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28th August 2023

A follow-up study into the hydrogen quality requirements

For the Dutch Ministry of Economic Affairs and Climate Policy (EZK)

Trust
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Kiwa Technology B.V.
Wilmersdorf 50
PO Box 137
7300 AC Apeldoorn

Tel. 088 998 33 93
Fax 088 998 34 94
technology@kiwa.com
www.kiwatechnology.com

Colophon

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Project manager	E.A. Polman
Contractor	Dutch Ministry of Economic Affairs and Climate Policy
Quality Assurance	J.A.M. Peters (Kiwa)
Author(s)	E.A. Polman, M.L. Doelman, S. van Greuningen (all Kiwa Technology), J.W. Turkstra, M. van Essen, H. Vlap (all DNV)

Summary

Kiwa and DNV have advised the Ministry of Economic Affairs and Climate Policy (EZK) on hydrogen quality requirements for the national hydrogen transmission network. This advice is a follow up of a previous advice and deals with the economic and technical consequences of a gas quality specification of at least 99.5% hydrogen purity. Interviews have been held with the future hydrogen network operator Hynetwork Services (HNS) and Hystock, a developer of the first salt caverns for storage of hydrogen in the Netherlands. From these interviews can be concluded that, the contaminations due to the use of retrofitted natural gas pipelines and due to the use of salt caverns for storage, are limited and do not hinder a hydrogen quality specification of at least 99.5%. This is under the condition that the sulfur limit is set at 3 molppm.

In addition, a high level market wide techno-economic analysis has been performed on seven projected production and off take scenarios for the years 2035 and 2050. Model parameters were consulted with stakeholders. The overall cost for purification is dominated by the “loss of value” associated with the tail gas produced by the purification unit, mostly a Pressure Swing Absorption (PSA).Tail gas is the hydrogen output of the PSA containing all the filtered contaminants and can only be used on-site as a source of heat. The value gap between hydrogen as a local source of heat compared to the hydrogen market value is the “loss in value” aspect of tail gas. The hydrogen purification cost model indicates that for the year 2035 the 99.5% hydrogen specification tends to be more optimal than a gas quality specification of 98.0%. However, the relative cost differences are expected to be small as the bulk of the producers will supply >99.5% hydrogen and the bulk of the demand can accept 98% hydrogen purities. Therefore, it is only a small section of the end user market, mainly industrial users, that determines the overall market cost preference for 99.5%. This relative market preference for 99.5% over 98% is set to decrease towards 2050. This is because the bulk market (export, power, heat) is expected to increase further over industrial applications and the value gap between hydrogen and natural gas, the benchmark for tail gas heat value, is also set to close. In the base case scenarios it was assumed that no transit of hydrogen with a varying purity would occur for Belgium or Germany. In the sensitivity analysis both are assumed to have a 98% purity standard. Additionally, the scenario in which blue hydrogen (ATR) does not need additional purification to reach 98%, has been analyzed. For both of these scenarios the relative cost advantage of 99.5% compared to 98% diminishes and becomes almost zero for the 2050 ‘Internationale Handel’ scenario.

The main model findings are summarized in the table below:

Year	Scenario (see Chapter 2)	Cost (€/kg) for 98% purity	Cost (€/kg) for 99.5% purity	Cost (€/kg) for 99.5% incl. transit*
2035	Klimaatambitie	0.34	0.26	0.28
2035	Nationale drijfveren	0.25	0.19	0.19
2035	Internationale ambitie	0.33	0.27	0.29
2050	Nationaal Leiderschap	0.092	0.057	0.063
2050	Decentrale Initiatieven	0.093	0.068	0.076
2050	Europese Integratie	0.11	0.094	0.11
2050	Internationale Handel	0.12	0.011	0.13

**The cost for 98% remains the same when including transit. For 99.5% the cost increase is dependent on the assumed transit volumes.*

In case of a minimum of 99.5% hydrogen purity, the following specification is advised:

Table A: proposed specifications hydrogen in the transport grid for entry- as well as exit-points (momentarily basis)

