# Insights from the European Commission consultation on Hydrogen quality

**DG ENER study: Technical Assistance on Hydrogen Quality Standardization**

Gas Quality Workshop - 19 November 2025

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# Technical Assistance on Hydrogen Quality Standardisation

ENER/C2/SER/2023-397 Specific Contract
under the Multiple Service Framework Contract N° MOVE/ENER/SRD/2020/OP/0008

## FINAL MEETING

26th March 2025
(November 2025 - Version for Publication)

# Agenda



# Study to support ongoing standardization at national, European, and international levels

## Summary of Report

- Transition from natural gas to hydrogen is central to Europe's climate neutrality & energy independence strategy, requiring **coordination & harmonisation of gas quality standards** across Member States.
- National differences currently block cross-border hydrogen trade; **a unified hydrogen quality standard for pipeline transport is seen as crucial for building an interconnected European hydrogen market.**
- The study reviews literature, existing standards, stakeholder positions, purity levels, contaminant limits & purification cost **to guide discussions on grid specification and responsibility.**
- Execution of project: **April 2024 – March 2025**

Report is published: here

# Defining $H_2$ specifications goes beyond purity level – trace components, physical properties and stakeholder requirements need to be considered

Key Take-Aways

- Early stage in $H_2$ infrastructure development with no unified EU agreement on $H_2$ quality despite existing guidelines → **unique opportunity for harmonisation** to avoid technical barriers & ensure efficient market integration
- Identifying **"optimal" $H_2$ quality is highly complex:** beyond minimum $H_2$ content, also **specific contaminants' limits** (e.g. sulphur) or **physical properties** (e.g. Wobbe index) are relevant
- **3 exemplary & indicative grid specifications** derived based on literature & stakeholder input (i.e. $H_2$ content of ≥98 mol%, ≥99.5 mol% and ≥99.97 mol% + limits for key contaminants)
- **Stakeholder views diverge:** certain storage & repurposed pipeline operators favour lower purity levels (i.e. ≥98 mol%), while other H2 TSOs, industrial grid operators & many end-users prefer higher levels of around ≥99-99.5 mol%.
- System-level cost analysis allows for **identification of key cost drivers & critical parameters** by assessing exemplary grid specifications applied for different grid composition & end-use scenarios via **modular cost tool**
- **Overall system purification costs** mainly driven by grid composition (e.g., share of repurposed pipelines & porous storage) and end-use scenarios – which may both differ among European MSs
  → upcoming harmonisation pathway not only be technically-driven but also requires policy agreement & commitment



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# Agenda





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# The upcoming standardisation request on hydrogen quality and related topics is key for providing guidance to hydrogen market participants

## Background – Upcoming Standardisation Request by European Commission

- **Hydrogen and Decarbonised Gas Market Package:**
  see Articles 44 and 50 of Directive (EU) 2024/1788 Articles 69 and 72 of Regulation (EU) 2024/1789, in line with TEN-E Guidelines

*"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)

- Aim:
  - Identifying **a reasonable approach** that can facilitate consensus finding towards a suitable, future-proof solution from an overall system perspective, while taking the limitations of different infrastructure elements into account.
  - 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**.



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# The report provides technical analysis as support for further standardization activities on gas quality in Europe

Project Overview

**Literature analysis:** influence of different supply chain elements on hydrogen gas composition & implications of varying purity levels for end-users

**Overview standardization landscape:** existing hydrogen gas quality standards & current developments in 12 EU Member States

**Stakeholder consultation:** gathering of positions of actors of future hydrogen markets via survey & interviews

**Understanding hydrogen quality specifications needs:** three quality specifications (incl. limits for key contaminants), rational behind & recommendation for further standardization efforts / gaps derived based on stakeholders' feedback

**Purification cost assessment**: illustrate purification efforts & cost drivers for 98 mol%, 99.5 mol%, & 99.97 mol% cases
(i) specific purification costs
(ii) analysis for different steps along supply chain (modular approach)
(iii) tool for scenario-based cost analysis

**Outlook - next steps towards standardisation**



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# The Final Report was submitted on 13th March 2025 to the European Commission (DG ENER)

## Structure of Final Report (Version 13th March 2025)


**Abstract**

**Executive Summary**

**1. Introduction**

1.1. Motivation

1.2. Study objective and reading guide

**2. Background – comparison with situation in natural gas markets**

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

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

**3. State-of-the-Art (overview)**

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

3.2. Standardization landscape

**4. Stakeholder groups and perspectives**

4.1. Methodology

4.2. Results and discussions - key issues identified

4.3. Recommendations

**5. Cost analysis**

5.1. Assumptions and methodology for cost estimation

5.2. Cost assessment of cleaning processes ("Inventory")

5.3. Scenario-based purification cost estimation for the hydrogen value chain

5.4. Uncertainties and limitations in cost analysis for hydrogen processing plants

**6. Summary & outlook**

6.1. Conclusions and key learnings

6.2. Limitations of the work

6.3. Outlook – next steps towards standardisation

# Literature analysis provides overview of current knowledge and discussions as basis for further work in project

## Key Learnings (Part 1/3) – Literature overview / State-of-the-Art

- In general: broad knowledge about **sources, risks and impact of contaminations** along the supply chain
  - However: practical experience from interconnected $H_2$ networks missing
  - Comparison with natural gas market shows need for harmonisation to facilitate cross-border trade – although hydrogen (pure product) differs significantly from natural gas (mixture of different components)
- **$H_2$ supply chain elements** in context of hydrogen quality and existing standardisation landscape:

**Production:** SMR / $NH_3$ cracking: grid specifications need extensive purification anyway, electrolysers without issues

**Grid perspective:** different specifications exist, e.g. EN 17977, EASEE-gas CBP 2022-001/01 or by Hynetwork NL

**Underground storage** and **rededicated pipelines** (in the short- to mid-term) bottlenecks for hydrogen qualities > 98 %

**End-users:** focus on $H_2$ as a fuel (e.g. ISO 14687) or EN 17124 (PEM FC), Wobbe index with relevance for combustion

**Industrial end-uses (feedstock):** application-specific, catalyst poisoning (e.g. for NH3, methanol, refineries) or product quality (e.g. steel industry) most relevant aspects → on-site purification of trace contaminants may be unavoidable

# This study shows and compares a set of existing standards – both for infrastructure and different end-use applications

## Key Learnings (Part 1/3) – Grid specifications – existing standards

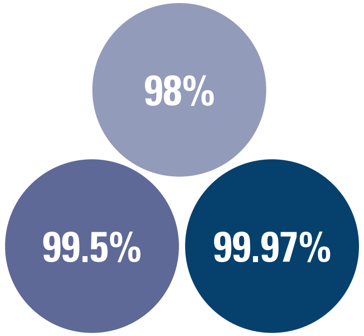
| | Standard | Name | Scope | Comment (Note % values in mol%) |
|---|---|---|---|---|
| Transport / Pipeline | CEN/TS 17977:2023 **(2023)** | Gas infrastructure - Quality of gas - Hydrogen used in rededicated gas systems | $H_2$ pipelines (repurposed NG pipelines) | $H_2$ quality: **≥98.0%,** Wobbe Index: 42-46 MJ/m$^3$ (15 °C/15 °C) *Note: different specifications compared to ISO 14687 Grade A* |
| Transport / Pipeline | EASEE-gas: Common Business Practice 2022 – 001/01 (CBP) **(2022)** | Hydrogen Quality Specification for dedicated Hydrogen Pipelines | $H_2$ pipelines (dedicated 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.* |
| Transport / Pipeline | 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 |
| Transport / Pipeline | 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) *Note: Currently under revision to (possibly) include **99.5%** as additional "grade" "group A+"* |
| Transport / Pipeline | 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 *Note: Former version (2022) with 98%.* |
| End-use | ISO 14687:2025 **(2025)** | Hydrogen fuel quality — Product specification | Specifications for different end-uses ($H_2$ as fuel) | Different Grades (A-F) for state of hydrogen and end-uses **≥98.0% (Grade A) – ≥99.995% (Grade C), + 50 % (Grade E1)** |
| End-use | 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 |

# Stakeholders’ feedback allowed identification of requirements for key contaminants and proposal of different specifications

## Key Learnings (Part 2/3) – Stakeholder Interaction

- **Stakeholder consultation:** gathering of positions of actors of future hydrogen markets via survey and interviews (N~50)
- Summary and analysis of **key stakeholder positions**
  - Clear perspective on market developments – heterogeneous supply structure, feedstock as initial key end-use
  - Relevant mismatch:
    **storage operators’ capabilities vs. end-users’ requirements** (feedstock, fuel cells)

- Output:
  - **Understanding hydrogen quality specifications needs:**
    list of technical requirements for specific contaminants of hydrogen
    and **technical rationale behind them**
  - Identification of standardization gaps based on stakeholders’ feedback
  - Exemplary specifications **for three different quality cases,** incl. limits for key contaminants)
    - with arguments for each specification → Basis for purification cost assessment





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# There are important arguments by stakeholders for both, low (98%) and medium/high (99.5%) as future grid specification

**Arguments for 98% purity in the proposed network:**

- Some independent research indicates that **98% purity is the weighted-average expected end-use**
- Storage operators, except salt caverns, claim that **anything above 98% purity is uneconomical for them**
- It is argued by stakeholders that the volume required for the storage needs of the new system **exceeds the salt cavern capacity in the EU**

**Stakeholders who require this quality level are generally:**

- TSOs directly associated with porous media storage operators and non-salt cavern storage operators
  - More cautious about the technical and economical feasibility of hydrogen storage
  - Geographically located further from salt cavern storages (IT, AT, CZ, FR)

**98%**

**Arguments for 99.5% purity in the proposed network:**

- **High confidence in technical feasibility**
- DSOs require a **buffer of quality** since their networks will contaminate the hydrogen (inleak, adsorbed odorants, low flow-networks)
- **99.5% is considered an economic supply/demand optimum** according to recent studies (to be confirmed)
- **EASEE-gas CBP pricing method will drive quality up**

**Stakeholders who require this quality level are generally:**

- TSOs directly associated with salt cavern storage
- Geographically located closer to salt cavern storages (NL, BE, DE, DK)

**99.5%**



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# End-use requirements are mostly focussed on possible contaminants and (for engines, turbines, burners) on combustion properties

Key Learnings (Part 2/3) – End-users' requirements based on stakeholder feedback

### $H_2$ as feedstock

Largest expected end-use:
- Haber-Bosch / $NH_3$
- SAF production
- DRI steel refining
- Oil refining

Requirements:
- Very stringent limits to contaminants that poison catalysts: **sulfur, ammonia**
- Limits to contaminants that lower process efficiency: **nitrogen, oxygen**
- Stringent limits → high purity

### Engines and Turbines

Diverse end-uses:
- Electricity generation
- Combined heat and power
- IC engines for maritime and heavy duty transport

Requirements:
- Limits for **variations in Wobbe index** in MJ/m³/min
- Contaminant levels should be steady over time
- Contaminants which contribute to emissions (NOx) should be reduced

### Burners

Limited expected end-use:
- Hard-to-decarbonize industries: high temperature (e.g. glass and ceramics)
- Process heat

Requirements:
- Limits for **variations in Wobbe index** in MJ/m³/min
- Direct heating processes have contaminant limits
- Indirect heating processes require affordability and calorific value

### Fuel Cells

Limited expected end-use:
- Mobility systems such as LDV / HDVs, trains, buses
- Stationary systems / off-grid

Requirements:
- Very **stringent contaminant limits** to prevent fuel cell poisoning (similar to feedstock)
- However, direct connection to hydrogen grid unlikely (at least for HRS)

**High expected volume** → **Low expected volume**

Please note: The report contains an extensive list of contaminants and their rationales for all end-users:

# Three exemplary grid specifications were derived based on stakeholders’ input and existing standards and serve as basis for cost assessment

## Key Learnings (Part 2/3) – Exemplary hydrogen specifications

- Three exemplary specifications were provided as input for cost assessment:
  - **98%:** derived from CEN TS17977:2023
  - **99.5%:** based on HyNetworks indicative spec
  - **99.97%:** based on (private) industrial pipeline
- The specifications are a combinations of **stakeholder input and existing standards**
- This approach may allow for **quick alignment with real market practices** since these standards are already well-known, and the changes in purification infrastructure are more limited

Important: **No recommendation for future standard** but only example for cost assessment!

| Property | Example Specifications | | |
|---|---|---|---|
| $H_2$ | >98 % | >99.5 % | >99.97 % |
| Wobbe Index | 41.89– 45.89 MJ/m$^3$, (15 °C/15 °C) | 43.45-45.89 MJ/m$^3$, (15 °C/15 °C) | n/a |
| ΔWobbe index | <0.5 MJ/m$^3$·minute | | n/a |
| Water | <250 ppm at <10 bar<br><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 | | |

# Assessments of purification efforts along supply chain results in additional costs of around 0.8 – 1.2 €/kg in analysed key scenarios

## Key Learnings (Part 3/3) – Approach and Results of Cost Assessment

- Assessment of **specific purification costs (in €/kg)** along supply chain allowed to compare
  - different hydrogen purity levels
  - but also cost for removal of key contaminants

$H_2$ $CO_2$ $H_2S$ $O_2$ $N_2$ sulphur compounds $H_2O$ hydrocarbons $CO$ $CH_4$

- Different **key cost drivers** for purification costs identified
  - Oxygen removal and pressure swing adsorption (with high impact of economies of scale and energy demand)
  - Repurposed pipelines and porous media storage
  - Grid & market development and share of different end-use groups
- **No-regret investments:** post-purification (production, use of repurposed pipelines and UHS), gas quality monitoring & analytics systems

→ Specific purification costs along supply chain: **~0.8 – 1.2 €/kg**

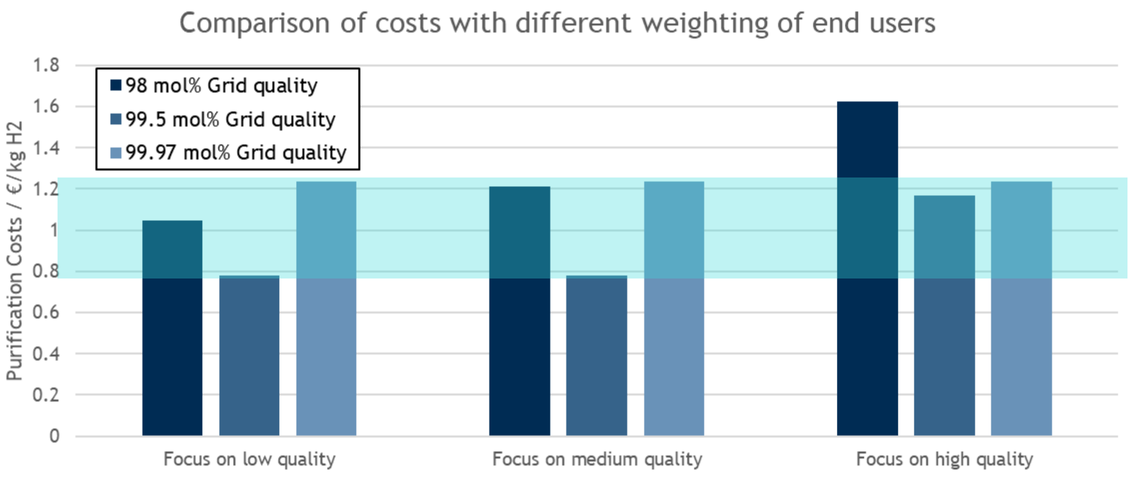
→ “Optimal” grid specification may significantly differ for European MSs; modular cost approach allows for individual assessment

* Assumptions: 40% new and 60% repurposed pipelines, 10% of hydrogen entering storage, 50% new salt caverns and 50% porous media storages, different end-use shares analysed.

