higher hydrocarbons can compromise the purity of stored hydrogen. Additional post-treatment measures, such as Pressure

Swing Adsorption (PSA) or dehydration units, are required to ensure the desired purity levels. These factors strongly depend on environmental conditions such as temperature and salinity.

- Porous media: methane and sulphur contamination, caused by residual methane gases or microbiological processes, as well as fluctuations in gas composition during transitions from methane to hydrogen storage, necessitate the use of combined purification technologies. This leads to higher operating costs.

Purification technologies

Uncertainties in purification technologies mainly concern their efficiency, scalability, and operating costs:

- Technologies like PSA and Temperature Swing Adsorption (TSA) offer various advantages and disadvantages. While PSA is cost-effective and achieves purities of up to 99.5 %, it faces limitations at higher purity requirements. TSA, on the other hand, can achieve purities above 99.97 % but entails significantly higher energy costs.
- The efficiency of these technologies strongly depends on operating conditions such as pressure and temperature, as well as manufacturer-specific differences, creating uncertainties in cost estimation.

Contamination and operating conditions

The use of existing gas infrastructure carries the risk of contamination:

- Repurposed pipelines: residues from natural gas usage, such as methane and sulphur compounds, require additional cleaning steps. The timeline for the reduction of these contaminants is difficult to predict.
- Odorization: different sulphur compounds and their removal costs represent a central challenge. The lack of standardization within the EU further complicates planning.

Demand and infrastructure

The future development of hydrogen demand and infrastructure also presents uncertainties:

- The demand for high-purity hydrogen varies by sector and is highly dependent on applications in industry, mobility, and energy. Decentralized systems may become inefficient if demand for centralized solutions increases.
- The impact of economies of scale, such as mass production of purification technologies, on cost reduction has not yet been sufficiently studied.

Measures to minimize risks

To reduce the identified uncertainties, the following measures are recommended:

- Monitoring and research: continuous monitoring of the quality of storage and pipelines is essential to minimize long-term risks.
- Standardization: uniform purity requirements and odorization methods at the EU level can reduce planning uncertainties.
- Flexibility: scalable technologies that address both centralized and decentralized requirements offer potential to balance uncertainties in the market environment.

This chapter highlights the key uncertainties in the context of purification costs that may arise in hydrogen purification and distribution. It emphasizes the need for research, standardization, and innovative technologies to minimize costs and risks in the long term.

Centralized hydrogen processing plants offer economic benefits for large-scale supply through economies of scale and technologically diversified systems. In contrast, decentralized facilities provide flexibility and adaptability. A hybrid strategy could significantly improve the economic and ecological sustainability of the hydrogen value chain in Europe.

6. Summary & outlook

6.1. Conclusions and key learnings

The development of a future European-wide hydrogen gas network can be considered as pivotal element for the emerging hydrogen market – connecting a wide set of producers, storages and end-users, allowing barrier-free hydrogen trading and providing the physical infrastructure for hydrogen transport and storage. For this, commonly accepted gas quality specifications are required. In the light of the existing challenges and obstacles in cross-border trading in natural gas markets, the importance of harmonisation of hydrogen quality becomes evident. By introducing a common specification, a scattered hydrogen gas quality landscape among Member States can be prevented. The current point in time before large-scale hydrogen pipeline projects and national standards are being implemented offers a unique opportunity to enable and ensure a jointly coordinated approach and guidance for different stakeholders. A common hydrogen standard will ensure and facilitate cross-border trade of hydrogen gas as well as to increase the uniformity of end-user equipment design requirements across Europe.

The present study provides the technical background and assistance for ongoing standardization processes for hydrogen gas transport networks. This is done by presenting key literature findings, summarizing a wide set of stakeholder positions, expectations and opinions, as well as discussing cost estimations for specific, pre-defined hydrogen quality levels. By taking not only the hydrogen level but also a wide set of relevant contaminants into account, the study provides profound insights and guidance for further development of gas quality regulation and standardisation. In addition, the modular set-up of the purification cost analysis allows an individual analysis for each Member State and their potentially highly heterogeneous future hydrogen gas systems.

State-of-the-art – Interplay of gas quality with hydrogen supply chain elements

Harmonisation of future hydrogen gas quality requirements poses one major challenge on all market participants: it can always only be a compromise between the (additional) upstream purification requirements during production and transport / storage and the minimum downstream purity needs of different end-use applications that allows safe operation without any significant losses in lifetime or efficiency. In order to enable a fact-based analysis, this study provides an overview of existing knowledge and experience on these quality-related aspects.

Impact of supply and infrastructure on hydrogen quality

The technical impact of different key infrastructure elements along the hydrogen supply chain on hydrogen gas quality and possible contaminations identified based on the available literature are summarized in Chapter 3.1.1. These elements are

- hydrogen production: electrolysis and steam methane reforming (SMR)
- hydrogen import/conversion: ammonia cracking
- hydrogen transport: newly built hydrogen or repurposed natural gas pipelines
- hydrogen underground storage: salt caverns and porous media storage sites (e.g. aquifers and depleted gas fields, incl. compressors)

Depending on the technologies, achievable hydrogen purity levels as well as sources of key impurities and contaminants are described. Table 6-1 summarizes potential sources of different contaminants along the supply chain.

Table 6-1: Overview of main contaminants along key elements of the hydrogen supply chain

Supply chain elements	Potential sources	Potential Impurities / contaminants (in brackets: indication of probability[1])
Production	Electrolysis - AEL	Nitrogen (+), water (o), oxygen (o), cations (o), argon (-)
	Electrolysis – PEMEL	Nitrogen (o), water (o), oxygen (o), carbon dioxide (-)
	Steam reformation (SMR) + (PSA)	Carbon monoxide (++), nitrogen (+), methane (o), water (o), argon (o), formaldehyde (-)
Conversion	Ammonia cracking	Ammonia (+), nitrogen (+)
Transmission and Distribution	Converted natural gas pipelines	Typical associated gas components, trace odorants (sulphur), condensate components (+) (decreasing over time)
	Operations and maintenance (new and repurposed pipes)	Nitrogen (purging) (o), Lubricants / compressor oils (piston compressors) (o)
Underground storage	Salt caverns (new)	Water (+), methane (o), sulphur compounds (o), higher hydrocarbons (o)
	Porous media storage	Water (+), methane (++), sulphur compounds (+), higher hydrocarbons (+)
	Operations and maintenance	Lubricants / compressor oils (piston compressors) (o) Glycol (dehydration processes) (o)

[1] Assumed probability: (++) frequent, (+) possible, (o) rare, (-) very rare (based on terminology used in Bacquart 2018[256], adapted for transmission and storage elements based on qualitative analysis performed in this study). Note: probability indicative only.