Parameter	**Unit**	**Value**
Wobbe number	MJ/m^3(n)	45.99-48.35 [A]
Hydrogen	mol%	≥ 99.5
Inerts	mol%	≤ 0.5 inert N_2, Ar, He
Hydrocarbons	mol%	< 0.5 incl. CH_4
Hydrocarbon dewpoint	°C	≤ -2 at 1 – 70 bar(a)
Water dewpoint	°C	-8 at 70 bar(g)
Oxygen	mol ppm	≤ 10
Carbon dioxide	mol ppm	≤ 20
Total S content (incl. H_2S)	mol ppm	≤ 3
Halogen compounds	mol ppb	≤ 50
Carbon monoxide	mol ppm	≤ 20
Formic acid	mol ppm	≤ 10
Ammonia	mol ppm	≤ 10
Formaldehyde	mol ppm	≤ 10
Dust particles (> 5 µm)	-	[B]
Temperature (entry)	°C	5 - 30 [C]
Temperature (exit)	°C	5 - 30 [C]

A. The volume in m^3(n) is defined at 0°C (measurement conditions) and 1013.25 mbar. The energy in MJ is derived from the thermodynamic values between 25°C (combustion conditions) and 0°C and at 1013.25 mbar according to ISO 6976.
B. The hydrogen may not contain any solid particles, liquids or gaseous components which could affect the integrity of the gas network or gas application.
C. The maximum temperature may be deviated from depending on the situation on site (types of materials, requirements of customers).

Compared to the proposed specifications in the previous advice (report "Kwaliteitseisen voor waterstof t.b.v. het transportnet", May 2022), that were proposed with a 98.0% hydrogen specification in mind, the following parameters have been changed:

- the lower limit of the Wobbe number, based on higher heating value, has increased since the quantity of trace components that may have an impact on the Wobbe number, is lower, leading to a lower bandwidth;
- the number of inert components as well as hydrocarbons are both maximized to 0.5 mol%, but from the ≥ 99.5 mol% hydrogen specification, it is obvious that the sum of all non-hydrogen compounds should never exceed 0.5 mol%.

Contents

1 Introduction

In 2022, Kiwa and DNV have written an advisory report on hydrogen quality requirements for the national hydrogen transmission network commissioned by the Ministry of Economic Affairs and Climate Policy (EZK) (available online via: https://www.internetconsultatie.nl/kwaliteitscriteriawaterstof/document/9634). The Ministry has held a market consultation in which the report's findings and recommendations were presented to stakeholders.

The market consultation has shown that the stakeholders prefer to establish quality requirements for a longer period of time, rather than setting the minimum purity at 98% and reviewing the specifications, and possibly adjusting them after a couple of years. The majority of the respondents also indicated a preference for a higher hydrogen purity requirement.

The responses to the market consultation are grounds for additional research. The starting point in this study is that the quality requirements are established for a longer period of time.

Problem statement and questions

The main research questions are as follows:

1. From a societal perspective, what is the **optimal purity** of hydrogen in the national transmission network based on realistic scenarios about the development of the hydrogen market?
2. What **specifications** would be suitable for a possible hydrogen quality of 99.5%?

A hydrogen purity cost model was used to gain insight into the overall system costs as a function of the hydrogen purity in the hydrogen backbone. The annual system purification costs are calculated using: a) demand and supply scenarios in 2035 and 2050 that reflect developments per market segment, b) the hydrogen purity specifications per segment without additional purification measures, c) impact of “Pressure Swing Adsorption” purification measures (“PSA”) per market segment and d) total market impact of the all PSA measures using 2035 and 2050 commodity cost projections.

A total of seven scenarios have been drawn up in consultation with EZK to answer question 1. A scenario is based on a set of producers, the number of production units, the production region, the technology used (e.g. green, blue, …), and consumer scenarios by sector (power, heat, industry, mobility, ...). A distinction between the years 2035 and 2050 is made to determine the best specification for the long term.

A high level hydrogen purity cost model was developed to provide guidance in resolving this debate. The model considers a wide range of specifications of <97% up to 99.99%, mainly to provide context to the 98% v. 99.5% discussion. The cost model also includes pipeline imports (transit) and salt cavern storages as distinct market parties that can take the required measures to meet the hydrogen backbone specifications. The actual upper limit to the backbone specifications will be set by the technical capabilities of the repurposed natural gas pipelines. In this analysis hydrogen specifications exceeding 99.5% will therefore not be considered.