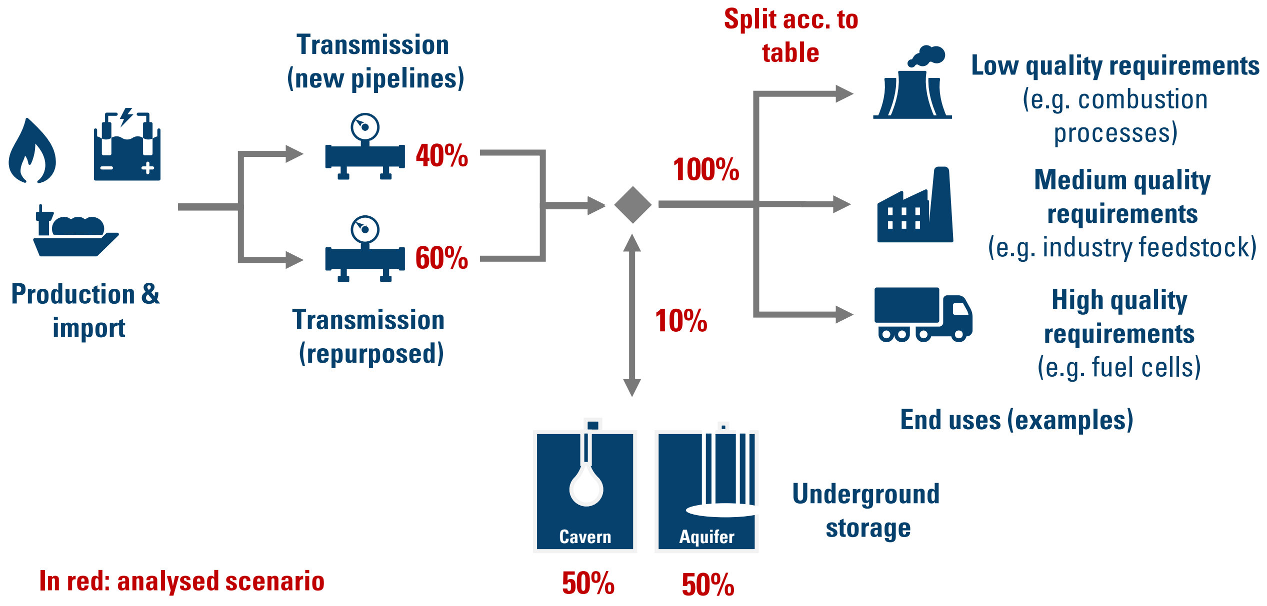
# By the modular approach of the cost model, the study allows estimations for a wide set of possible grid and consumers configurations

## Key Learnings (Part 3/3) – Scenario-based purification cost estimation for the hydrogen value chain

- Costs strongly depend on assumed grid configuration and end-users' shares (see diagram below) – range around **0.8 – 1.2 €/kg** (for reference scenario)
- Medium grid quality may be beneficial from overall system perspective (infrastructure, storage & end-users), however: not necessarily for individual market participants!
- See Annex for application of purification cost tool




| 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 % |



# Further discussion should look for minimum common requirements to allow for cross-border trade among countries, already in transition phase

Summary

- Finding cost-optimal system design provides key challenge for this and other studies (see e.g. (DNV/KIWA, upcoming EASSE-gas study)
  → It strongly depends on assumptions for hydrogen market and infrastructure
  → It will be different depending on study scope (MS level, EU wide)
- However: cost optimum for system not necessarily drives investment at different stages of supply chain
  → appropriate **cost sharing mechanism** needed

- **Step-phase introduction of hydrogen grid standard** may be considered as alternative option to direct harmonisation
  - Short-term (0–2 years): Introduction of **interim purity standards** with minimum common requirements, 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.



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# Harmonisation process needed to ensure transformation of European energy infrastructure and interoperability in the transition phase

## Recommendations & Next Steps

Following initiatives to be integrated into future standardization efforts:

(1) **Systematic collection of data** on $H_2$ quality & purification costs in $H_2$ network, including pipelines & storages
→ better understanding of all elements connected to (future) grid

(2) **Economic assessment** to ensure cost-effective grid operation – also considering major contaminants & risk of unsuccessful harmonisation process on cross-border trade

(3) **Foster EU wide harmonisation for market development**, preventing costly market fragmentation & stranded investments / adaptation needs for end-users

(4) Facilitate **fair distribution of financial burden & responsibility** for gas quality (i.e. market design in EU MSs)

(5) **Purification cost analysis can be applied as a tool** to gain cost estimates for different scenarios on grid composition and end-users' shares, providing a valuable insights for market participants & regulators

→ **Further ongoing European activities will complement this picture**
(e.g. upcoming EASEE-gas study for $H_2$ quality, German H2Optimum or EISMEA HyQualNet projects)

→ Standardisation activities will proceed via **CEN/CENELEC**
A respective **standardisation request by the European Commission to be sent to CEN/CENELEC in Q1/2026**

# Project Team

## Contact Details


| | |
|---|---|
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# Agenda



# The comparison with natural gas market shows that a different approach should be used for hydrogen hurdles in cross-border trade

## Why is hydrogen different from natural gas?

### Comparison hydrogen vs. natural gas

- **Hydrogen gas**: composed of one component: $H_2$ molecules (=pure product), other molecules considered contaminants
- **Natural gas:** gas mixture with variety of molecules, source-dependent
- Differences in market & infrastructure developments

| Parameter | Pure Hydrogen | Dutch G-gas | Russian gas | Canadian gas |
|---|---|---|---|---|
| Typical composition[1] [vol%] | 100 % $H_2$ | 81.3 % $CH_4$<br>2.9 % $C_2H_6$<br>14.4 % $N_2$<br>0.9 % $CO_2$ | 98 % $CH_4$<br>0.6 % $C_2H_6$<br>0.8 % $N_2$<br>0.1 % $CO_2$ | 95 % $CH_4$<br>4.5 % $C_2H_6$<br>0.4 % $N_2$<br>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 |

### Learnings from NG markets (selected examples for existing market challenges)

1. Different gas quality in gas grid in NL (G-gas, L-gas, H-gas)
2. Wobbe index differences among EU Member States led to highly different end-users' equipment / future harmonisation considered not feasible
3. Different contaminant limits – example oxygen limits hinder cross-border trading
   High biomethane injection in DK – but very low limits in DE (due to storage tolerance)
   → current situation – gas blending before export needed in Denmark, no gas with sign. biomethane shares to be exported to Germany

# A variety of aspects need to be considered in the discussion of identifying suitable the future hydrogen grid specification

## Overview impact factors of overall grid quality discussion

**System design (EU level)**
- Cost approach (system vs. individual perspective)
- Cross-border trading / different situation in EU Member States

**Grid specifications (entry/exit specifications):**
- Hydrogen level / purity level (in mol%)
- Type and limit of allowed contaminants (e.g. sulphur, CO, hydrocarbons)
- Physical gas properties (e.g. Wobbe index)

**Market design (national level)**
- Liability / responsibility for maintaining quality
- Cost division among actors
- Hydrogen valorization

**Purification technologies for production, infrastructure, storage and end-users, incl. specific costs**

**Production / Imports**
- Technology mix / production volumes (today / future)
- Product gas quality per technology + purification efforts
- Sources of impurities and risk of contamination

**Transmission & distribution**
- Grid configuration (new & rededicated pipelines)
- Interconnected networks vs. locally confined (industrial) hydrogen grids vs. complex
- Sources of impurities and risk of contamination
- Odorisation options

**Underground Storage**
- Type of storage / former use
- Pre- and post-purification
- Sources of impurities and risk of contamination
- Quality impact on storage

**Distribution grids**
- Specific challenges for distribution systems

**End-uses / applications**
- Demand volumes (today / future) + relevance for grid
- Contaminant limits per application
- Physical gas properties per application (e.g. Wobbe index range

→ End-users' specifications

**Infrastructure operation**
- Quality / contaminants' monitoring
- Leakage detection & monitoring (emissions)
- Leakage detection with/without odorisation (safety)
- Safety protocols and technical leakage and explosion prevention, measurement and management procedures

# Due to high complexity of the topic, the key issues, bottlenecks and minimum common specifications must be identified

## Suggested approach for further standardisation discussions

- Assessing impact of different aspects to identify key elements

- Underlying questions for further discussion:
  (1) **What** aspects **can / must be defined on a European level** and which are subject to national regulation?
  (2) What are the **no-regret decisions?**
  (3) Where do **attractive alternatives exist** compared to a central standardization approach?
  (4) How could a **future-proof, minimum common specification for a European infrastructure** look like that considers the key elements and questions identified?
    a) What are contaminants that must/need to be removed anyway?
    b) Which are the "pain points" and open questions, which need further discussion / analysis?

→ The study aims to provide valuable input for this further discussion – but can not formulate specification!

# Agenda





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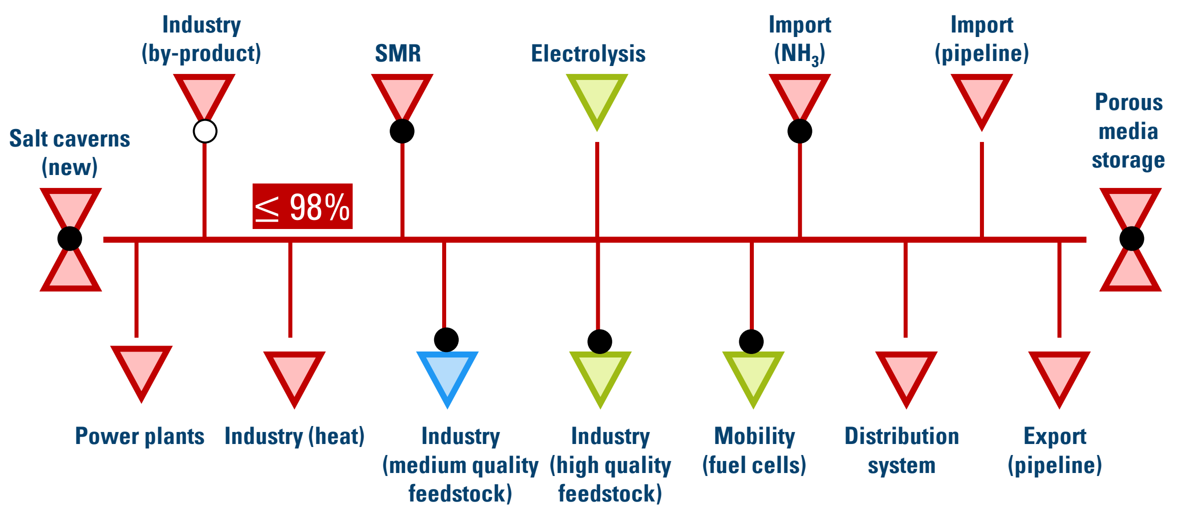
# Setting a uniform minimum grid specification is relevant for all steps along hydrogen supply chain

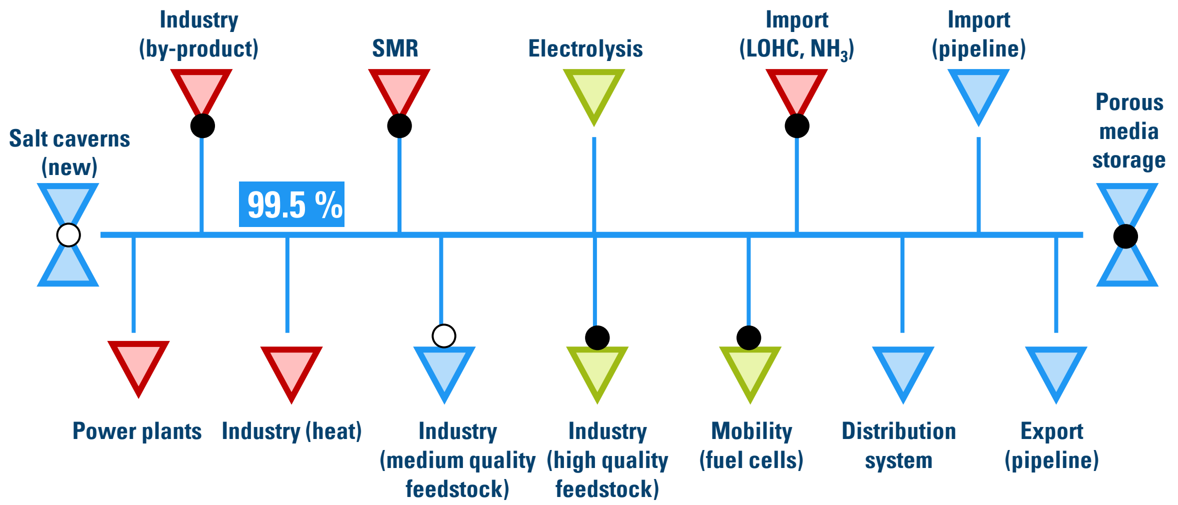
## Grid specifications – $H_2$ level / purity level (in mol%)

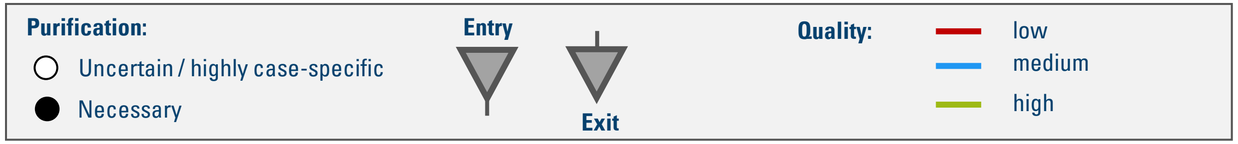
- Decision for certain quality level as **(minimum) grid specification** (=entry and exit specifications) impacts all actors
  - Aim: **harmonisation key for unhindered cross-border trade** within European MSs
  - Important: not only about **minimum $H_2$ content** (in mol%) – but also about **limits for key contaminants**
  - Key question: **responsibility for purification** (in line with additional costs)