In summary, the following conclusion can be drawn:

- After the first (common) drying step, **AEL** (alkaline electrolysis) and **PEMEL** (polymer electrolyte electrolysis) do not introduce contaminants to a level that would affect the use of hydrogen in various applications (i.e. for needs between 99.6 % - 99.95 %). With additional purification efforts, the oxygen (and nitrogen) traces can be reduced to enable the supply to highly sensitive customers (e.g. fuel cell or feedstock): with deoxo units (reaching >99.99 %) or even filtering via PSA (pressure swing adsorption; reaching >99.999 %).
- Other key production technologies like **steam methane reforming** as well as **ammonia cracking** require post-purification to inject hydrogen into grids with specifications above 98 % hydrogen content. High purification efforts via PSA are required to achieve very high hydrogen purity levels (e.g. >99.97 % for fuel cell application) and remove probable contaminants (e.g. carbon monoxide, ammonia and nitrogen). For ammonia, the many reformer and filter technologies are still under development and, hence, these are subject to higher uncertainties (esp. for ammonia crackers).
- In general, gas transport via **pipelines** itself is not considered as a critical element from a perspective of contamination as significant experience with industrial hydrogen pipeline networks with specifications of >99.5 % exist. **Repurposed pipelines,** however, have the disadvantage that – at least during a transition phase – different contaminations from the former use for natural gas transport can be introduced into the hydrogen stream. Accordingly, intensive cleaning and purging procedures are needed for repurposing – however, it will not be possible to remove all potential sources for contamination. Within a highly interconnected grid with several feed-in facilities, prevention of contamination will be more difficult compared to industrial point-to-point pipelines. In total, achieving quality grades > 98 % hydrogen should be possible. For higher hydrogen purities, the use of **new pipelines** is clearly advantageous.

[256] *Bacquart, T. (2018): Probability of occurrence of ISO 14687-2 contaminants in hydrogen: Principles and examples from steam methane reforming and electrolysis (water and chlor-alkali) production processes model. International Journal of Hydrogen Energy, Volume 43, Issue 26, Pages 11872-11883, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2018.03.084.*

- The situation is more complex for **underground hydrogen storage**. Existing salt cavern storage sites in the UK and US only guarantee a minimum hydrogen level of 95 %. Contaminations from brine, natural gas residues in the reservoir / cushion gas as well as a range of possible microbiological reaction under extreme conditions in the storage facility may add different contaminants to the stored hydrogen gas. The risks for contaminations can be considered highly site-specific. In any case, pre- and post-treatment of hydrogen gas will be required to ensure injection of a stable quality back into the grid. Achieving hydrogen quality levels of 98 % is considered feasible for most storage sites, although purification efforts to separate hydrogen from natural gas may be significant after repurposing or in case of depleted gas fields. For higher qualities, industry experience is still rare. Therefore, hydrogen underground storage can be considered as an important bottleneck for a higher hydrogen quality from an overall system perspective.

In summary, the literature provides an overview of a wide range of possible contaminants, potentially introduced at the different stages along the supply chain. Repurposed pipelines and certain underground storage sites (e.g. depleted gas fields) may be considered as key bottlenecks which require high purification efforts in case of high grid qualities significantly above 99 %.

End-users' quality requirements

In addition, the purity requirements and the effect of different contaminants on **end-use sectors** are described in chapter 3.1.2. Arriving at general conclusions regarding the different sectors and applications are difficult, due to the large number of possible applications. The international standard ISO/DIS 14687:2024 (E)[257] already provides a solid database and definition of a wide range of hydrogen quality specifications – each defined for specific end-uses.

Table 6-2 summarises key learnings on the tolerance of different end-user sectors and applications on relevant hydrogen specifications.

Table 6-2: Quality requirements of different application without further on-site purification

Quality requirements by sector / application		≥ 98 mol% H_2 = "low" quality	≥ 99 mol% H_2 = "medium" quality	≥ 99.97 mol% H_2 = "high" quality
Building (low temperature heat)		(✓)	(✓)	✓
Energy / power generation		(✓)**	(✓)**	✓
Mobility	ICE	✓	✓	✓
	PEM FC	Not suitable	Not suitable	✓
PtX		Not suitable	✓	✓
Industry (examples)	Construction aggregates (Stones and soils)	✓	✓	✓
	Paper	✓	✓	✓
	Glass and ceramic	✓**	✓**	✓
	Iron and steel	✓*	✓*	✓
	(Petro-) chemistry (feedstock / non-energy use)	Not suitable	✓*	✓

Source: Adapted based on DBI GUT & Frontier (2022)[258]. Low- and high-quality specifications referring to DVGW G260 Group A & D.

Please note: parathesis ( ) indicate that suitability depends on type of use or specific contaminant / trace component
*Dependent on the composition of trace components.
**Dependent on stability of the Wobbe index over time.

[257] *Final version not published at time of witing (end of 2024).*
[258] *DBI GUT & Frontier Economics (2022): H2 Rein - H_2 short study: Hydrogen quality in an all-German hydrogen network, https://www.dvgw.de/medien/dvgw/forschung/berichte/g202140-finalreport-h2shortstudy-engl.pdf*

Due to high technological readiness, there is a good understanding of the impact of different contaminants on **fuel cell mobility applications** using PEM technology. Grade D (≥ 99.97 mol%) is considered as the minimum hydrogen concentration. With regard to the criticality, carbon monoxide, hydrogen sulphide and ammonia impurities are typically seen as the contaminants with the largest negative effect on PEM fuel cell performance.

In contrast to that, **combustion processes** for energy use are mostly seen as not critical with regard to the composition of the gas. In those cases, it is more important that burning properties (Wobbe index and heating value) of the fuel gas do not fluctuate too much. Certain industries, where product properties may directly be impacted by flame properties (e.g. temperature and flame speed), may show stricter quality requirements, as is the case for e.g. the glass industry.

Sectors, where hydrogen is used as a **feedstock** (today or in the future) show very case-specific quality requirements, both regarding the hydrogen purity and the tolerated level and type of contaminants. Due to possible poisoning of process catalysts, very high qualities of up to 99,97 % or even higher seem to be most desirable, as this also limits the possibility for potentially critical contaminants.

Existing standardization landscape and developments in selected Member States

A comprehensive set of different standard documents, technical rules and/or other harmonisation activities already exist aiming to specify common requirements for admissible (minimum) hydrogen purity levels as well as (maximum) concentrations of key contaminants. These documents in general focus on certain infrastructure elements (e.g. pipeline transport) or end-use specifications (see Chapter 3.2). An overview of key documents including a short explanation is presented in Table 6-3..