In order to achieve a well-considered advice for quality requirements for hydrogen with a specified desired minimum purity and maximum trace component fractions, a few other research questions must first be answered, taking into account the technical possibilities, the costs and expected cost developments and the highest possible chain efficiency.

These further research questions are:

- What is the expected pollution of hydrogen during transport? New insights may have emerged in this regard after the publication of the first report.
- What is the influence of hydrogen storage in salt caverns on the hydrogen quality?
- What are the considerations for the previously chosen bandwidth with regard to temperature and what are the consequences if this bandwidth is adjusted to the preference expressed by several stakeholders in the market consultation?
- Choosing a different (higher) minimum hydrogen quality, has consequences for the limit values of the permitted trace components and physical parameters. What impact will a higher minimum quality have on these limit values?
- The costs associated with hydrogen purification are significant and more technical innovation is warranted. Can the network be designed in such a manner that critical end users (industry, mobility) receive the purest possible hydrogen? How can PSA systems be placed such that tail gas utilization can be optimized? Is it possible to develop PSA systems with much lower tail gas output? What other purification techniques should be considered?

2 Scenarios

Introduction
This chapter provides a brief overview of the hydrogen production and demand projections for years 2035 and 2050 as outlined in the 'Integrated Energy System Exploration 2030-2050: Scenarios' report, published by Netbeheer Nederland [1]. These projections have been chosen by EZK to form the input scenarios for the hydrogen purity cost model. Each scenario represents a distinct pathway for the development of the hydrogen energy system in the Netherlands. Here, only the major differences in hydrogen demand and production between the different scenarios for 2035 and 2050 are discussed. For a more detailed analysis of various scenarios, r to the report by Netbeheer Nederland is referred to [1].

Scenario Overview
The Integrated Energy System Exploration 2030-2050 report presents a range of scenarios developed by a team of experts and stakeholders in the energy sector (Figure 1). These scenarios explore different trajectories for the future energy landscape, considering factors such as policy, technological advancements, and societal preferences.

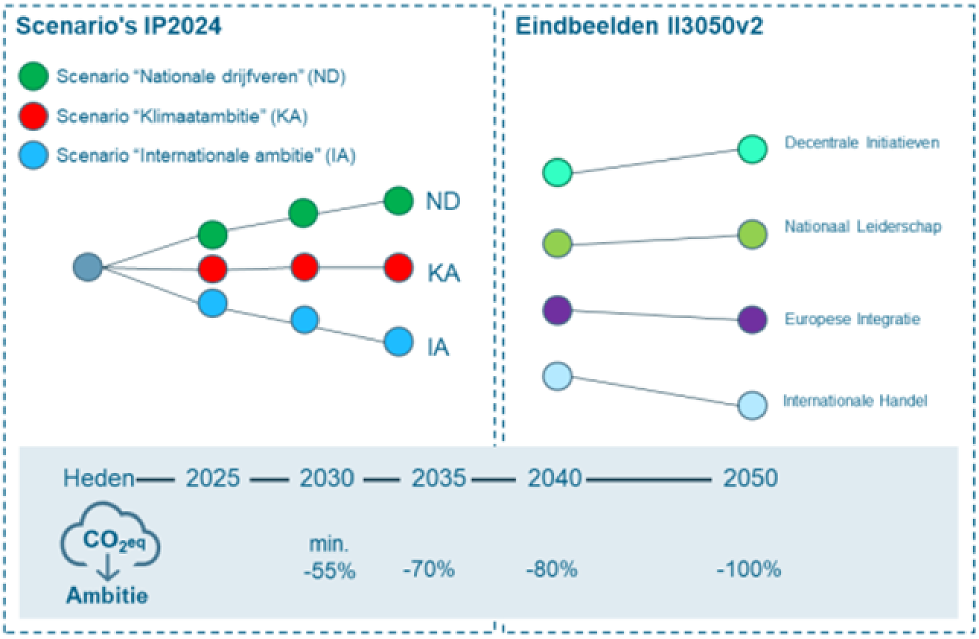

Figure 1: Connection between the scenarios for IP2024 and images for the second version of II3050