**Example "low purity grid specification" (≤ 98%)**




**Example "medium purity grid specification" (99.5%)**



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## Grid specifications – existing standards

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| 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* |
| Transport / Pipeline | 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.* |
| Transport / Pipeline | 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 |
| Transport / Pipeline | 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) *Note: Currently under revision to (possibly) include **99.5%** as additional "grade" "group A+"* |
| Transport / Pipeline | 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 | Specifications for different end-uses ($H_2$ as fuel) | Different Grades (A-F) for state of hydrogen and end-uses **≥98.0% (Grade A) – ≥99.995% (Grade C)** |
| End-use | 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 |

# A wide range of possible contaminants and physical properties are covered in existing standards on gas & hydrogen quality

- Key specifications of $H_2$ quality in most relevant standards

| Key Constituents: |
| --- |
| Hydrogen fuel index (minimum mole fraction) |
| Total non-hydrogen gases (maximum) |
| Total gases without calorific value |

| Physical properties: |
| --- |
| Wobbe index / calorific value |
| Water dew point |

| Maximum concentration of individual contaminants: |
| --- |
| Water ($H_2O$) |
| Hydrocarbons except methane (C1 equivalent) |
| Methane ($CH_4$) |
| Oxygen ($O_2$) |
| Helium (He) |
| Nitrogen ($N_2$) |
| Argon (Ar) |
| Carbon dioxide ($CO_2$) |
| Carbon monoxide (CO) |
| Sulphur compounds (S1 equivalent) |
| Formaldehyde (HCHO) |
| Ammonia ($NH_3$) |
| Halogenated compounds (Halogen equivalent) |
| Maximum particulate concentration |
| Particulate concentration / permantent particulates |

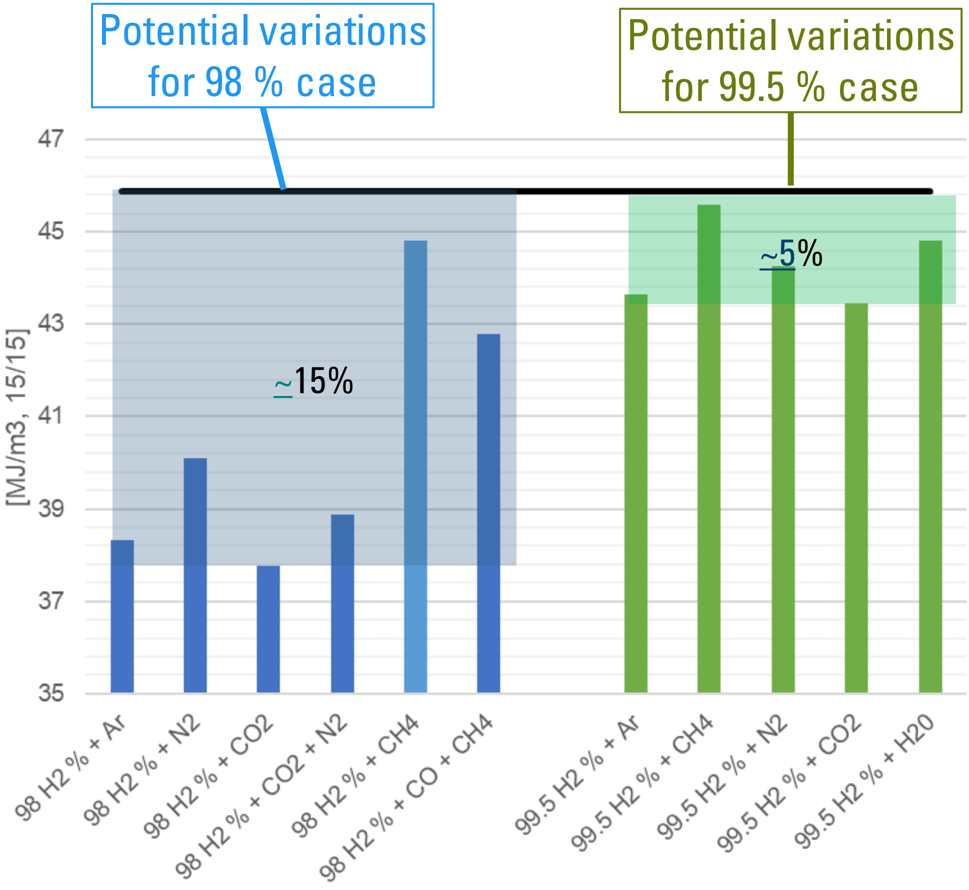
# In case of low minimum hydrogen content (e.g. 98%), also calorific and combustion related properties of the gas are relevant

- Grid specifications – physical gas properties (i.e. Wobbe index)

- Wobbe index describes **combustion-relevant gas properties** (for burners, engines, furnaces)
  - In those applications, **rather constant gas properties** as well as **limited timely variations** are needed (see end-use)
  - Not relevant for other applications where $H_2$ is used as feedstock
- Especially with **low purity requirements** (e.g. 98 %), variation in level of other contaminants **can lead to significant differences in calorific properties**: 38.3 – 45.8 MJ / m$^3$ (~15%)
- Changing grid specifications to higher levels at later stage may require adaptation of certain end-use equipment

→ Question: Share of relevant processes in overall demand?

**Exemplary calculations of Wobbe index**



# Agenda



# Depending on hydrogen production technology, different contaminants will be introduced into the gas stream

## Impact of production technology on hydrogen quality

**Possible contamination depend on production technology and purification method applied:**

- Electrolysis (AEL, PEM, also others): no major issue identified, de-oxy dryer SoA to remove $O_2$ and $H_2O$ for achieving >99.97 %
- SMR: CO and $N_2$ as key contaminants,
- Ammonia crackers: $NH_3$ and $N_2$ as key contaminants

} All technologies except electrolysis **require PSA / gas treatment anyway**

- Others: $LH_2$ imports → very pure due to liquefaction; Pipeline imports: question of cross-EU-border specs?
- Key literature sources:
  - Risk of contamination: see ISO 14687 / Bacquart et al. 2018
  - Also: analytical technologies (out of scope here): see A. Casola (SNAM) – presentation at ENTSOG meeting 17.11.2024

Overview of key contaminants and risk of occurrence

| 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 (+) |

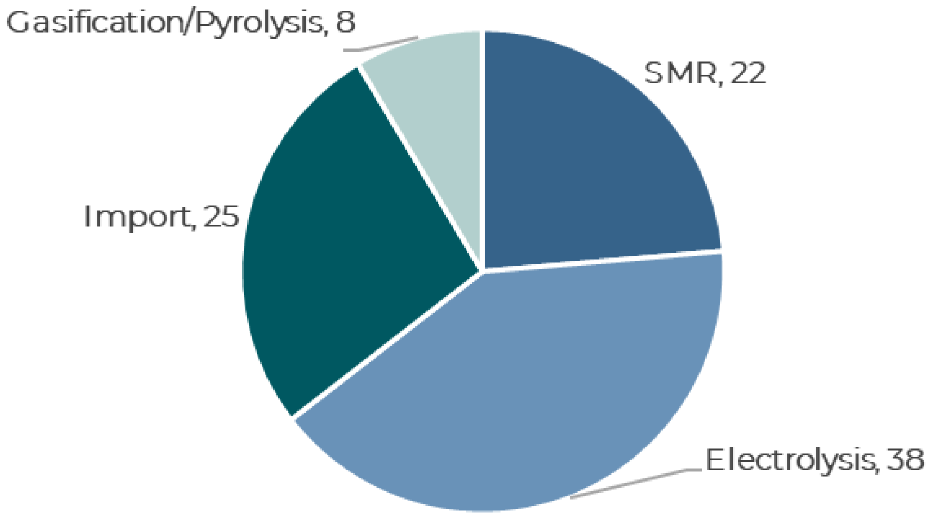
Probability: (++) frequent, (+) possible (o) rare (-) very rare (based on terminology used in Bacquart 2018).
No probability analysis performed for cases without rating.

# Stakeholder survey showed that there is an expectation for a very heterogenous supply situation in Europe

## Hydrogen supply – technology mix

**Stakeholders' perception on further market development**

- Strong agreement among stakeholders among which production technologies will dominate long and short-term
- Supply mix of different production technologies (electrolysis, steam methane reforming, import and gasification / electrolysis)
- Short-term: import and blue hydrogen
    - Coastal nations more inclined to mention import
- Long-term: dominant role of electrolysis




(Source: Stakeholder survey)

Explanation: 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=53.

# Taking into account hydrogen end-users' quality requirements and existing standards is considered important element in European legislation

## Regulatory background in Gas Package on considering end-users' perspective

- **DIRECTIVE (EU) 2024/1788:**
  - *(94) […] In that sense, it is important for the hydrogen system to transport, store and handle hydrogen of a high grade of purity **taking into account hydrogen end-users' quality requirements**, as opposed to hydrogen blended into the natural gas system. It is also important that hydrogen quality standards provide further criteria to determine the commonly acceptable hydrogen purity levels. It is necessary for a bandwidth of acceptable hydrogen purity levels and other relevant hydrogen quality parameters, for example contaminants, to be defined by means of a technical standardisation process by European standardisation bodies.*

  - *(95) In some cases, depending among others on the topography of hydrogen networks and the population of end-users connected to the hydrogen networks, hydrogen quality management by hydrogen network operators could become necessary (for example, purification). Therefore, regulatory authorities should task hydrogen network operators with ensuring efficient hydrogen quality management in their networks where necessary for system management. When undertaking such activities, hydrogen network operators should **ensure stable hydrogen quality for end-users**, including in hard-to-decarbonise sectors, **by complying with applicable hydrogen quality standards**.*

- **REGULATION (EU) 2024/1789:**
  - *(99) In order to fully take into account the quality requirements of hydrogen end-users, technical specifications and standards for the quality of hydrogen in the hydrogen network should **take into account already existing standards** setting such end-user requirements, for example, the standard EN 17124.*

# End-use applications are very divers when it comes to suitable hydrogen specifications

## Overview - 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.

# End-use requirements are mostly focussed on possible contaminants and (for engines, turbines, burners) on combustion properties

## End-users' requirements based on stakeholder feedback

### $H_2$ as feedstock

Largest expected end-use:
- Haber-Bosch / $NH_3$
- SAF production
- DRI steel refining
- Oil refining

Requirements:
- Very stringent limits to contaminants that poison catalysts: **sulfur, ammonia**
- Limits to contaminants that lower process efficiency: **nitrogen, oxygen**
- Stringent limits → high purity

### Engines and Turbines

Diverse end-uses:
- Electricity generation
- Combined heat and power
- IC engines for maritime and heavy duty transport

Requirements:
- Limits for **variations in Wobbe index** in $MJ/m^3/min$
- Contaminant levels should be steady over time
- Contaminants which contribute to emissions (NOx) should be reduced

### Burners

Limited expected end-use:
- Hard-to-decarbonize industries: high temperature (e.g. glass and ceramics)
- Process heat

Requirements:
- Limits for **variations in Wobbe index** in $MJ/m^3/min$
- Direct heating processes have contaminant limits
- Indirect heating processes require affordability and calorific value

### Fuel Cells

Limited expected end-use:
- Small mobility systems such as LDV / HDVs, trains, buses
- Stationary systems / off-grid

Requirements:
- Very stringent contaminant limits to prevent fuel cell poisoning (similar to feedstock)
- However, direct connection to hydrogen grid unlikely (at least for HRS)

**High expected volume** → **Low expected volume**

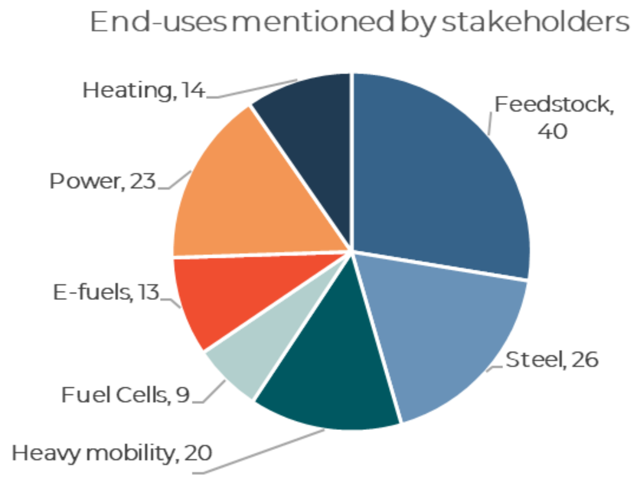
Please note: The report contains an extensive list of contaminants and their rationales for all end-users:

# Industry feedstock, steel and power sector (re-electrification) are considered as key markets for hydrogen in the future based on stakeholders' feedback



**Stakeholders' perception on further market development**

- Key applications: feedstock and steel, power sector
- Only limited role in residential heating
- Mobility sector: hydrogen use for e-fuel production and directly in fuel cells / heavy duty transport




(Source: Stakeholder survey)

**Key issues for end-use stakeholders**

- 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.

Explanation: 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=53.