Table 6-3: Overview relevant hydrogen quality standards, technical rules and further harmonisation activities in Europe

	Standard	Name	Scope	Comment
Transport / Pipeline	CEN/TS 17977:2023 **(2023)**	Gas infrastructure - Quality of gas - Hydrogen used in rededicated gas systems	H_2 pipelines (rededicated NG pipelines)	H_2 quality: **≥98.0%**, Wobbe Index: 42-46 MJ/m³ (15 °C/15 °C) Note: different specifications compared to ISO 14687 Grade A
	EASEE-gas: Common Business Practice 2022 – 001/01 (CBP) **(2022)**	Hydrogen Quality Specification	H_2 pipelines (rededicated NG pipelines)	**≥98.0%** (reference to ISO1467:2019 Grade A, Specification of critical components only) Note: on-site purification for O_2 or sulphur components.
	DVGW G260:2021 (DE) **(2021)**	Technical Rule on gas quality ("Gasbeschaffenheit")	H_2 pipelines (for gases in public infrastructure in Germany)	Gas family 5, group A with **≥98.0%** and group D with **≥99.97%** (reference to EN 17124:2019) Currently under revision to (possibly) include **99.5% (tbc)** as additional "grade" "group A+"
	Fluxys Hydrogen specification proposal (BE) **(2022)**	Hydrogen Specification Proposal	H_2 pipelines (transmission system by Fluxys Belgium)	H_2 quality: **≥98.0%** Aligned with EASEE-Gas (CBP H2), CEN, specifications for UK, NL and DE, + further stakeholder input
	Indicative quality specification for Hynetwork (NL) **(2024)**	Indicative quality and temperature specification for Hydrogen Network Netherland	H_2 pipelines (for Hydrogen Network Netherland)	H_2: **≥99.5%**, indicative only, based on results of DNV/KIWA studies, final decision by Ministry open Note: Former version (2022) with 98%.
End-use	ISO/DIS 14687:2024 (E) **(2024)**	Hydrogen fuel quality — Product specification	End-uses (different)	Different Grades (A-F) for state of hydrogen and end-use **≥98.0% (Grade A) – ≥99.995% (Grade C)**
	EN 17124:2022 **(2022)**	Hydrogen fuel - Product specification and quality assurance for hydrogen refuelling points dispensing gaseous hydrogen - (PEM) fuel cell applications for vehicles	PEM fuel cell (vehicles)	H_2 quality: **≥99.97%** Fuel quality requirements at the dispenser nozzle + risk assessment / probability of occurrence + severity class, impact on fuel cell at certain concentrations

The present analysis also screens ongoing activities in selected Member States. The results highlight Belgium, the Netherlands and Germany as those Member States that can be considered as so-called "front runners" in terms of discussions about hydrogen quality definitions and requirements. These countries also show a high level of natural gas use, strongly developed existing natural gas infrastructure and ambitious plans for future deployment of hydrogen networks. From these countries, the transmission system operators (TSOs) as important stakeholders also are (among others) promoting a uniform hydrogen standard of >99.5 mol % purity level.

The country analysis for twelve selected Member States can be summarized as follows:

- Austria also supports 99.5 % and domestic H_2 quality standards: Whilst not being at the forefront of the Member States and TSOs advocating for 99.5 %, Austria can be seen as supporter. The country is generally quite active in the planning of H_2 infrastructure.
- Belgium was the first country that assigned an HTNO (Fluxys). Fluxys is part of a coalition of TSOs that push for a purity level of 99.5 %.
- Finland aims at position itself as a leader of the hydrogen economy but there is a contradiction between activities for the planning of a H_2 infrastructure plans and a lack of initiatives for regulating H_2 quality.
- France has no hydrogen purity regulation in place, with discussions focusing on industrial hubs and domestic hydrogen production, at least in the short-term, where pipelines will serve more to connect users within these hubs; imported H_2 should be blended in existing gas pipelines. There is no publicly-available information on ongoing discussions on H_2 quality.
- Germany has very ambitious plans and a strategy to establish a hydrogen 9,700 km core grid by 2032. The country is currently reviewing its existing H_2 standards for 98 % (most applications) and 99.97 % (PEMFC) with the discussion to establish a 99.5 % purity standard for networks.
- The Netherlands is moving towards a minimum hydrogen purity standard of 99.5 % for its national transmission network, reflecting stakeholder preferences and feasibility studies.
- Other countries: There is an ongoing discussion on H_2 quality level in Denmark (between 98 and 99.5 mol %). In contrast to that, no advanced discussions among hydrogen quality are identified for Czech Republic, Italy, Spain, Sweden, and Poland, yet.

Key insights from stakeholder engagement

This study also collects and analyses the opinion and perspectives of stakeholders on quality levels in the EU hydrogen infrastructure (Chapter 4). Central stakeholders were identified and approached through questionnaires, interviews or in workshops. Over 50 stakeholders were included in the review. Care was taken to include as much regional variation as possible, and to include both hydrogen-specific and stakeholders from the traditional energy and gas sector.

The main overarching learnings and results are:

- Expectations on the future hydrogen market and volumes with relation to production, end-use and supply and demand: stakeholders are generally in agreement on how the future hydrogen market will look in terms of production and end-use. The initial supply will be composed of low-carbon hydrogen and imports whilst the production of renewable hydrogen ramps up and initial demand will be for use as feedstock and in the steel industry.

- Rationale for desired purity levels: The main drivers towards high purity levels are production quality, technical feasibility in networks, studies which show that 99.5 % is the optimum in terms of purification cost, and proposed hydrogen pricing methods. The main drivers towards lower purity are the high cost of gas storage in porous media and the belief that the majority of end-users will not require high-quality hydrogen.

- Key issues for end-users: requirements for stringent contaminant limits on substances that can poison catalysts in industrial processes and fuel cells. End-users are less focused on the purity level and more on the beforementioned contaminants and the stability of the purity level.

- Concerns of storage operators: regarding hydrogen quality and how this affects end-use stakeholders: Storage operators believe that purification systems required at storage sites in case of high transmission system purity levels will make storage operation uneconomical.

- An overview is provided of stakeholder statements on their desired contaminant limits and, where mentioned, their technical rationale behind these requirements.

- Transmission operators' concerns: metering and equations of state, SEVESO III and odorants were mentioned.

Based on the above issues, relevant recommendations are made for changes to existing and proposed standards based on stakeholder inputs. Furthermore, three exemplary specifications are made: a 98 % purity level in the backbone (mainly beneficial to storage operators), a 99.5 % specification (as proposed by some transmission operators), and a 99.97 % purity level (which benefits end-users most).

Table 6-4: Example specifications for all three purity grid level ("cases") based on stakeholder input. Existing standards were used as reference to allow to show the changes made.