2035 Scenarios
In the 2035 timeframe, several scenarios are presented, each representing a unique vision of the energy system. The three scenarios "Klimaatambitie (KA)", "Nationale Drijfveren (ND)", and "Internationale ambitie (IA)" illustrate the overarching goals and priorities of each pathway. The Klimaatambitie (KA) scenario forms the central scenario based on all existing and planned energy and climate policies (Climate and Energy Outlook 2022), supplemented with additional policy from the Coalition Agreement. Nationale Drijfveren (ND) is a supporting scenario that, compared to the Klimaatambitie scenario, places even stronger emphasis on electrification and sustainable energy generation on land. The Internationale ambitie (IA) scenario is a supporting scenario that prioritizes sustainable gases (molecules). In addition to direct

electrification, there is a greater focus on biomethane and hydrogen. Below, the three scenarios are summarized.

- The **Klimaatambitie (KA)** scenario aligns with existing and planned climate policies, emphasizing a diverse mix of technologies across all sectors in the Netherlands. It involves strong government guidance, taking into account regional and sectoral developments. The scenario focuses on insulation, hybrid and electric heat pumps, district heating, and blending biomethane to decarbonize the built environment. Electrification is prominent in all sectors, with increased electric mobility and heating. Expanding renewable energy generation is crucial to meet growing electricity demand and achieve decarbonization goals.
- In the **Nationale Drijfveren (ND)** scenario, the Netherlands aims for self-sufficiency through increased renewable energy generation and a transition to a circular economy. The scenario emphasizes electrification in the built environment, mobility, and industry, while also highlighting the importance of hydrogen as an energy carrier. Energy efficiency measures and a growing need for flexibility in the electricity system due to high levels of renewable energy are key aspects.
- The **Internationale ambitie (IA)** scenario emphasizes strong global cooperation and free trade. It focuses on sustainable gases like biomethane and hydrogen, along with hybrid heat pumps, biofuels, and CCS. The role of electricity is reduced, and the Netherlands becomes a transit country for biofuels, CO_2, and hydrogen. The scenario promotes renewable energy production, particularly offshore wind and solar PV, and envisions increased use of biomethane and hydrogen in the energy mix, potentially through import.

2050 Scenarios:
In 2050 four distinctive scenarios of a completely climate neutral energy system including fully climate-neutral electricity production have been composed. The visions for 2050 vary on several important factors, classified by the Dutch network operators, including the role of the government, the form of societal support base, market functioning and different technical possibilities. Below, the four scenarios are summarized.

- In the **Nationaal Leiderschap (NL)** scenario focus lies on national leadership and aims for an efficient energy system. The government implements mandatory policies, supports new industries like synthetic fuel production, promotes electrification, and encourages district heating systems. Nationally significant projects include offshore wind farms and flexible nuclear power plants. Green hydrogen plays a crucial role in balancing the electricity system and supplying high-temperature heat in industries in this scenario.
- In the **Decentrale Initiatieven (DI)** scenario the Netherlands supports regional action and private business cases for climate-neutral technologies. Citizens and local communities have autonomy in making sustainable choices, supported by incentives from local governments. This leads to numerous local initiatives utilizing solar and wind energy, as well as transitioning industries towards bio-based and circular materials. Heating solutions for buildings include a mix of technologies and local renewable sources such as geothermal energy, heat pumps, and green hydrogen. However, the variable nature of sustainable energy supply and limited CCS acceptance result in some energy-intensive industries relocating.
- In the **Europese Integratie (EI)** scenario the Netherlands aims for an efficient European energy system with coordinated policies and shared resources. Key elements include widespread production and use of biomethane, significant growth in renewable energy (solar and wind), increased nuclear energy, industry sustainability through electrification and European biomass

and hydrogen use, large-scale CCS deployment, district approaches for sustainable buildings, and extensive electrification of transportation.