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# Rededicated pipelines pose a risk of contamination with hydrocarbons during transition phase – increasing quality level over time may be possible

Infrastructure - pipelines

| Application | Relevant quality aspects | Summary & Key Learnings |
|---|---|---|
| Transport – new pipeline | High quality $H_2$ transport (>99,97%) not considered an issue | • Contaminations in general very unlikely ($N_2$, $O_2$ as major risk due to improper purging)<br>• Existing pipeline networks show feasibility of >99.99% |
| Transport – rededicated pipeline | >98% considered feasible, e.g. CEN/TS 17977:2023 | • Intensive cleaning required before repurposing<br>• Transition phase: residues (liquid and solid deposits) from NG usage will be present / impact of gas flow<br>→ risk to exceed limits for e.g. hydrocarbons (>2 ppm or sulphur compounds<br>• Significant decrease of contaminant content after transition time (however, time period unclear) |

- Possible further contamination by compressor oils / lubricants
- Higher quality levels may be feasible for repurposed pipelines after transition period (several years)

# Distribution grids can represent high-quality "pockets", able to ensure higher quality specifications that interconnected transmission systems

Specific challenges / aspects for distribution grids

What is special about distribution grids

- Local, decentral production with focus on electrolysis, no direct import connection or large-scale SMR plant
  → **high-quality "pockets**" possible
  → option for dedicated supply of industrial hubs or other users, e.g. HRS
  → purification needed at interconnection points between transmission and distribution system (at pressure-reducing stations / reverse flow stations)
- Use of (new) **PE and PVC pipes** instead of steel pipes will not introduce additional contaminants
- Options for **odorization** (on DSO level only or TSO & DSO level) as well as alternative safety measures to be discussed

# Underground hydrogen storage considered a critical element with high purification efforts (post-treatment) in case of high grid quality levels >98%

Infrastructure – underground storage

| Application | Relevant quality aspects | Summary & Key Learnings |
|---|---|---|
| Storage – salt caverns | Sign. higher than ≥98 mol% not considered economically feasible (multi purification steps required, incl. drying, desulphurisation, PSA etc. ) | • Possible contaminations: brine residues, former usage (for rededicated caverns), microbiological activity |
| Storage – porous media | See salt caverns<br><br>Additional purification needs compared to salt caverns required (separation $CH_4$ and $H_2$) in multi-step purification (PSA + membrane) | • Key contaminants: $CH_4$, $H_2O$, sulphur compounds.<br>• Depleted gas (and oil) fields: continuous decrease in hydrocarbon content, purification from low $H_2$ level (e.g. 50%) required<br>• For Aquifers: higher quality may be feasible<br>• Microbiological activity (consuming $H_2$ and forming e.g. $H_2S$ or $CH_4$) considered as major risk |

- Pre- and post-treatment required (level of contaminants / risk highly site-specific)
- Storage sites: considered as pivotal element / bottleneck for higher $H_2$ quality levels within the grid



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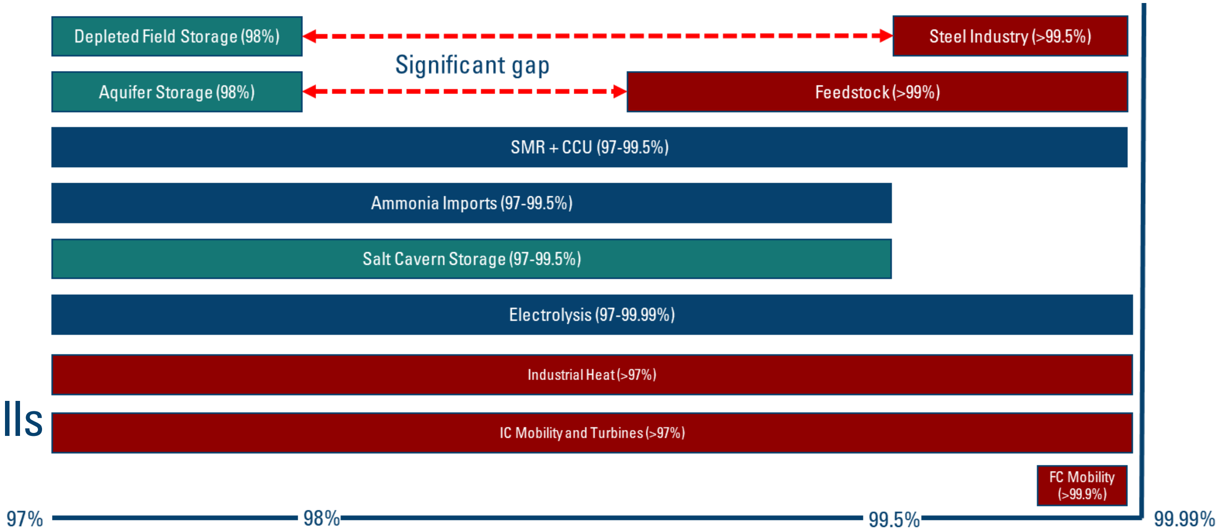
# Based on stakeholders' input, there is a mismatch between hydrogen storage capabilities and end-use requirements for certain applications

## Mismatch in preferred hydrogen quality

- End-use requirements can be very stringent
- Non-salt cavern storage operators have economic/technical difficulties delivering very high quality

→ **gap between the highest-volume end use (chemical feedstock) and gas supply (from storage)**




- Sulphur-based contaminations caused by microbiological activity can poison catalysts in industrial processes & fuel cells
- If the limits are not stringent enough in the network, end-users could prefer current hydrogen delivery methods instead of the backbone

- **Purification at storage exit is expensive**, new equipment will need to be purchased and there is often no use for the off-gas (high hydrogen content, >10%!)
- Applied research is needed to **understand risk and reduce contaminants from gas storage** by storage selection and limiting entry contaminants or more affordable local or centralized purification



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# A set of different purification technologies is applied along the hydrogen supply chain, incl. PSA, adsorbers and drying processes

Overview of key purification technologies along supply chain

| | |
|---|---|
| **Production** | • **Pressure Swing Adsorption (PSA)** for carbon monoxide (CO), carbon dioxide ($CO_2$) and ammonia ($NH_3$)<br>• **De-Oxy Dryer** for oxygen ($O_2$) and water ($H_2O$)<br>• **Adsorber technologies** for removing sulphur compounds (e.g. $H_2S$) and hydrocarbons |
| **Transport (repurposed NG pipelines)** | • Regular cleaning operations, such as **pigging**<br>• **Adsorption** for removal of residual sulphur traces |
| **Underground $H_2$ storage (UHS)** | • **Pre- and post-treatment** required<br>• **Gas drying processes, PSA** and **adsorption technologies** (to remove water / sulphur compounds) |
| **End-use** | • Fuel cells: highly specific **filter units (via adsorption)** for critical impurities such as ammonia, sulphur compounds and odorants |

**Potential use of existing purification technologies and assets:** amine scrubbing for $CO_2$ and $H_2S$ removal and molecular sieves for dehydration widely used for natural gas but not optimized for $H_2$. PSA and membrane systems used for existing $H_2$ purification (e.g. from SMR) rather decentral and not established for interconnected networks

# The steps of oxygen removal and PSA (for $N_2$, CO, $CO_2$ & $CH_4$) are considered main cost drivers among the purification technologies

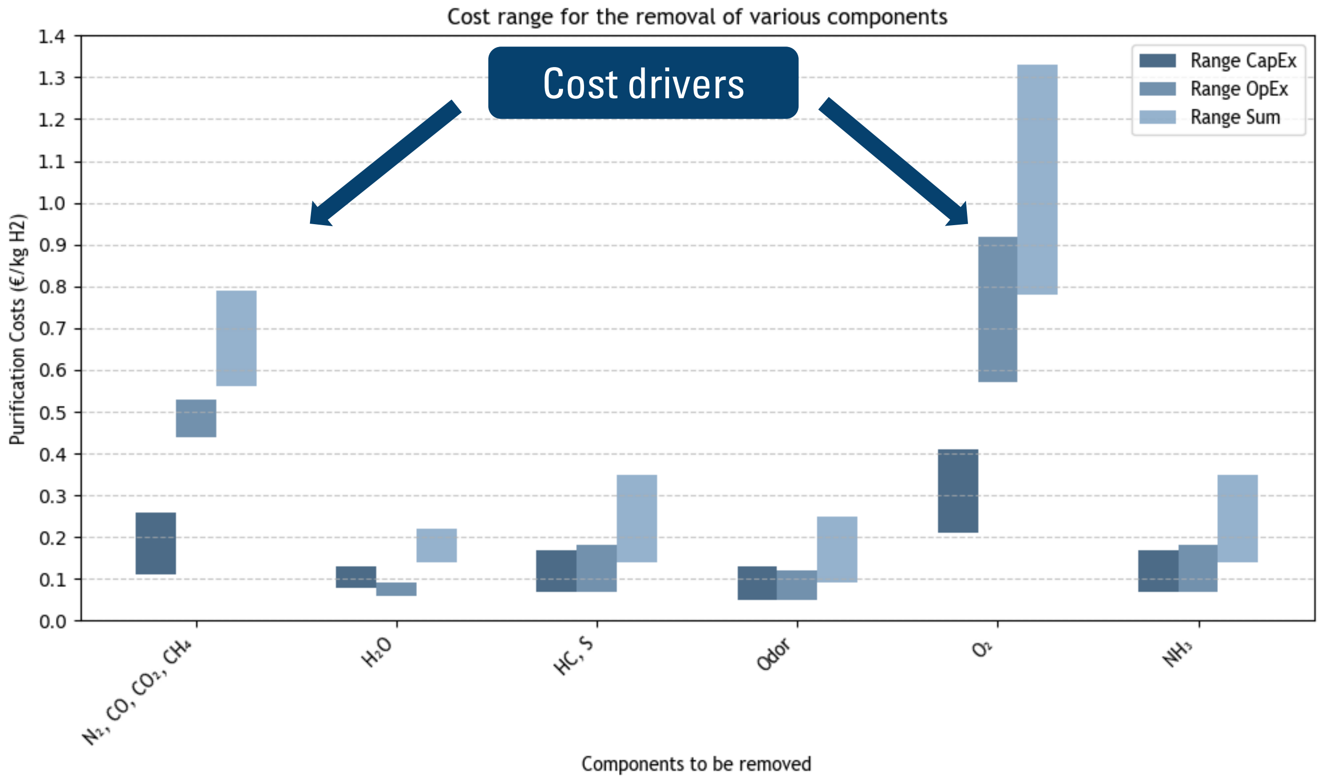
Cost analysis – Part 1: Specific purification costs

**Results of literature & market analysis:**

- Costs for removing various impurities were analyzed (CAPEX and OPEX)
- Examined contaminants: $N_2$, CO, $CO_2$, $CH_4$, $H_2O$, hydrocarbons (HC), sulphur compounds (S), odorants, $O_2$, and $NH_3$

**Key findings of cost analysis:**

- Highest costs: oxygen removal and PSA
- Lowest costs: Removal of odorants and $H_2O$
- Cost drivers:
  - Varying complexity
  - Resource intensity / energy demand
  - Scaling effect




*Cost range considers the full range of treatment costs in the different cases, as well as the inclusion of different plant sizes

# The analysis takes purification needs at production sites, at underground $H_2$ facilities and purity requirements for different end-user groups into account …

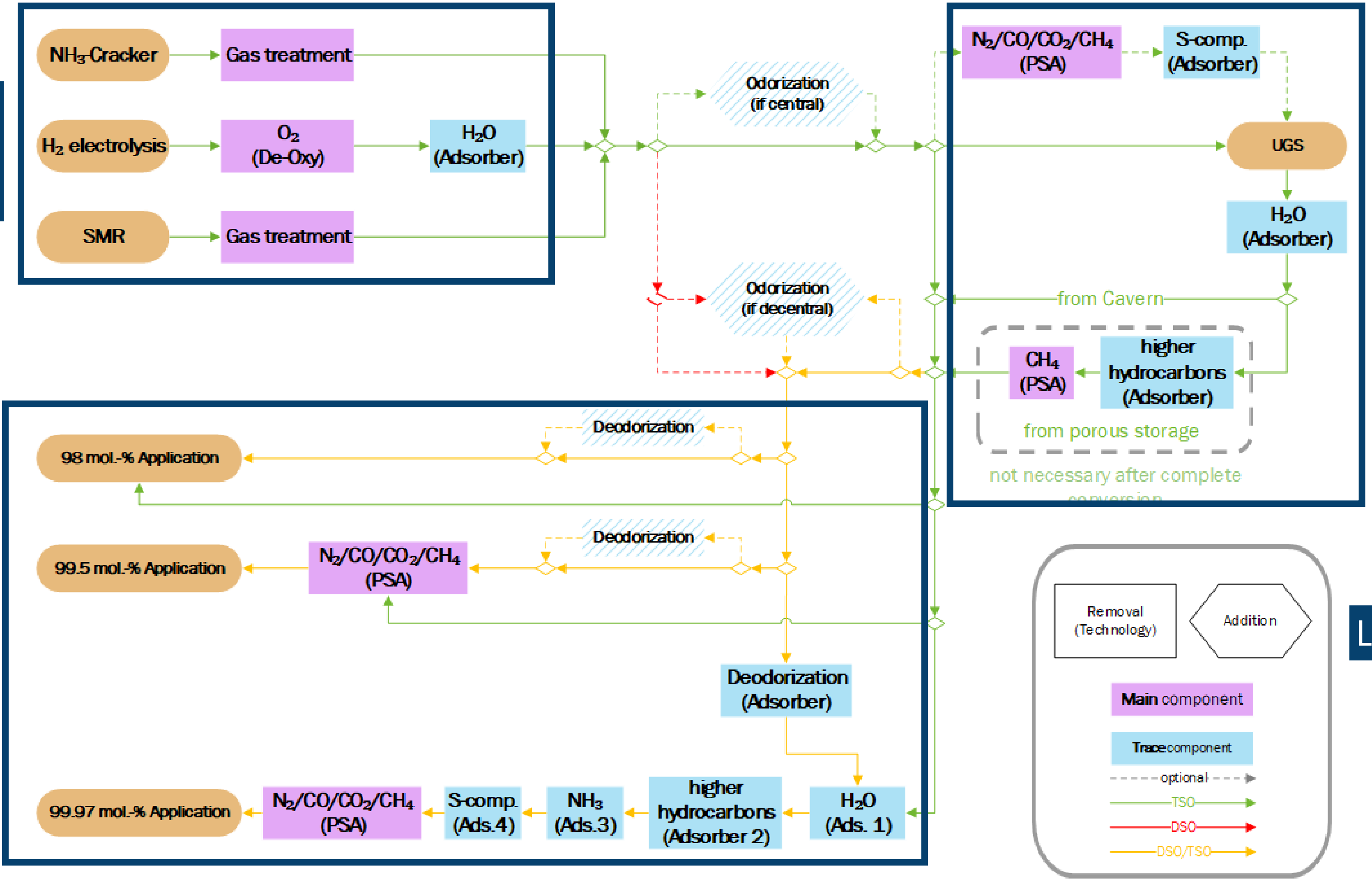
- Explanation (1/2)

$H_2$ production (exemplary pathways) + purification steps

$H_2$ storage (in salt caverns and porous media)