Property H_2	Purity Level Case >98 %	>99.5 %	>99.97 %	Notes
Wobbe Index	41.89– 45.89 MJ/m³, (15 °C/15 °C)	43.45-45.89 MJ/m³, (15 °C/15 °C)	n/a	The 98 % specifications require a lower limit to the Wobbe index to prevent significant variation. Lower calorific value must be used.
ΔWobbe index	<0.5 MJ/m³minute		n/a	Derived from turbine and burner end-users. Change limits are unlikely to be exceeded at very high quality.
Water	<250 ppm at <10 bar <60 ppm at >10 bar		<5 ppm	Aligned with ISO standards and DVGW G260.
Water Dewpoint	<-8 °C at 70 bar			Aligned with HNS specification.
Hydrocarbons	<20,000 ppm	<5,000 ppm	< 2 ppm	Aligned with ISO standards and DVGW G260. Expected to be mostly methane.
Oxygen	<10 ppm			A higher oxygen level is preferred by some stakeholders for 98/99.5 % quality, however, stakeholders from the feedstock industry and storages want to limit oxygen as much as possible.
CO and CO_2	<40 ppm (20 ppm each)		<2 ppm (total)	CO and CO_2 levels are limited for the 98 % scenario for gas storage and to reduce Wobbe index fluctuations. At higher quality the specification is aligned with ISO standards.
Ammonia	<10 ppm		<0.1 ppm	Aligned with HNS specification, industrial specification provided by a stakeholder. and DVWG G260.
Inert Gases	<20,000 ppm	<5,000 ppm	< 300 ppm	He + Ar + N_2. Although some stakeholders want to reduce fuel-bound nitrogen, nitrogen is notoriously difficult to remove using PSA, and relatively inert for other end-uses. Therefore, limits are aligned with ISO standards and DVGW G260 and will be mostly limited by the Wobbe requirements.
Halogenated Compounds	<0.05 ppm			Aligned with ISO standards.
Dust and Particulates	<1 mg/kg			Common particulate limit among standards, combined with size limit of stakeholders.
Total Sulphur	<7 ppm	<3 ppm	<0.05 ppm	Derived from ISO, HNS and G260 respectively. This specification might have to be changed after the odorization practice has been agreed upon.
Formaldehyde	<10 ppm		<0.01 ppm	Derived from HNS and G260 respectively. Can be harmful to end-users. 99.97 % limit is aligned with industrial specification provided by a stakeholder.
Formic acid	<0.2 ppm			Limit is aligned with industrial specification provided by a stakeholder.
Hydroxides (KOH, NaOH)	<2 ppm			Derived from end-user stakeholder input. These contaminants can be released by alkaline electrolysis and can be harmful to end-users.

Conclusions on purification cost analysis

The final element of this study is a cost analysis that goes beyond the purely qualitative discussion of different quality levels and assess the economic impact hydrogen purification has in case of different grid specifications (i.e. 98 %, 99.5 % and 99.97 %) and for different configurations of the gas infrastructure (e.g. role of new vs. repurposed pipelines). The aim is to identify the main cost drivers,

highlight specific purification cost optimisation potential and derive strategic recommendations that contribute to the realisation of a cost-efficient hydrogen network.

The analysis focusses on the comparison of the **three pre-defined grid quality purity levels ("cases")**:

4) 98 % - particularly suitable for combustion processes with lower quality needs.
5) 99.5 % - suitable for many industrial applications and suitable for most end-use applications.
6) 99.97 % - required for sensitive applications such as fuel cells or certain chemical processes.

The methodological approach is based on four key steps: (1) literature and market research, (2) definition of the hydrogen supply chain and grid configurations, (3) identification of purification cost parameters, and (4) calculation of purification costs at individual supply chain steps and along the overall supply chain. The assessment is thus based on a combination of literature research, market data and own calculations. **By introducing a modular approach** – the tool provides the basis for future analysis taking different potential developments of the future hydrogen market as well as potential differences between national hydrogen grids into account.

As a basis for the analysis **purification steps and suitable technologies** are first described for the different elements of the supply chain. A differentiation between TSO and DSO systems as well as the role of odorization is taken into account. Purification efforts and costs for removal of specific contaminants (e.g., N_2, CO, CO_2, CH_4, H_2O, sulphur compounds, O_2, NH_3) are summarised in an "inventory". The analysis highlights that the choice of purification strategy is crucial for the overall economic efficiency of the system. While upstream purification directly after production can reduce downstream treatment efforts, it is associated with higher costs, particularly if strict purity requirements must already be met at the source. Downstream purification, for example at end-users' site after transport and storage, offers greater grid flexibility but results in additional energy consumption and increased operational costs.

Another decisive factor is the **choice of purification technology**. Pressure swing adsorption (PSA) is currently the most widely used method for removing impurities such as CO, CO_2, and CH_4 but has technical and economic limitations for very high purity requirements. Membrane separation is a cost-effective alternative for moderate purification levels but is insufficient for achieving the highest purity standards. Cryogenic separation allows for the nearly complete removal of unwanted components but comes with significant energy requirements and operational costs. The analysis also highlights that combinations of multiple technologies, such as membrane separation with PSA or temperature swing adsorption, can be particularly efficient in certain scenarios.

Regardless of future infrastructure developments, certain purification steps represent **"no-regret" investments**, as they are essential for ensuring hydrogen quality across the value chain. In particular, purification is always required after production, especially for SMR and ATR processes, where CO, CH_4, and sulphur compounds must be removed via PSA. Likewise, hydrogen transported through repurposed natural gas pipelines will inevitably require membrane separation or PSA to eliminate residual CH_4 and CO_2. The most critical purification needs arise after storage in porous underground formations, where contamination with CH_4, CO_2, and H_2S is unavoidable, necessitating a combination of PSA and cryogenic separation. These purification steps are indispensable for maintaining network compatibility, ensuring efficient end-use applications, and meeting regulatory standards, making them fundamental investments in any hydrogen infrastructure scenario.

An additional key aspect of cleaning requirements along the hydrogen value chain is the **(potential) use of existing purification technologies and assets** from the natural gas and hydrogen infrastructure. Based on the available knowledge, however, this can be considered as a complex challenge. Examples are existing amine scrubbing (for CO_2 and H_2S removal) or molecular sieves (for dehydration) facilities that would require significant adaptation for the use of hydrogen. Also, for existing PSA and membrane solutions, a thorough technical and economic assessment would be required before considering them as possible assets in a future hydrogen infrastructure.

The cost data is presented as **specific purification costs in € per kg hydrogen** that would be needed at each element in the supply chain. Two extreme configurations of the infrastructure setting are discussed qualitatively and quantitatively. In the best-case configuration, an infrastructure specially designed for hydrogen is considered. This uses modern materials, advanced monitoring systems and optimised processes, resulting in low overall pipeline cleaning costs. In the worst-case configuration, on the other hand, existing natural gas infrastructures are repurposed. This conversion requires extensive retrofitting and leads to higher purification costs.

In a first step, a **sensitivity analysis** with variation in the configuration of the infrastructure and end-users' composition allows to assess the of the best vs. worst case configuration and potential combinations of both on the purification costs. This modular cost tool allows also to perform a detailed and individual **cost assessment along the overall supply chain** in a second step, as individual scenarios on future market development can be considered.