+ pre & post-purification

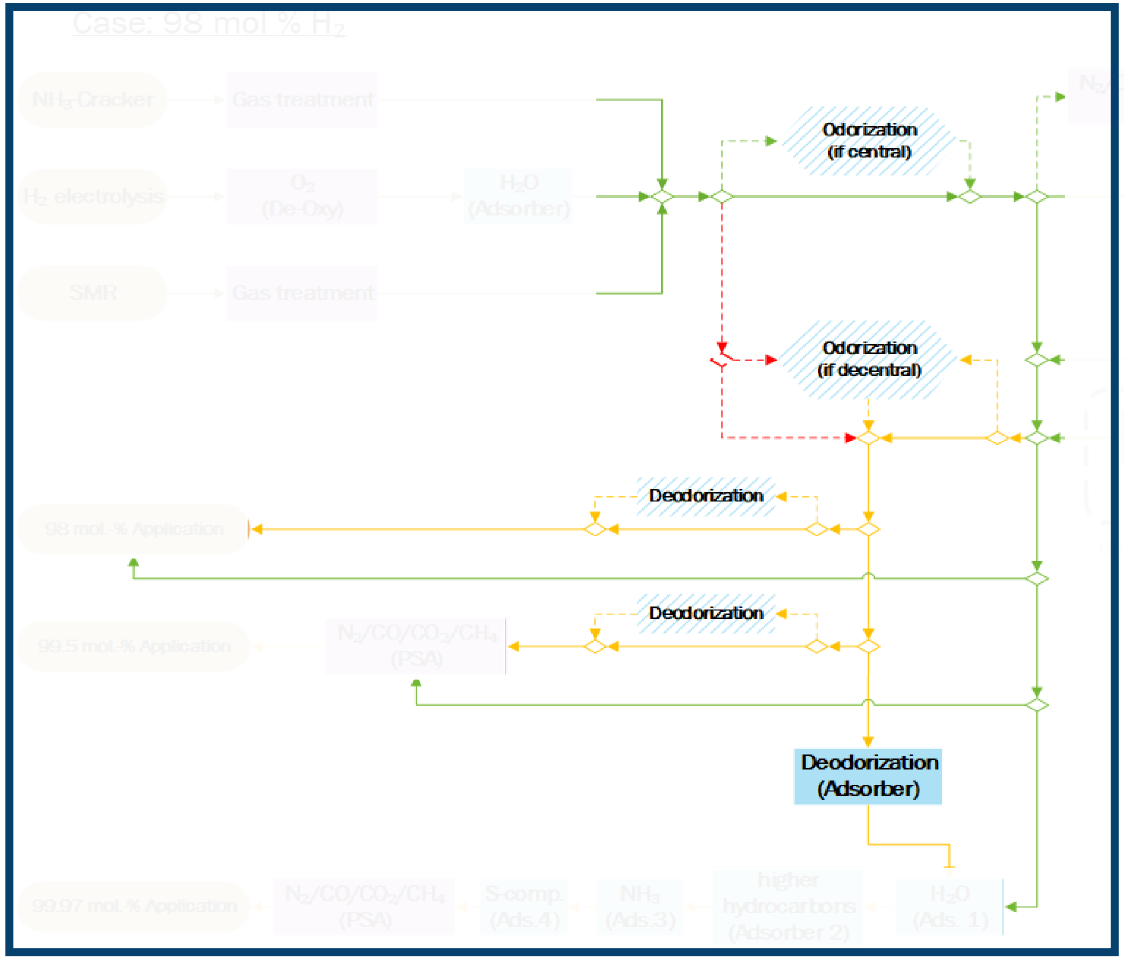
$H_2$ end uses + purification steps




Legend

# … under the assumption of a certain grid quality specification (= “Case”)

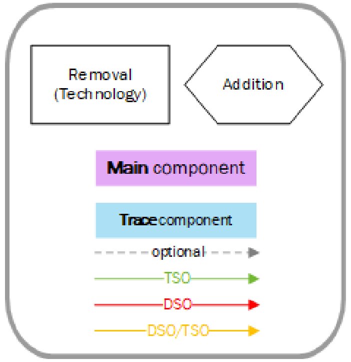
- Explanation (2/2)




**Hydrogen grid**
= transmission (green) and distribution grid (red / yellow)

**Grid specifications according to each “Case”**
(=98, 99.5 & 99.97 mol%)

**Optional: odorization** (= yellow)
(DSO level only or DSO & TSO level)




Legend



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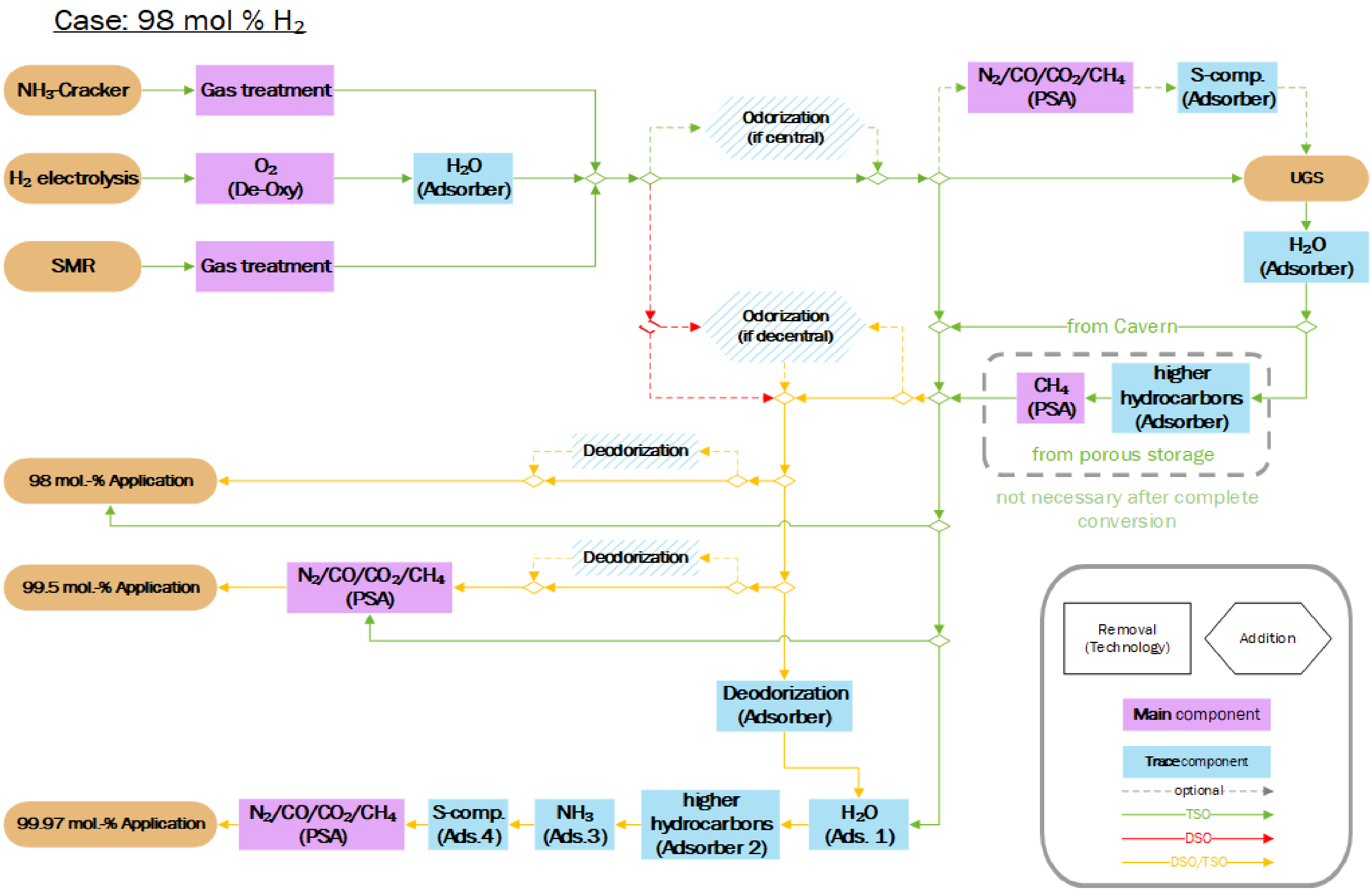
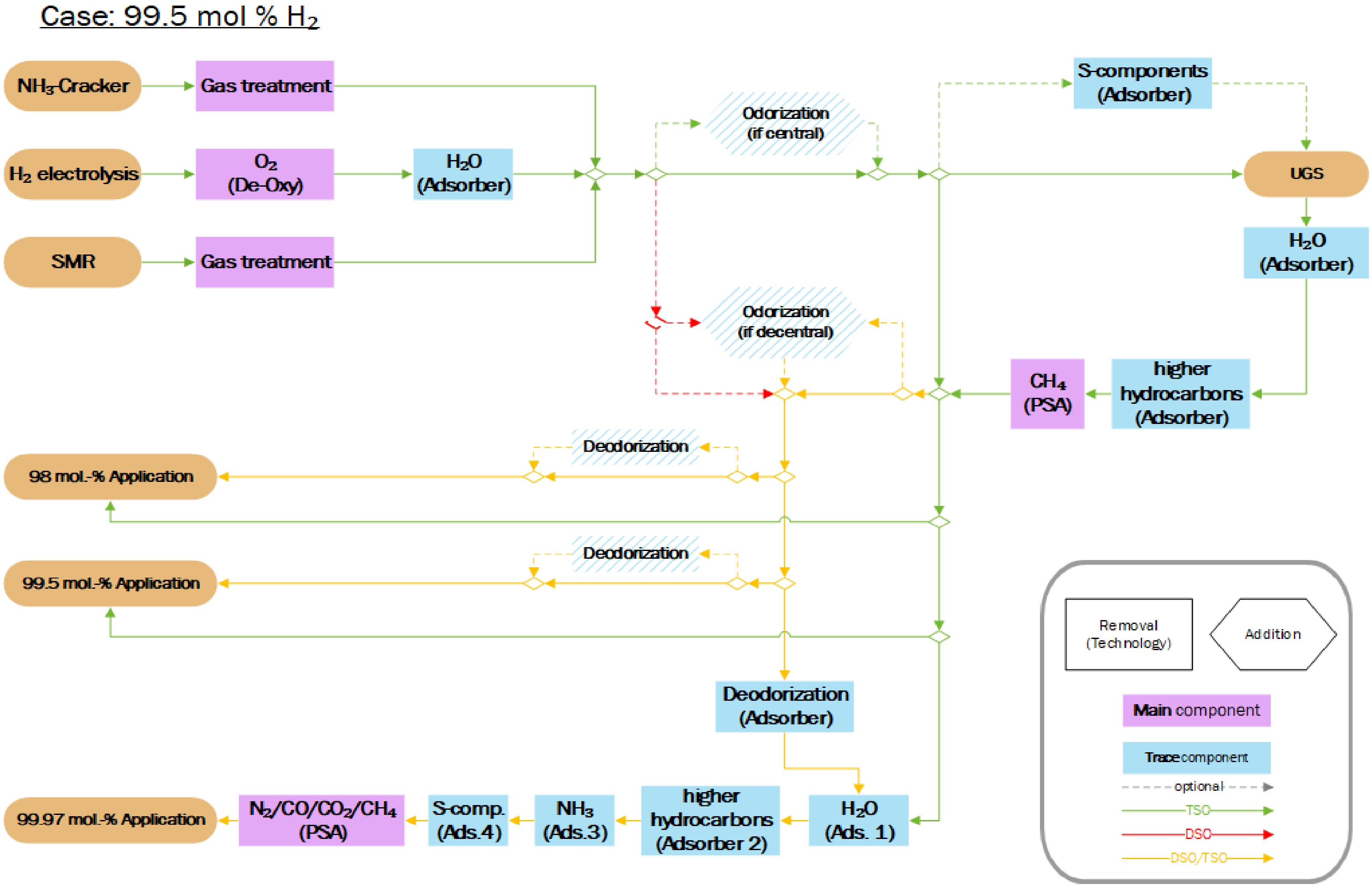
# In case 1, a low grid quality of 98 mol% requires high purification efforts at storage inlet and for sensitive hydrogen consumers

- Case 1: 98 mol %



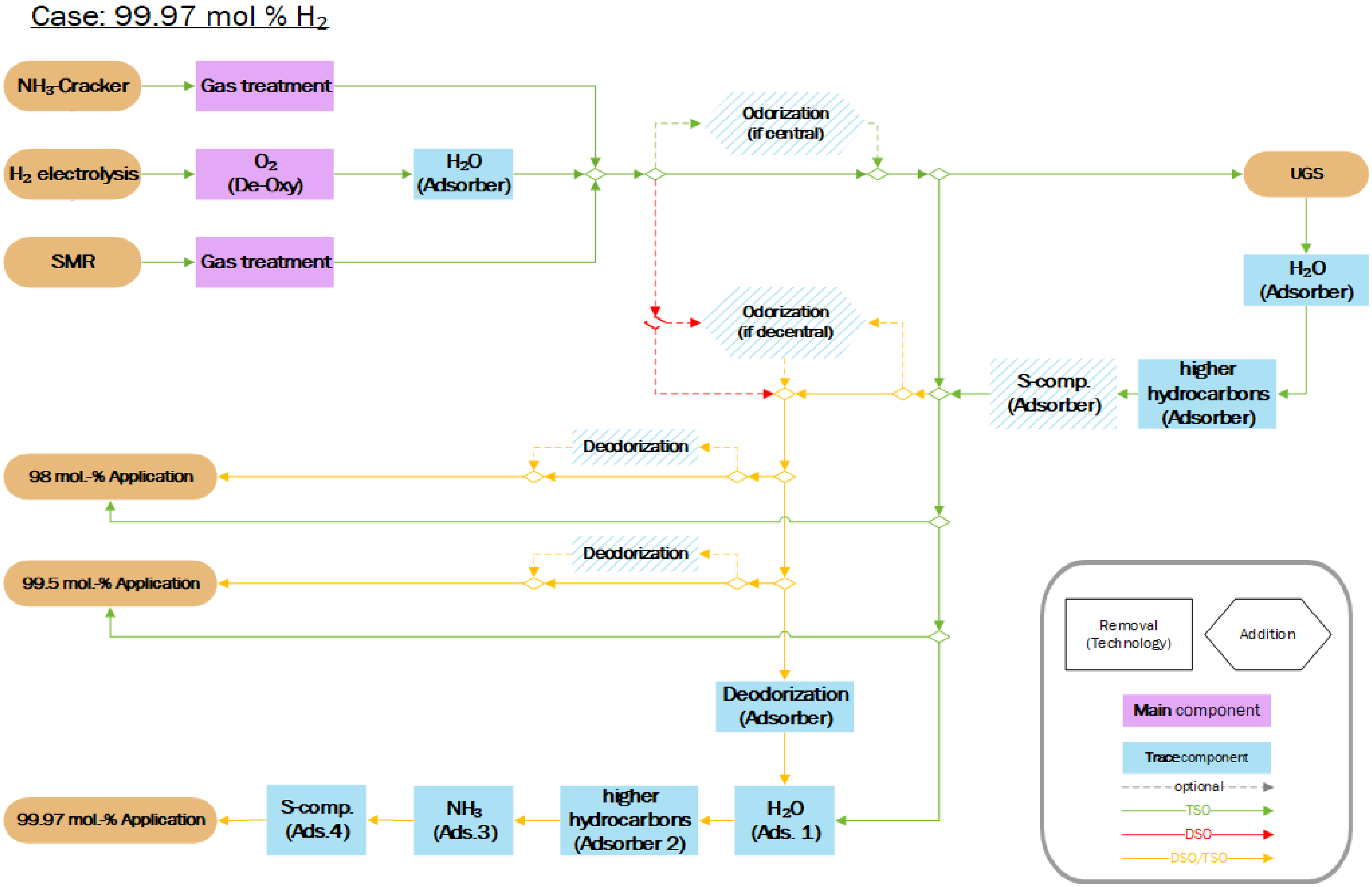
# A medium grid quality of 99.5 mol% leads to no additional PSA steps at storage inlet and for most customer groups. UGS will require post purification.

- Case 2: 99.5 mol %



# Purification of trace components at highly-sensitive customers will also be required in case of high grid quality of 99.97 mol%

- Case 3: 99.97 mol %



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# A specific nomenclature is introduced in the study to differentiate between cases, configurations and scenarios

## Nomenclature

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 exemplary cases with differing grid specifications are considered (i.e. 98 mol%, 99.5 mol%, 99,97 mol%).

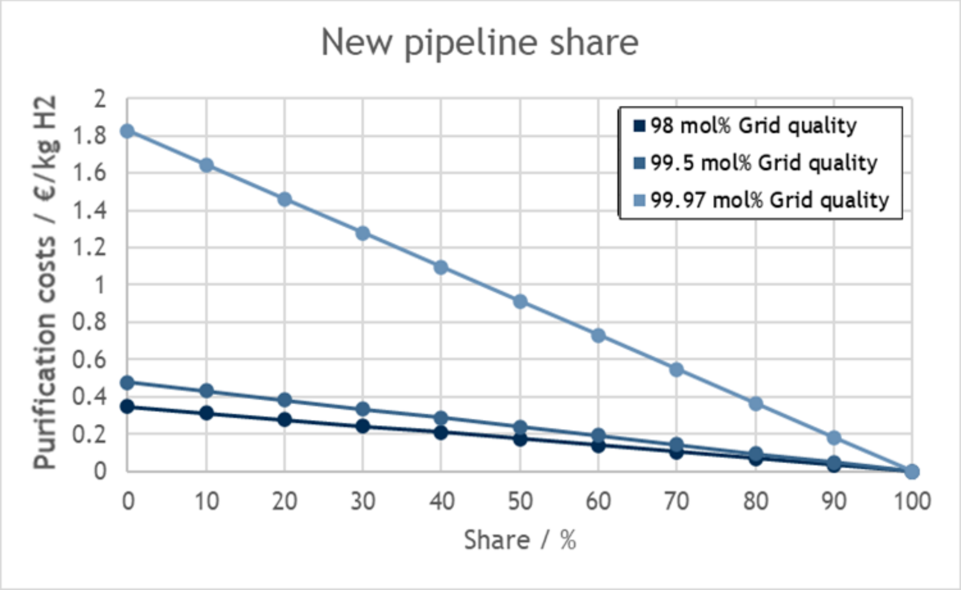
**Configuration:** The term (grid) configuration is referring to a **certain composition of the hydrogen infrastructure** in terms of pipeline (new vs. repurposed) or underground storage sites (salt caverns vs. porous media storages).
Here, two extreme configurations with different impact on the gas quality are distinguished:
- **best-case** (new pipelines and salt cavern storages) and
- **worst-case configuration** (repurposed pipelines and porous media storage sites).

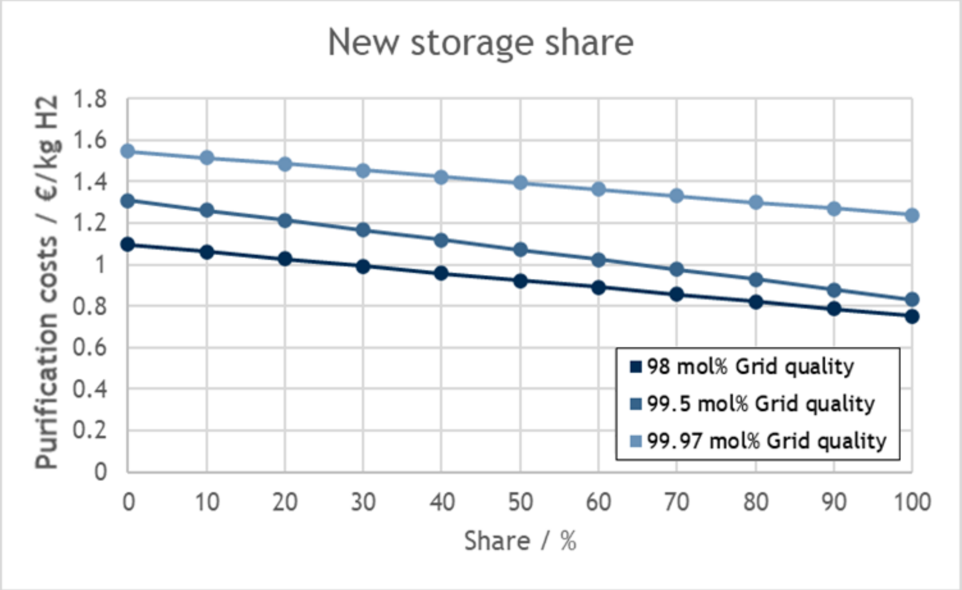
**Scenario:** With scenarios, **different developments of the hydrogen market or different country characteristics** are taken into account. Here, a certain set-up of infrastructure, storages and end-user demand compositions are assumed, including the hydrogen volumes that are considered in the infrastructure.

# Modular cost assessment allows to identify use of repurposed pipelines and porous media storage sites as important overall purification cost drivers

## Cost analysis – Part 2: Modular cost assessment (sensitivity analysis) – (1/2)

- Analysis based on the pre-defined grid specifications ("cases") – considering all purification needs described above based on average purification costs
- Impact of grid configuration for pipelines (left) and underground storages (right)
- Results: Repurposed pipelines and porous media storage significant cost drivers – also for 98% and 99.5% case



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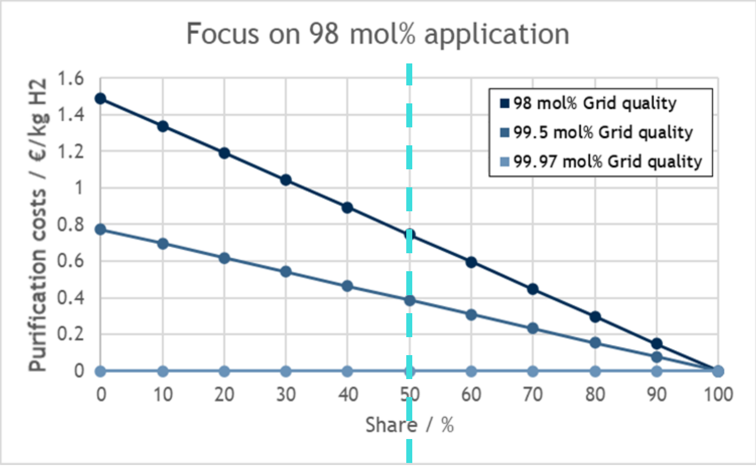
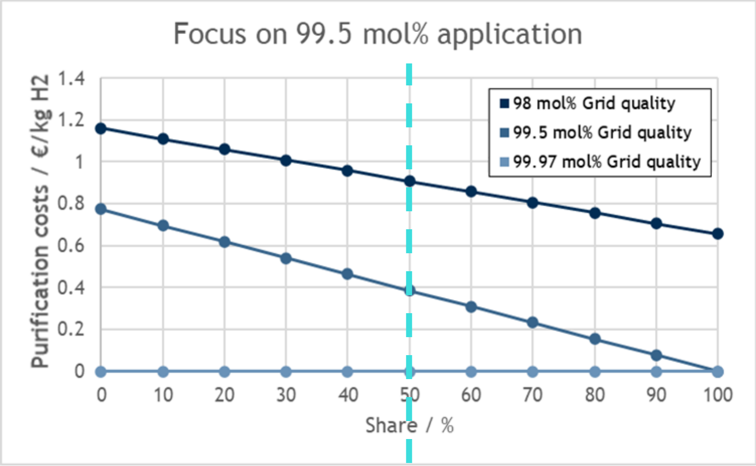
# Assumptions on end-user groups are – however – major cost driver (except of case with very high grid quality of 99.97%)

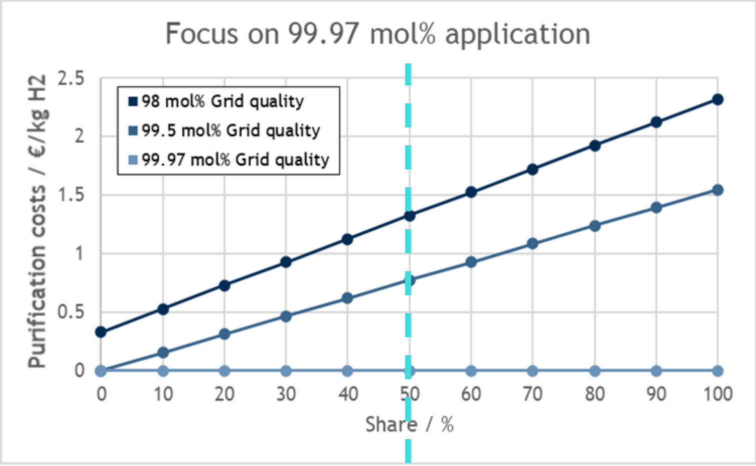
## Cost analysis – Part 2: Modular cost assessment (sensitivity analysis) – (2/2)

- Specific purification costs at end-users' sites for varying demand composition (see table).
- Results: purification needs at end-users with high quality requirements significantly drive costs

| Grid quality ("case") | Share end-user groups (98 / 99.5 / 99.97 mol% purity requirement) in % | | |
|---|---|---|---|
| | 50 %/25 %/25 % | 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 |




X-axis: variation in share of end-user group requiring 99.97 mol% hydrogen (with equal split among the other two end-user groups)

See table above

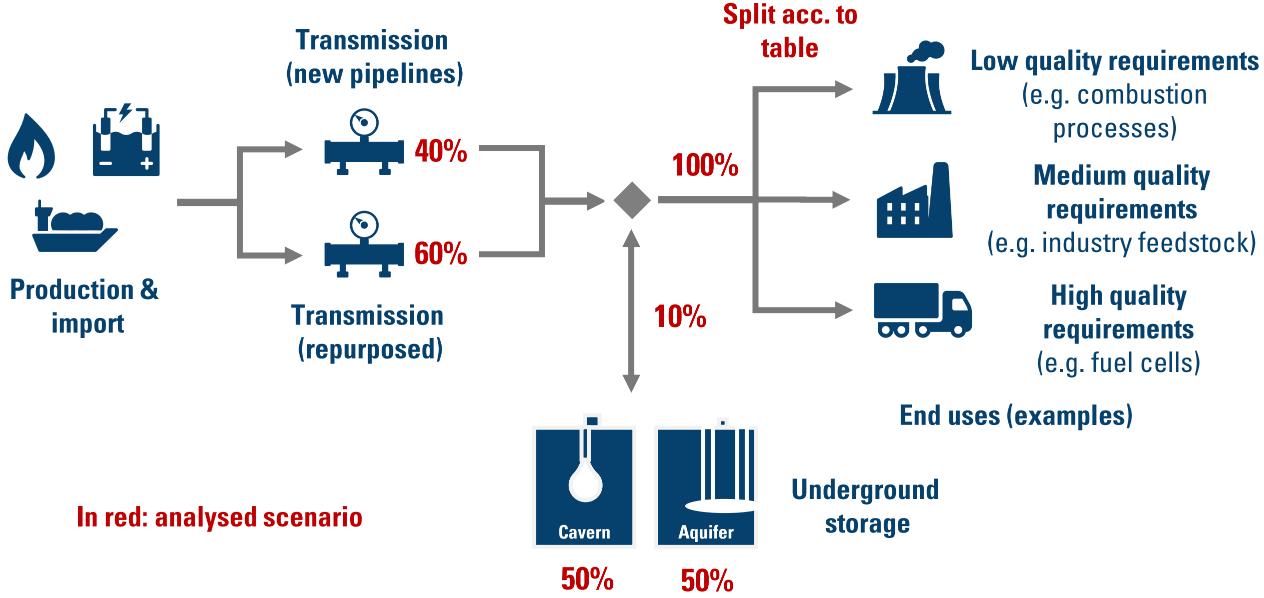
# Scenario-based cost assessment indicate additional purification costs of around 0.8 – 1.2 €/kg for main scenarios

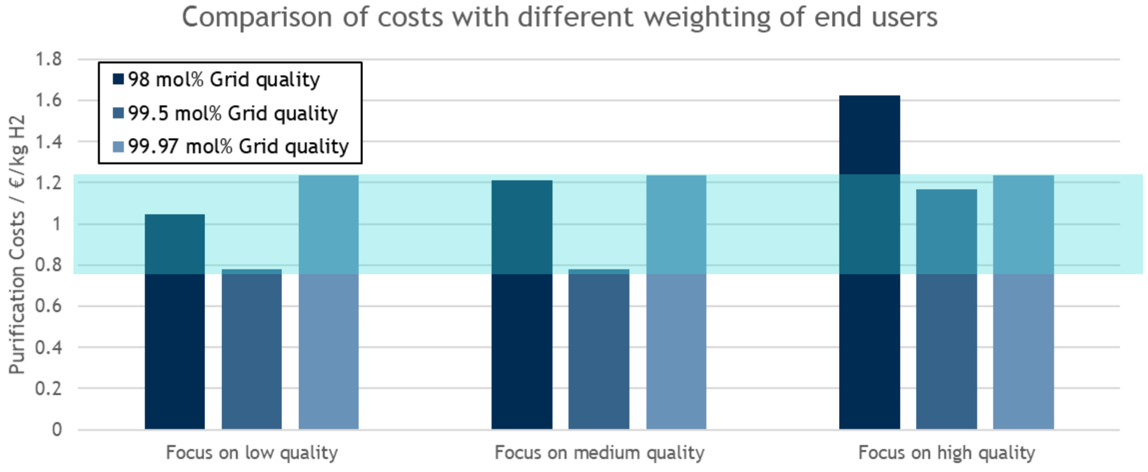
## Cost analysis – Part 3: Scenario-based purification cost estimation for the hydrogen value chain

**Key learnings from cost analysis:**

- Costs strongly depend on assumed grid configuration and end-users' shares (see diagram below) – range 0.8 – 1.2 €/kg
- Medium grid quality (here: 99.5 %) may be beneficial from overall system perspective (infrastructure, storage & end-users)
- However: not necessarily for individual market participants!

| 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 % |



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# Agenda



# The following example shows how purification costs along supply chain can be calculated for different assumptions

EXAMPLE

## Modular Purification Cost Tool - Example

Example distribution to illustrate the handling of the tool:

- 40 % of the hydrogen is transported via newly built pipelines
- 60 % flows through repurposed natural gas pipelines
- 90 % of the hydrogen is supplied directly to end-users
- 10 % is injected into underground storage facilities and are then equally split between new and repurposed storage infrastructures → 5 % allocated to each.
- Differentiation for end user groups according to the following table:

| 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 % |



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# The following example shows how purification costs along supply chain can be calculated for different assumptions