The modular **sensitivity analysis** shows that the contamination level of hydrogen before purification is one of the most critical influencing factors. While hydrogen from e.g. electrolysis generally contains only small amounts of impurities and can be purified with relatively little efforts, repurposed natural gas infrastructure and underground storage, particularly porous reservoirs and former natural gas fields, present significant challenges when it comes to high grid specifications. Residual gases from previous use, including methane, carbon dioxide, and sulphur compounds, can affect hydrogen quality over long periods and require more intensive post-purification. Especially in the first years after repurposing, the hydrogen content in stored gas withdrawals can fluctuate significantly, making additional treatment necessary to maintain a consistent network quality.

Consequently, a dedicated hydrogen network with new infrastructure ("best case configuration") results in the lowest additional purification costs, as impurities can be minimized in advance. In contrast, the use and repurposing of existing natural gas networks and porous underground storages ("worst case configuration") lead to a higher purification effort due to the need to remove significant amounts of residual gases and contaminants. The analysis also highlights that economies of scale play a crucial role: larger, centralized purification units are significantly more efficient than multiple smaller, decentralized facilities.

In a second step, **an exemplary scenario ("reference scenario")** is applied to illustrate the practical application of the modular purification cost data provided in order to assess the overall purification costs along the supply chain.

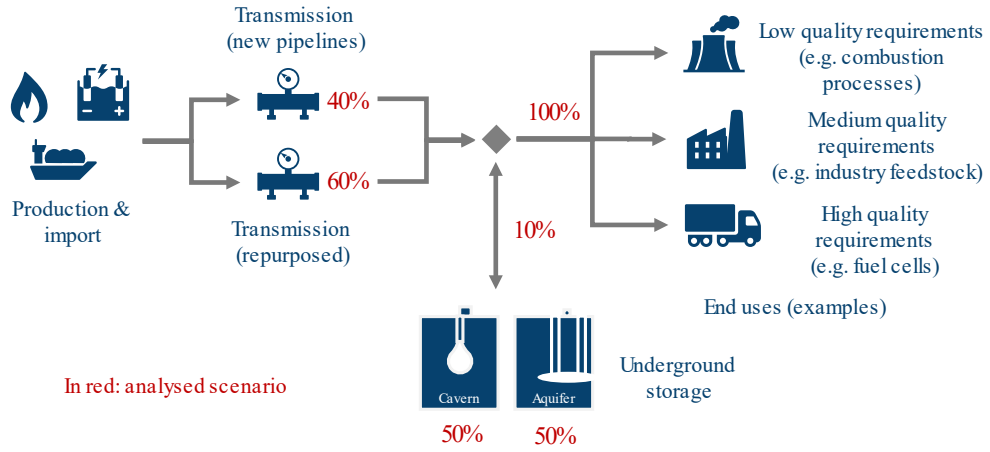

Figure 6-1: Graphical illustration of the reference scenario. Note: different compositions of end-uses is applied.

For this, the **following exemplary distribution of hydrogen across different infrastructure** components and end-use applications is considered.

- 40 % of the hydrogen is transported via newly built pipelines, while 60 % flows through repurposed natural gas pipelines.
- 90 % of the hydrogen is supplied directly to end-users, while 10 % is injected into underground storage facilities. These stored 10 % are then equally split between new and repurposed storage infrastructures, with 5 % allocated to each.

The hydrogen distributed for direct end-use applications follows different purity requirements: 50 % is allocated to applications requiring a minimum purity of 98 mol% H_2, 25 % requires 99.5 mol% H_2, and 25 % must meet the highest standard of 99.97 mol% H_2.

For this specific example distribution, the resulting final specific purification costs along the overall supply chain are

- €1.05/kg in case of a grid quality of 98 mol% purity,
- €0.78/kg in case of a grid quality of 99.5 mol% purity and
- €1.24/kg in case of a grid quality of 99.97 mol% purity.

In other words, these are the costs that need to be added for purification along the supply chain on top of the levelized cost of hydrogen production per kilo hydrogen. A grid quality of 99.5 mol% shows the lowest additional purification costs among the three qualities analysed here. It should be noted that these values are specific to the chosen assumptions and can vary for different configurations of the infrastructure, usage paths and end-uses. However, this example demonstrates how the cost data from the modular sensitivity analysis can be used to determine total purification costs for various scenarios.

Variations of this reference scenario with different compositions of the hydrogen demand structure are presented in the analysis – considering a focus use of hydrogen (=50 % of overall demand) in applications requiring a low, medium or high hydrogen quality, respectively.

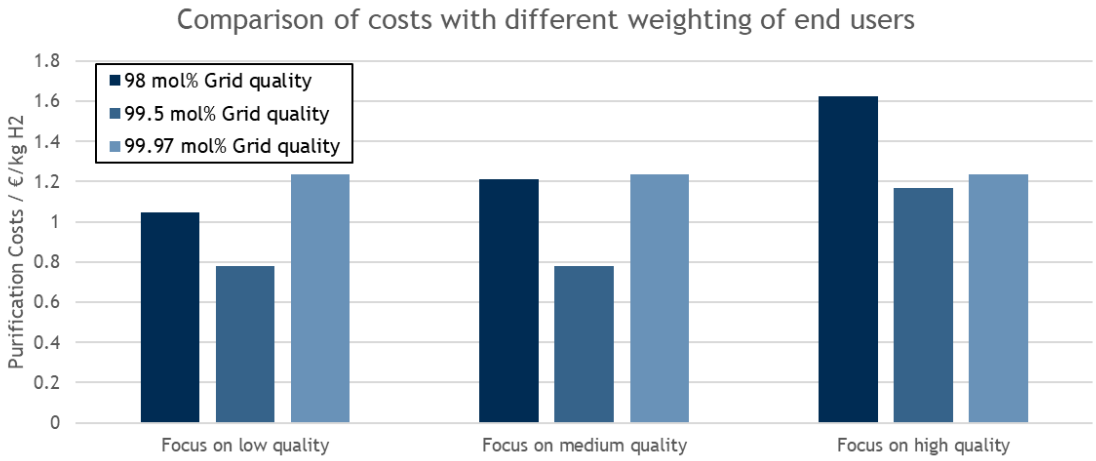

Figure 6-2: Comparison of overall purification costs along the supply chain (transport, storage and demand) under the assumptions of the reference scenario with variations in end-users' composition as indicated in Table 5-3

The overall results indicate that – independently of the assumed composition of end-users' demand – the lowest additional purification costs along the supply chain are observed for the cases with a grid quality of 99.5 mol% (medium blue bars in). In addition, it can be observed that costs for this grid quality remain exemptional low (around 0.80 €/kg) for both scenarios with a focus on end-users with low and medium quality requirements. In contrast to that, for an assumed grid quality of 98 mol% (dark blue bars) purification costs significantly increase from 1.05 €/kg to up to 1.60 €/kg – when a significant share of end-users requires high hydrogen quality of above 99.97 mol% and, hence, need to implement additional on-site purification facilities. This cost even surpasses the additional purification costs that

are estimated, in case a grid quality of 99.97 mol% is assumed (around 1.24 €/kg (light blue bars). These costs are the same – independent of end-users' composition – as no additional purification is assumed at end-users site – anyway.