EXAMPLE

Modular Purification Cost Tool - Example of determining specific purification costs (1/10)

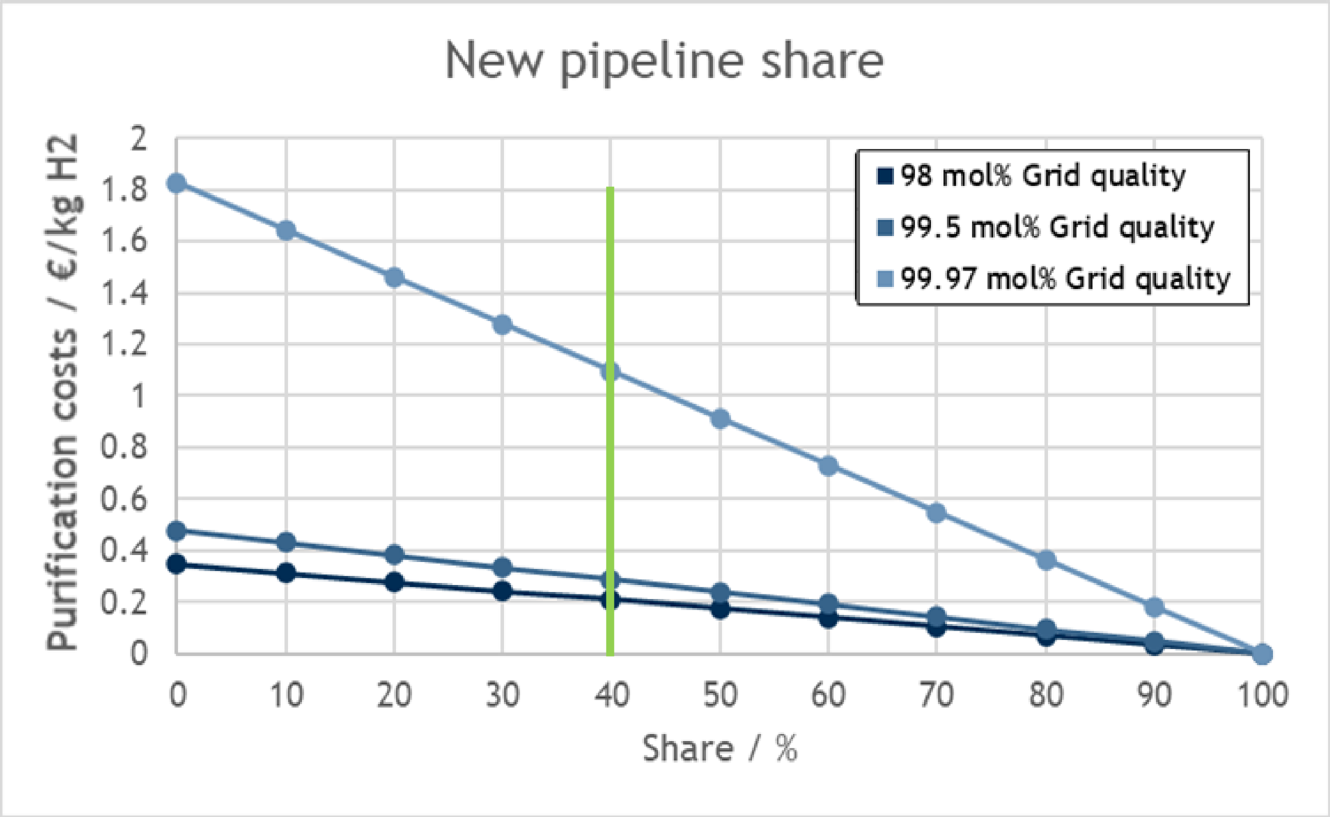
| Element | 98 mol% Grid quality | 99.5 mol% Grid quality | 99.97 mol% Grid quality |
|---|---|---|---|
| Pipeline | | | |
| Storage | | | |
| Focus low quality | | | |
| Focus medium quality | | | |
| Focus high quality | | | |
| Total costs | | | |

# Depending on the grid configuration in each MS, the share of new vs. repurposed pipelines is determined

EXAMPLE

- Modular Purification Cost Tool - Example of determining specific purification costs (2/10)

| Element | 98 mol% Grid quality | 99.5 mol% Grid quality | 99.97 mol% Grid quality |
|---|---|---|---|
| Pipeline | 0.21 €/kg $H_2$ | 0.29 €/kg $H_2$ | 1.10 €/kg $H_2$ |
| Storage | | | |
| Focus low quality | | | |
| Focus medium quality | | | |
| Focus high quality | | | |
| Total costs | | | |





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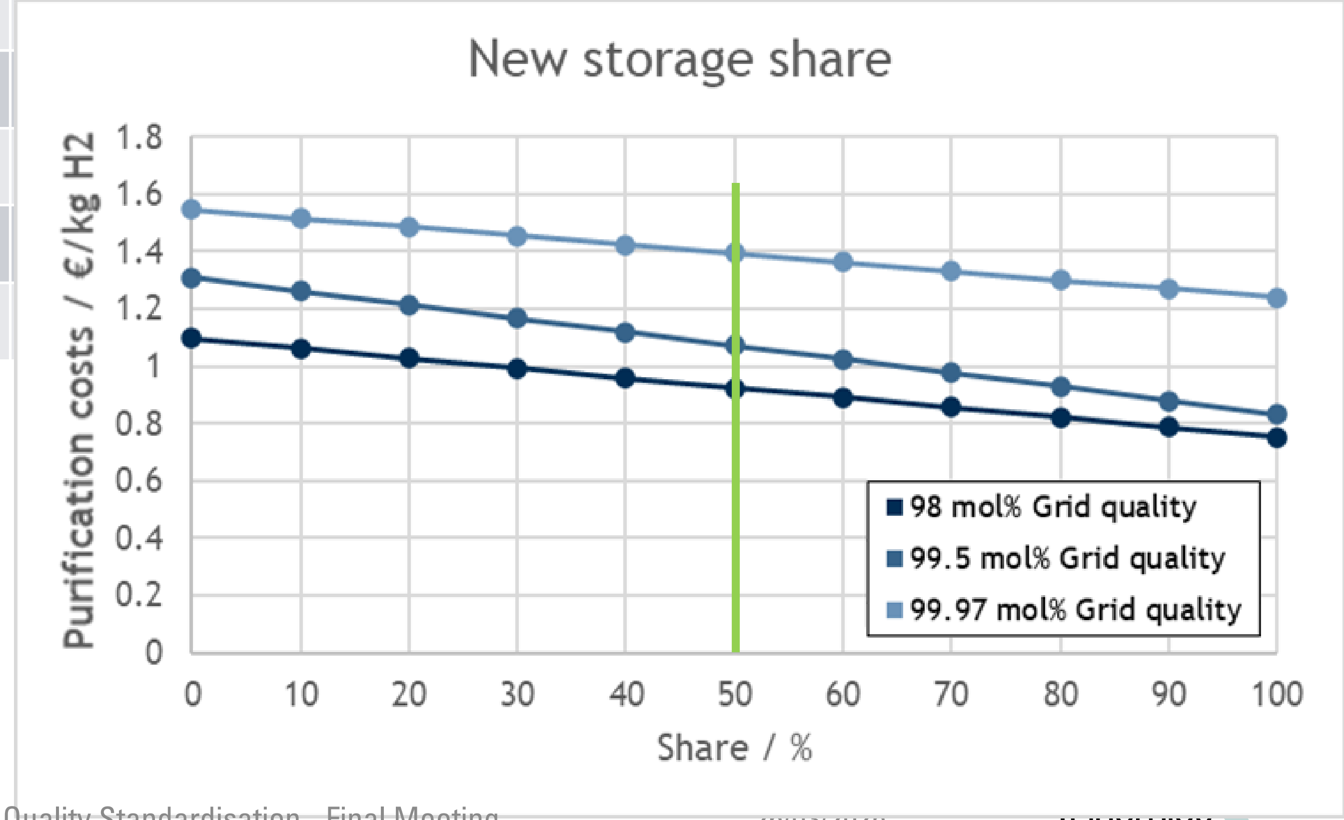
# Similar approach is taken for available underground storage (new salt cavern vs. porous media) – including the share of $H_2$ flow going into storage

EXAMPLE

Modular Purification Cost Tool - Example of determining specific purification costs (3/10)

| Element | 98 mol% Grid quality | 99.5 mol% Grid quality | 99.97 mol% Grid quality |
|---|---|---|---|
| Pipeline | 0.21 €/kg $H_2$ | 0.29 €/kg $H_2$ | 1.10 €/kg $H_2$ |
| Storage | 0.92 €/kg $H_2$ x 10%* = 0,09 €/kg $H_2$ | 1.07 €/kg $H_2$ x 10%* = 0,11 €/kg $H_2$ | 1.39 €/kg $H_2$ x 10%* = 0,14 €/kg $H_2$ |
| Focus low quality | | | |
| Focus medium quality | | | |
| Focus high quality | | | |
| Total costs | | | |



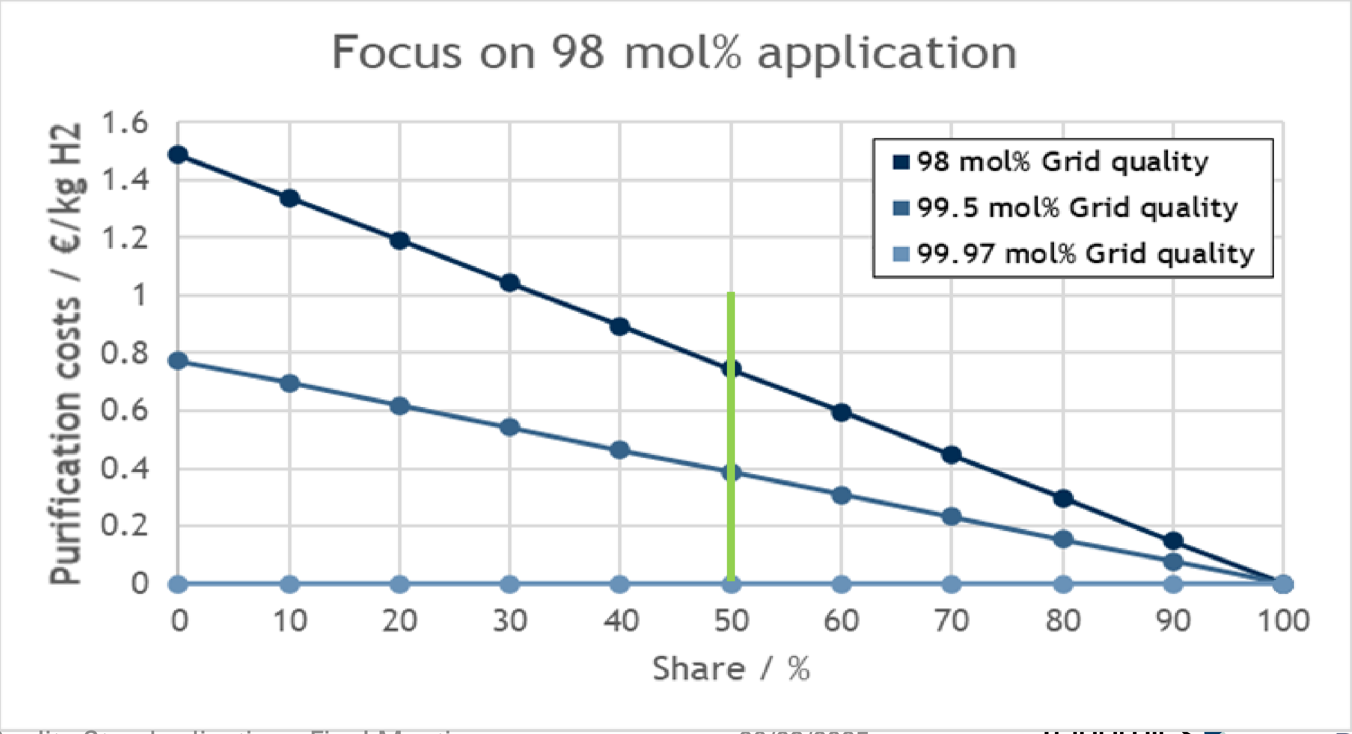

*Assumption: 10% of overall hydrogen flow in the grid will be put into underground storage.

EXAMPLE

# Assumption on end-user composition (1/3): 50% low quality (>98 mol%), 25% medium (>99.5 mol%) and 25% high (>99.97 mol%) quality

- Modular Purification Cost Tool - Example of determining specific purification costs (4/10)

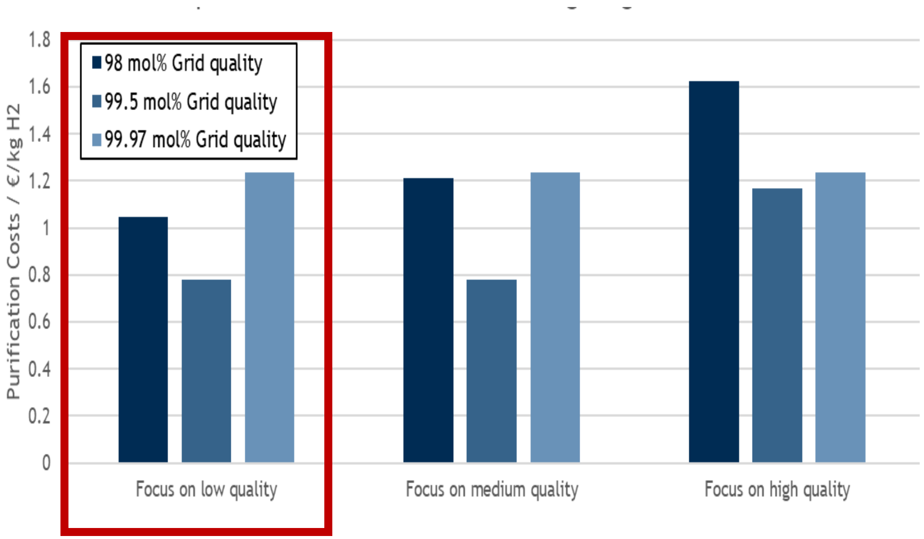
| Element | 98 mol% Grid quality | 99.5 mol% Grid quality | 99.97 mol% Grid quality |
|---|---|---|---|
| Pipeline | 0.21 €/kg $H_2$ | 0.29 €/kg $H_2$ | 1.10 €/kg $H_2$ |
| Storage | 0.09 €/kg $H_2$ | 0.11 €/kg $H_2$ | 0.14 €/kg $H_2$ |
| Focus low-quality end-user | 0.74 €/kg $H_2$ | 0.39 €/kg $H_2$ | 0.00 €/kg $H_2$ |
| Total costs | | | |



# In this scenario (1/3) , overall purification cost range from 0.79 €/kg $H_2$ for 99.5 mol% grid quality to 1.24 €/kg $H_2$ for 99.97 mol%

- Modular Purification Cost Tool - Example of determining costs along the chain using sensitivity analyses

| Element | 98 mol% Grid quality | 99.5 mol% Grid quality | 99.97 mol% Grid quality |
|---|---|---|---|
| Pipeline | 0.21 €/kg $H_2$ | 0.29 €/kg $H_2$ | 1.10 €/kg $H_2$ |
| Storage | 0.09 €/kg $H_2$ | 0.11 €/kg $H_2$ | 0.14 €/kg $H_2$ |
| Focus low quality end-user | 0.74 €/kg $H_2$ | 0.39 €/kg $H_2$ | 0.00 €/kg $H_2$ |
| Total costs | 1.04 €/kg $H_2$ | 0.79 €/kg $H_2$ | 1.24 €/kg $H_2$ |

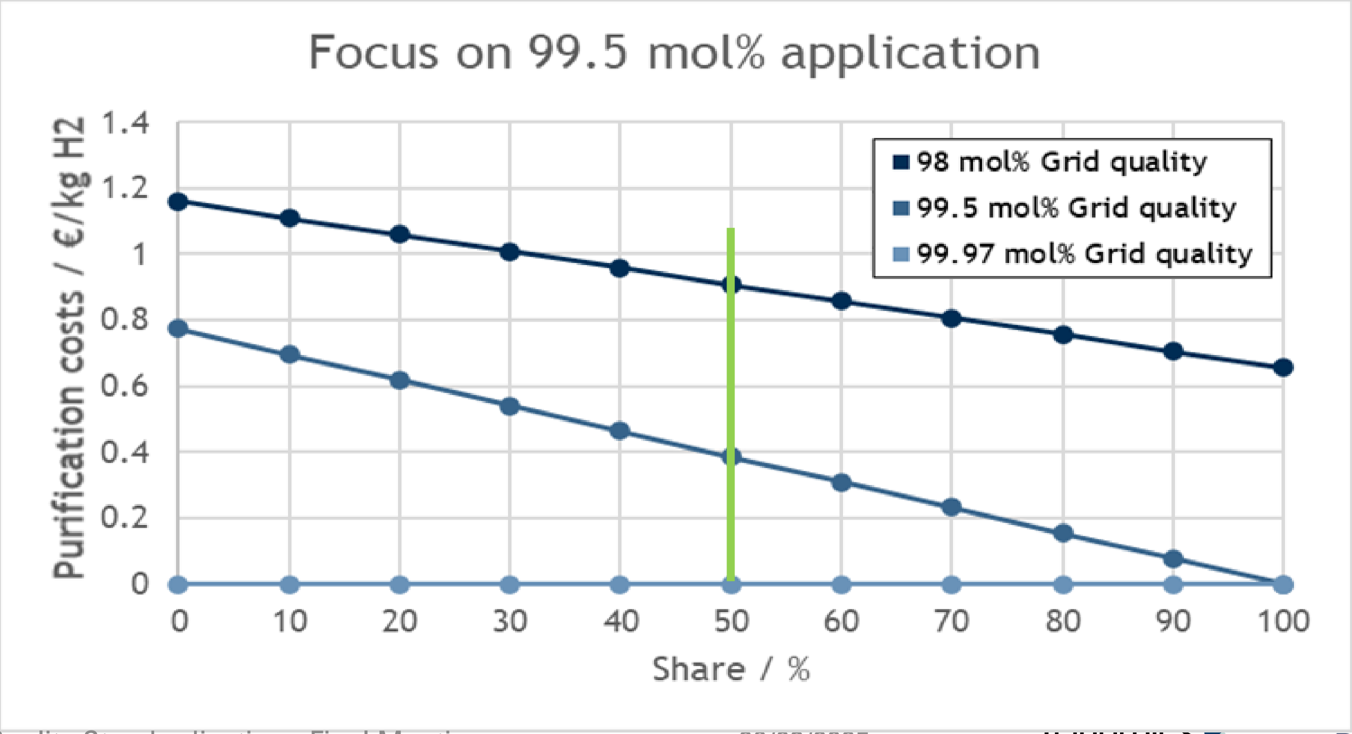


EXAMPLE

# Assumption on end-user composition (2/3): 25% low quality (>98 mol%), 50% medium (>99.5 mol%) and 25% high (>99.97 mol%) quality

- Modular Purification Cost Tool - Example of determining costs along the chain using sensitivity analyses

| Element | 98 mol% Grid quality | 99.5 mol% Grid quality | 99.97 mol% Grid quality |
|---|---|---|---|
| Pipeline | 0.21 €/kg $H_2$ | 0.29 €/kg $H_2$ | 1.10 €/kg $H_2$ |
| Storage | 0.09 €/kg $H_2$ | 0.11 €/kg $H_2$ | 0.14 €/kg $H_2$ |
| Focus medium quality user | 0.91 €/kg $H_2$ | 0.39 €/kg $H_2$ | 0.00 €/kg $H_2$ |
| Total costs | | | |

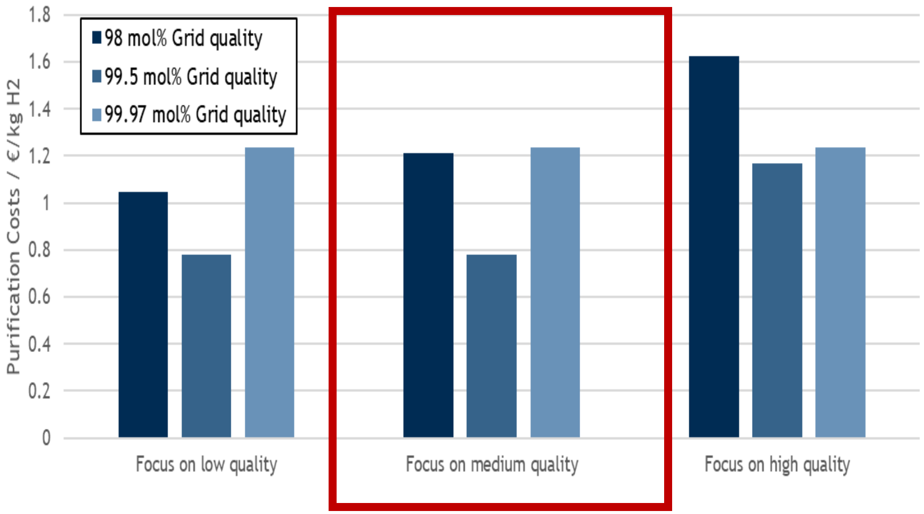


# In this scenario (2/3), overall purification cost range from 0.79 €/kg $H_2$ for 99.5 mol% grid quality to 1.24 €/kg $H_2$ for 99.97 mol%

EXAMPLE

- Modular Purification Cost Tool - Example of determining costs along the chain using sensitivity analyses

| Element | 98 mol% Grid quality | 99.5 mol% Grid quality | 99.97 mol% Grid quality |
|---|---|---|---|
| Pipeline | 0.21 €/kg $H_2$ | 0.29 €/kg $H_2$ | 1.10 €/kg $H_2$ |
| Storage | 0.09 €/kg $H_2$ | 0.11 €/kg $H_2$ | 0.14 €/kg $H_2$ |
| Focus medium quality user | 0.91 €/kg $H_2$ | 0.39 €/kg $H_2$ | 0.00 €/kg $H_2$ |
| Total costs | 1.21 €/kg $H_2$ | 0.79 €/kg $H_2$ | 1.24 €/kg $H_2$ |

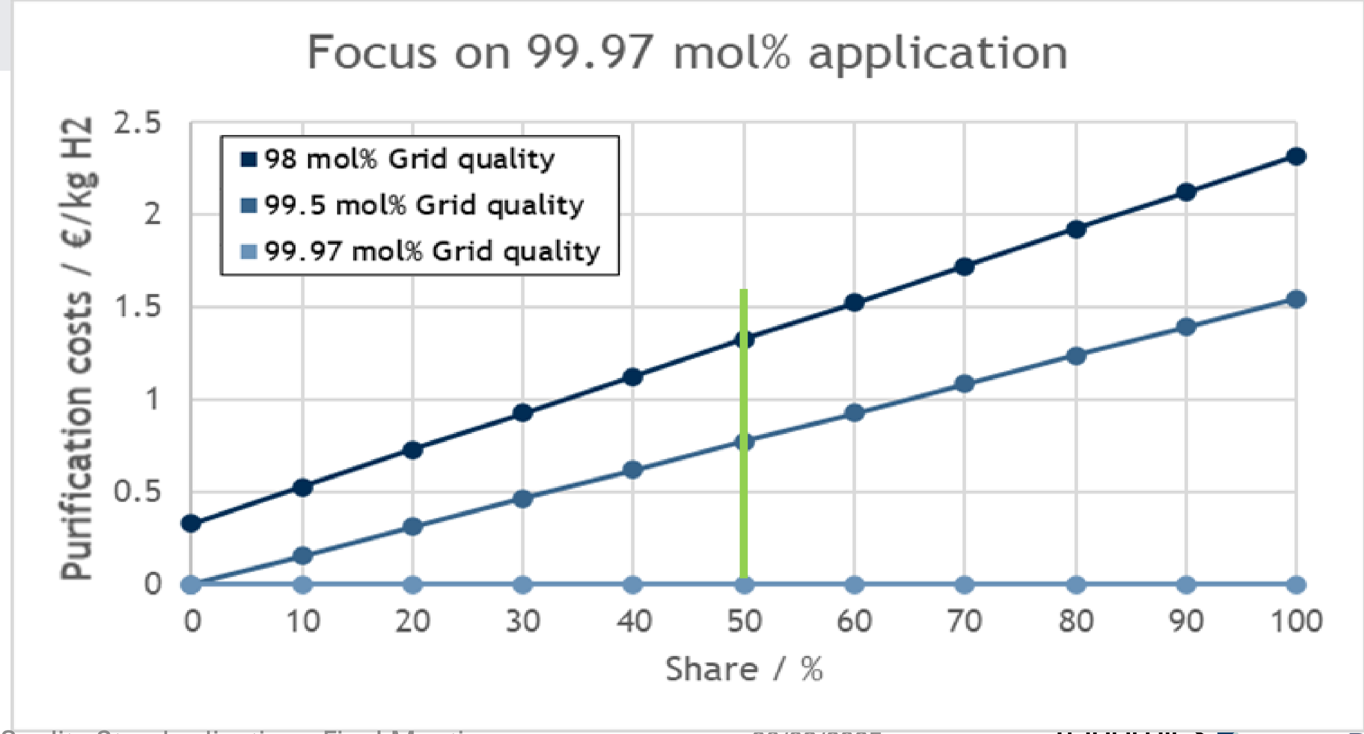


# Assumption on end-user composition (3/3): 25% low quality (>98 mol%), 25% medium (>99.5 mol%) and 50% high (>99.97 mol%) quality

EXAMPLE

- Modular Purification Cost Tool - Example of determining costs along the chain using sensitivity analyses

| Element | 98 mol% Grid quality | 99.5 mol% Grid quality | 99.97 mol% Grid quality |
|---|---|---|---|
| Pipeline | 0.21 €/kg $H_2$ | 0.29 €/kg $H_2$ | 1.10 €/kg $H_2$ |
| Storage | 0.09 €/kg $H_2$ | 0.11 €/kg $H_2$ | 0.14 €/kg $H_2$ |
| Focus high quality end user | 1.32 €/kg $H_2$ | 0.77 €/kg $H_2$ | 0.00 €/kg $H_2$ |
| Total costs | | | |

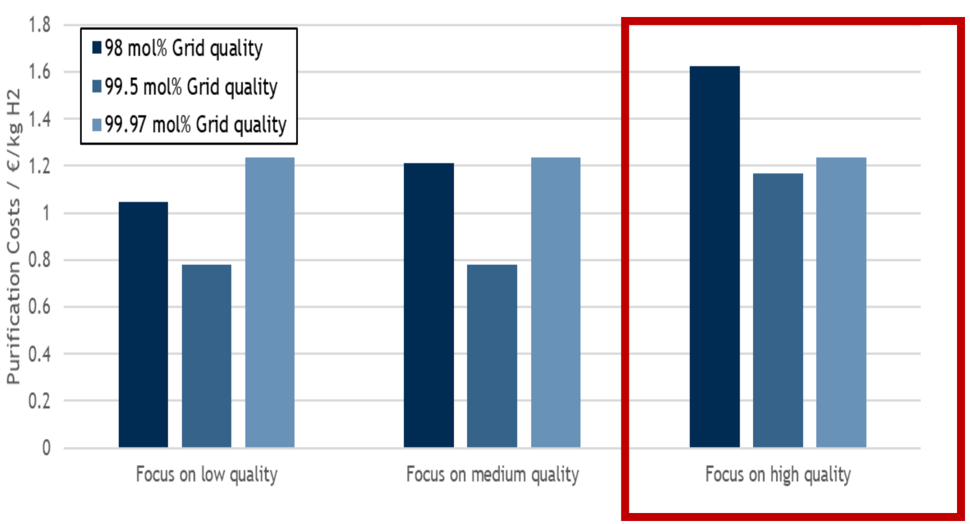


EXAMPLE

# In this scenario (3/3), overall purification cost range from 1.17 €/kg $H_2$ for 99.5 mol% grid quality to 1.62 €/kg $H_2$ for 98 mol%

- Modular Purification Cost Tool - Example of determining costs along the chain using sensitivity analyses

| Element | 98 mol% Grid quality | 99.5 mol% Grid quality | 99.97 mol% Grid quality |
|---|---|---|---|
| Pipeline | 0.21 €/kg $H_2$ | 0.29 €/kg $H_2$ | 1.10 €/kg $H_2$ |
| Storage | 0.09 €/kg $H_2$ | 0.11 €/kg $H_2$ | 0.14 €/kg $H_2$ |
| Focus high quality end-user | 1.32 €/kg $H_2$ | 0.77 €/kg $H_2$ | 0.00 €/kg $H_2$ |
| Total costs | 1.62 €/kg $H_2$ | 1.17 €/kg $H_2$ | 1.24 €/kg $H_2$ |



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# Scenario-based cost assessment indicate additional purification costs of around 0.8 – 1.2 €/kg for main scenarios

## Modular Purification Cost Tool– Comparison between the results

- 98 mol%:
  - Cost-effective only for low purity demand
  - significantly higher costs (up to 1.60 €/kg) with high purity demand
- 99.5 mol%:
  - Most cost-efficient option
  - consistently low costs (0.8 €/kg)
  - flexible for all user needs
- 99.97 mol%:
  - High costs (1.24 €/kg)
  - but no further purification required – regardless of end-user demand