The main cost drivers can be divided into three categories.

- Firstly, infrastructure modifications are a significant factor. The conversion of existing natural gas pipelines requires extensive cleaning and flushing processes to remove residues. New hydrogen pipelines, on the other hand, offer the advantage that they can be specially designed to meet high purity requirements. In this context, the significantly higher investment costs of new pipelines compared to repurposed natural gas pipelines, need, however, also be considered.
- Secondly, the investment and operating costs increase with increasing purity requirements. Technologies such as pressure swing adsorption (PSA) and other adsorption technologies play a central role here. The removal of trace elements such as sulphur and nitrogen are particularly cost-intensive. In addition, modern purification technologies such as optimised PSA plants or innovative membrane processes can significantly reduce energy consumption and operating costs
- Thirdly, a particularly significant factor for cost assessment is the dependence on storage technology: underground storage facilities, in general, pose a challenge on the system. These can contaminate hydrogen, making both pre-treatment and post-treatment processes necessary in order to fulfil the grid specifications. While newly built salt cavern storage facilities lead to lower purification costs in the long term, porous storage sites (e.g., former natural gas reservoirs) require additional purification efforts.

The results suggest that a minimum hydrogen purity of 98 mol% can be achieved with reasonable efforts from infrastructure side but is insufficient for many applications. Hence, the additional purification costs at end-users' sites have to be considered as well. A medium grid purity level (like the 99.5 mol% H_2 analysed in this study) can represents a reasonable compromise between purification requirements and infrastructure compatibility, taking the cost results of this analysis into account. In contrast, a quality of 99.97 mol% H_2 is – although technically feasible – connected with significantly higher purification costs along the upstream supply chain, which only is attractive, if the major share of end-users uses such a high hydrogen quality for their processes. Otherwise also other supply modes, e.g. via trailer, may be a more cost-efficient solution in case only a small number of end-users with very high hydrogen specifications develop (e.g. for hydrogen refuelling stations).

6.2. Limitations of the work

Despite the broad scope of this study, the present work also has limitations which can suggest avenues for further work. Some key elements are listed below:

This study aims to provide a comprehensive overview of the available knowledge for the different elements along the hydrogen supply chain in Chapter 3 – both on the role of hydrogen quality on grid components as well as the impact of grid components on the hydrogen quality. Due to the lack of practical experience with the operation of a hydrogen infrastructure connecting different producers and end-users, the impact of the complex interplay between the individual (infrastructure) elements and the effect on hydrogen quality needs further understanding. This challenge increases as not only the hydrogen content itself but also the level of different contaminants needs to be considered. Within a future hydrogen infrastructure, measuring and monitoring the hydrogen gas composition at different points in the supply chain will be important.

While the analysis follows the development of the relevant standardisation activities and regulatory environment regarding hydrogen quality on European / international as well as on national level, their highly dynamic character sets limits to the ability of an overall coverage of all latest developments (especially for those beyond 2024). Hence, stakeholders' input was considered of high importance and included to support the analysis.

The **stakeholder interaction** in Chapter 4 represents one key element of this work. In total, over 50 questionnaires were returned to the project partners, and several follow-up interviews were performed. Continuous improvements in knowledge base within the project period also allows for an updated questionnaire during the project. This updated version, however, could not be made available to the first set of responders.

Also, it became clear that there is a different perception on the topic of hydrogen quality among the different stakeholder groups (and Member States) resulting in heterogenous response rates. While analysis of stakeholder feedback is performed on a neutral, fact-based basis, such analysis always faces the challenge of identification (and distinction) of actual technical barriers and potential other motivations.

Lastly, it was initially part of the scope of the stakeholder investigation to receive cost data for various hydrogen purification technologies. Unfortunately, no parties were willing to directly divulge new information which could be used as input for the costs analysis in Chapter 5 as part of the survey.

One further objective of this work was the identification of the cost impact of different hydrogen grid specification as well as the key cost drivers of purification needs at entry and exit points of hydrogen pipelines along the supply chain, including interconnected underground storages. Accordingly, a **purification cost analysis** is performed in Chapter 5. A comprehensive database of purification cost data for CAPEX and OPEX was required, which needed to be based on internal sources as well as available literature as no industry feedback on costs experience for large-scale purification for hydrogen projects was obtained (see survey limitations above). As a result, unfortunately, no details on electricity costs assumed as part of the OPEX can be stated.

The analysis is performed based on the specific purification costs in € per kg hydrogen and calculated for each infrastructure element (i.e. at entry and exit points of pipeline and underground storage) separately. In addition, further purification steps at different end-user groups are included, based on their specific purity requirements set out in ISO standards and identification of critical contaminants. The production element, on the contrary, is not analysed as in principle all production technologies can fulfil the grid specifications with appropriate purification efforts. These efforts itself, however, (and thus the additional costs and competitiveness of each technology) are technology-specific and can be considered as inherent part of the levelized cost of hydrogen (LCOH).

While this bottom-up approach allows for a detailed understanding of specific purification needs and costs, no system-wide cost optimization is performed. Hence, no identification of an optimal general grid quality under certain volume projections is possible. Nevertheless, a sensitivity analysis is conducted to assess the purification cost impact of different infrastructure configurations (incl. different typology of underground storages, new vs. re-purposed pipelines) as well as the impact of variations in demand volumes meeting technical specification requirements (e.g. specified in ISO standards) for different end-uses like combustion engines vs. fuel vehicles).The analysis is done taking three different grid quality specifications (“cases”) into account.

The high complexity in individual purification cost estimations is driven by impacts of assumed contamination concentrations input and output streams as well as gas flows on optimal plant layout and energy requirements. Therefore, case-specific process designs are needed to identify cost-optimal solutions. In the context of this work, this level of detail cannot be provided and overall assumptions needed to be taken. One of these aspects is e.g. a detailed cost analysis taking the different limits for each contaminant into account. Instead, purification efforts and costs for removal of specific contaminants (e.g., N_2, CO, CO_2, CH_4, H_2O, sulphur compounds, O_2, NH_3) are summarised in an inventory as a basis for further analysis. Thus, the decision is taken whether a specific purification technique is needed for removal of certain contaminants or not.

6.3. Outlook – next steps towards standardisation

The study results as well as the limitations described above allow us to draft the following possible next steps towards a standardization of hydrogen gas quality for the upcoming European hydrogen gas pipeline infrastructure. In these efforts, it is key to involve stakeholders from different categories: (i) legislative (e.g. regulatory authorities, incl. energy regulators in EU Member States), (ii) independent standardisation organisations like ISO and CEN/CENELEC and (iii) individual national key stakeholders, like grid and storage operators but also other actors along the supply chain.

Understanding the future hydrogen grid by implementing a technical inventory of key elements of the future European hydrogen infrastructure

The limitations of this study show – a thorough analysis of the European hydrogen infrastructure requires a high level of understanding of the (existing and future) infrastructure and the individual components of the whole relevant network. To enhance decision-making on infrastructure development (incl. sector coupling elements or even the question of potential decommissioning of certain natural gas grid areas), a centralized infrastructure database should be established to systematically collect and monitor hydrogen gas quality data. This should also include cost data related to hydrogen purification (CAPEX and OPEX), as highlighted in Chapter 5, to support cost-optimized infrastructure planning. This would allow for a more detailed collection of (real-life) experience and data on the effect of different hydrogen specifications on the customer groups than what could be performed in this study. In this context, also existing natural gas grid materials and components should be considered in view of their repurposing, as these available assets can have impact on both – hydrogen quality and to cost-efficiency.

As some of the data might be considered highly sensitive, a data collection by public authorities like national regulatory authorities or even a European infrastructure database is suggested. With this, key data of the different stakeholder groups can be collected and used as basis for the support of future infrastructure development. Stronger involvement of the European stakeholders in the international (standardisation) committees (e.g., in ISO/TC 197 WG27) should be supported in view of aligning data collection efforts globally, to coordinate and to avoid duplication. Key elements that may be subject to such a data collections on existing and available grid elements are listed in the following:

- Contaminants (potentially) released in existing hydrogen production processes and description of purification systems that are already installed. In previous work, a qualitative view of these contaminants has been described. However, for further work, a quantitative description should be made how much of which contaminant is released in hydrogen for a specific production process under certain process variables. E.g. what the methane fraction is for hydrogen produced in an SMR process operating at a volume flow of *x*, using catalyst *y*, under pressure *z*. With that, also a technology-specific "fingerprint" in hydrogen gas composition could be developed.
- Characteristics of existing infrastructure elements that are part of the natural gas grid (e.g. pipelines, compressors, etc.) and can be repurposed for future hydrogen use. Hydrogen impact and hydrogen quality-related challenges identified for repurposed pipelines during a transition period can thus be considered in order to have a coordinated roll-out of the infrastructure without avoiding taking repurposed pipelines into operation in grid areas, that already can provide a high hydrogen purity without further contaminations.
- Gas storage facilities are considered a key and essential element in the hydrogen infrastructure – although only a share of the overall gas transported will be injected and stored. Typology and geography of underground storages across the EU are of high impact on both – purification needs before injecting hydrogen into storages and purification of hydrogen before injecting it back into the pipeline network. The analysis shows that purification costs will especially be high in case of porous media storage sites. Data collection is key on the following aspects:

  - Information on geology of the storage location as well as type and level of contamination that is to be expected after hydrogen is stored. Furthermore, storage operators should indicate what kind of cushion gas is used and whether their storage is particularly vulnerable to any possible contaminant in the hydrogen gas injected at entry in terms of microbiological activity.
  - Information on compressor and purification equipment (e.g. PSA/TSA systems and adsorbent materials in use, gas drying and desulphurization equipment) present at storage sites, their capacities (in m^3/h) and an assessment of potential re-use for hydrogen.
  - The amount of physical space at the storage facility site for new process equipment or connections for tail gas streams.

- Overview of **catalysts applied in industrial processes** where hydrogen is used as a feedstock like in chemical industry or steel. Concrete process specifications for hydrogen purity as well as available on-site purification facilities are needed. The focus should – of course – be on those sites that are to be connected to other interconnected hydrogen transport infrastructure instead of today's common on-site hydrogen production without external connection (e.g. in geographically confined networks). Based on the analysis of potential contaminants as well as installed purification techniques, the suitability to remove these contaminants from the supply side can be assessed. For this analysis, it is critical to assess the vulnerability of catalysts to contaminants which are unique to hydrogen, and which are unique to repurposed natural gas infrastructure.
- Finally, an **overview of (small- and large-scale) purification systems** available in the market to remove contaminants and separate methane contaminations from the hydrogen stream would be a helpful tool for market participants to estimate additional purification costs and provide the regulator with detailed information on purification efforts. Where possible, data on costs and efficiency should be collected.

Other topics may include:

- An overview of available **(sulphur-free) odorants** for hydrogen infrastructure and their potential effects on storages and infrastructure elements (pipeline, compressors), underground storages and end-users. An analysis of cost for different options should also be included, comparing the options for odorization on certain grid levels only (e.g. DSO pipelines) or in the overall grid.
- An inventory of what **equations of state (EoS)** are currently used in metering systems for all stakeholders would be helpful as well as an assessment on whether these equations are suitable for hydrogen.

Several of these aspects may also be part of the work in the upcoming **EISMEA HyQual Net project**[259] that aims to further support pre-normative research for hydrogen gas quality in dedicated grids. The results will complement the basis for (further) development and/or revision of European standards. Topics covered here include,

(1) Leakage detection with and without odorization (safety).
(2) Leakage detection and monitoring (emission reduction).
(3) Odorants without sulphur.
(4) Safety protocols and technical leakage and explosion prevention, measurement and management procedures.
(5) Purification.
(6) Hydrogen quality parameters.

[259] *CEN/CENELEC (2025): Open call for tender for Hydrogen Quality in Dedicated Gaseous Grids – HyQual Net EISMEA project.*

Identification of common hydrogen gas specification that is supported by a wide stakeholder base

In the further process of identifying the future hydrogen gas specification(s), several aspects should be considered:

Each cost analysis aiming for identification of the "optimal" hydrogen quality is – to a high extent – driven by assumptions on further development of the hydrogen markets and infrastructure. This, however, is inherently subject to uncertainties and subject to controversial discussions among stakeholders. Variations in volume projections for production and end-use sectors shift the optimal hydrogen quality to either lower or higher levels. A harmonized and agreed scenario set on supply, demand and flows (e.g. into the storages) can contribute to a robust and widely accepted database.

The overall analysis, however, also need to take potential contaminants in the hydrogen gas and the costs of their removal into account – which drives complexity of each of those studies. High purity requirements in these terms allow for a better control of physical hydrogen gas properties and contaminants, as the respective limits are rather strict. Lower limits, on the contrary, may enable higher flexibility in terms of supply and grid operation. Comparing maximum concentrations in the hydrogen specifications proposed in this study, the major difference between 98 mol% and 99.5 mol% quality, however, lies in the different limits for hydrocarbons (mostly methane) or inert gases. Depending on the minimum hydrogen level, the respective limits are either <20.000 ppm or <5.000 pm. For other contaminants, the same limits are suggested in this study for both quality levels. A key question which is still open to discussions is the selection and role of odorization in future hydrogen systems.

In any case, it is clear that each solution has its inherent advantages and disadvantages and in the end, a compromise will be required. In order to achieve a commonly accepted solution, also accompanying policy measures (e.g. cost sharing mechanism) should be discussed.

Existing studies in the Netherlands (by DNV/Kiwa) or on European level (upcoming EASEE-GAS study (announced for 2025) in combination with the approach taken in this study contribute to a better understanding of key cost drivers as well as no-regret investments into the infrastructure. Despite that, identifying no-regret investments as well as making use of existing assets in order to prevent stranded investments should be considered.

Still, due to uncertainties as well as individual perspectives of each market participants, even the most cost-efficient solution from the overall system perspective may not be ideal when it comes to the question of supporting the hydrogen market ramp-up. In each scenario, costs are put on individual market participants impacting their business model. It must therefore also be considered what the additional costs of a lack of harmonisation are, as they would result in a fragmentation of the hydrogen market before it is even established (i.e. with individual grid qualities in each Member State).

Additionally, the economic risks of market fragmentation due to varying hydrogen quality standards across EU Member States must be evaluated. Chapter 2 suggests that non-harmonized grid specifications could lead to inefficient purification investments and stranded assets. A cost-benefit analysis should, therefore, also be conducted to compare the long-term savings of early standardization with the investment costs required for infrastructure and production adjustments. It should also examine how purification costs can be fairly distributed among market participants.

In case, no agreement on a uniform hydrogen standard can be reached in this early market phase, a phased roadmap could be developed to ensure a structured and cost-effective implementation:

- Short-term (0–2 years): Introduction of interim purity standards, initial regulatory alignment, and data collection on existing infrastructure.
- Mid-term (3–5 years): Large-scale pilot projects, industry-wide consultation on cost implications, and refinement of standards based on real-world findings.
- Long-term (5+ years): Full implementation of standardized hydrogen quality requirements across the European hydrogen network.

Introduction of uniform hydrogen quality standards in European Member States

Still, the preferred, ultimate goal of an interconnected grid from a cross-border trade perspective is the introduction of a **uniform specification among all Member States and grid levels** – meaning for all entry and exit points as well as transmission and distribution level. This approach would not only facilitate the cross-border flow without limitations. It would also facilitate decentral production and injection of hydrogen and would allow for the potential reverse-flow from distribution to transmission level.

In order to implement this from the very beginning of the grid development, a rather **timely and pragmatic approach** and decision is required resulting in an international standard. Only this can prevent local or national standards to be implement first with the need of further adaptation / harmonization at a later stage or continued adaptation measures in the grid. With a fast decision, one may not necessarily select the "optimal" solution for a specific (pre-defined) market scenario. With the high uncertainties regarding future market development and the heterogeneous stakeholder positioning, however, a "one-fits-all-solutions" may not be possible to reach anyway. Whether this, however, can be achieved cost-efficiently in the short-term – or whether, depending on national grid and market characteristics a phased market ramp-up may as described above rather serve this goal – needs further debate among stakeholders.

The high **importance of repurposed pipelines** in the European hydrogen infrastructure planning, however, may pose a significant challenge on the ability of the overall grid to guarantee a high grid quality (at least during a transition period). A coordinated network development plan which also considers the character of the pipeline (repurposed vs. new) and hence the risk of introducing specific contaminants should be set up. After a first period, where a large number of repurposed pipelines are starting their operation, focus should be on new pipelines in order to maintain a stable quality in the interconnected grid.

Consider cost division mechanism as important element to increase acceptance of harmonized gas quality among stakeholders

In general, different infrastructure elements (e.g. pipeline and storage operations) are considered as being key for future hydrogen market development. At the same time, major challenges for maintaining a certain purity level are expected for repurposed pipelines and certain storage technologies. While these are a fundamental pillar of a low-cost hydrogen infrastructure, the high purification efforts needed in case of high grid specifications may impact the operators disproportionately. Hence, although the underlying discussion on a future hydrogen quality often focusses on supply and demand volumes, in the end, **all market participants may need to contribute to overall purification cost sharing** (e.g. via grid tariffs).

Aim of a future cost-sharing mechanism should be a fair burden-sharing among stakeholders. While a grid tariff model that covers the purification along the supply chain could be one (extreme) option, also the "Polluter Pays Principle" may be considered for certain market participants, which introduce severe contaminants into the system which result in unproportional purification efforts.

Regarding the different **sources of potential hydrogen** supply, it should be noted that – in principle – all gas specifications can be met by different technologies as long as appropriate on-site purification systems are applied before injection. The technology-specific purity characteristics are at the same time an important criterion of competitiveness against each other. Therefore, independently of the future grid quality, a level-playing-field among hydrogen production technologies should be preserved and purification costs considered as a key element of the levelized cost of hydrogen LCOH and, therefore, not be considered in the grid fees.

This, however, also leads to an important challenge in the future **"valorisation" of hydrogen gas**. Its value can either be based on its energy content[260] (relevant e.g. for combustion processes as for natural gas)

[260] *See e.g. approach in Common Business Practice 2023-001/01 "Hydrogen units".*

or on its purity level (i.e. the level of contaminants which is more relevant for its use as feedstock or in other highly sensitive applications). The latter option can further be differentiated between valorising the hydrogen content only or it can also consider a "penalty" for certain other contaminants that require removal.

In any case, there will be certain market participants which observe negative consequences of a certain grid quality specification: In case of lower quality values (e.g. 98 %), certain hydrogen producers (e.g. electrolyser) that are able to inject highly purified hydrogen gas of e.g. (99.5 % or more) will "loose" a certain value of their product due to a "downgrading" to grid quality after injection. On the other hand – especially in case of high grid specifications (e.g. >99.5 %) there will be certain end-user groups, which are forced to take an overly pure hydrogen from the grid – which will be traded at higher prices than the quality they actually need (e.g. all applications where the hydrogen quality is not considered critical, e.g. combustion processes). Both cases are leading to economic losses of certain stakeholders due to using the hydrogen infrastructures – impeding their own business cases. A successful market design should take these challenges into account, i.e. by adapting the cost-sharing mechanism accordingly.

In summary, the following measures should be integrated into future standardization efforts:

- Data on hydrogen quality and purification costs in hydrogen network, including pipelines and storages, should be systematically collected and analyzed to enable fact-based decision-making.
- Economic feasibility must be incorporated into all standardization decisions to ensure cost-effective grid operation. The assessment should, however, also take the possibility of no successful harmonisation process into account, making an option of a step-wise introduction of quality standards and continuous improvement more attractive.
- In the long term, harmonization at the EU level is, however, essential to prevent costly market fragmentation and stranded investments.
- Purification costs must be transparently assessed and allocated to ensure a fair distribution of financial burden.

By integrating these aspects, hydrogen quality standardization will not only be technically robust but also economically sustainable, creating a stable and widely accepted regulatory framework for the European hydrogen market development.

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