- The **Internationale Handel (INT)** scenario is based on the Netherlands focussing on international trade for economic development by leveraging global energy markets and pursuing low-cost options. Climate-neutral energy carriers, particularly hydrogen, are imported and individual transition paths in the built environment are encouraged. In this scenario the industry undergoes electrification and utilizes hydrogen as sustainable energy carrier. Some energy-intensive industries relocate abroad, while Netherlands imports semi-finished products for local processing. Green hydrogen production is prioritized and connected to offshore wind parks. Due to the focus on large amounts of energy import, self-production is less emphasized.

Hydrogen production and demand volumes for 2035 and 2050

All seven scenarios (2035 + 2050) included in the hydrogen purity-cost model can be found in the Energy Transition Model (ETM) (see page 152 of [1] for weblinks). Table 1 presents the demand and supply scenarios for hydrogen and ammonia for the time periods selected by EZK, 2035 and 2050. These scenarios have been expanded with the category 'Import (transmission networks)' (import) and ‘cavern storage’. Import (transmission networks) refers to imported hydrogen intended for transit via pipelines. Cavern storage refers to the volumes that can be stored in salt caverns in the Netherlands. The transit volume was chosen as 10% of the import volume. Cavern storage volumes were based on the seven scenarios in 2035 and 2050 [1].

Table 1: Hydrogen demand volumes based on the seven scenarios in 2035 and 2050 [1], including hydrogen transit and storage

	2035			**2050**			
Demand (PJ)	**KA**	**ND**	**IA**	**NL**	**DI**	**EI**	**INT**
Fertilizer (feedstock)	33	17	35	52	50	35	51
Fertilizer (heat)	3	0	2	7	4	15	3
Mobility	24	15	63	32	47	21	125
Electricity	26	50	87	135	151	84	124
Export	183	151	304	253	224	446	541
Chemical industry (feedstock)	12	13	12	13	15	19	0
Steel	8	13	44	47	43	38	11
Other chemical applications	35	35	36	30	5	22	61
Refineries	92	89	89	243	52	163	63
Other (heat)	14	3	12	15	0	0	37
Agriculture	0	0	8.3	0	0	14	120
Households	-	-	-	0	0	0	18
Heat networks	-	-	-	0	0	0	12
Buildings	-	-	-	0	0	0	0
Cavern storage	9	26	23	30	40	35	55
Distribution losses (+rounding differences)	3	3	5.7	6	5	3	6
Total	**442**	**415**	**721**	**863**	**636**	**895**	**1227**

Table 2: Hydrogen production volumes based on the seven scenarios in 2035 and 2050 [1], including hydrogen transit and storage

	2035			2050			
Production (PJ)	**KA**	**ND**	**IA**	**NL**	**DI**	**EI**	**INT**
Import (ammonia, liquid hydrogen, LOHC)*	180	56	385	202	182	407	803
Residual gasses	50	54	43	57	26	45	28
Biomass +CCS	5	0	5	5	8	10	11
Power to gas	52	163	72	263	232	156	93
Offshore wind (electrolysis)	32	21	65	228	91	0	91
Import (transmission network)	18	6	39	20	18	41	80
Cavern storage	9	26	23	30	40	35	55
SMR/ ATR +CCS	96	89	89	58	39	201	66
Total	**442**	**415**	**721**	**863**	**636**	**895**	**1227**

**For all scenarios only ammonia is imported, except for 2050 INT, where ammonia, liquid hydrogen and Liquid Organic Hydrogen Carriers (LOHC) are split 50:25:25.*

At the core of the Hydrogen purity cost model, and which is directly influenced by the scenarios, is the amount of tail gas produced and the associated loss of value. After hydrogen production from synthesis gas (“syngas”) using conventional SMR, ATR, gasification, or Partial Oxidation (Pox) techniques, the hydrogen needs to be purified. The current industry standard for hydrogen purification is Pressure Swing Adsorption (PSA). Along with a purified hydrogen stream, PSA also produces a waste gas stream known as “tail gas”. Each technique has its own syngas composition, and therefore, a unique production of tail gas. The main issue with tail gas is that it can only be used locally and mainly as a source of high temperature heat. Using tail gas for anything else will only be useful for large scale applications and will require complex modifications of turbines or combined heat and power systems. The scenarios will need to be rebalanced to account for all the tail gas losses that occurred throughout the system. To this end both the ammonia import volume upwards and the pipeline export volume downwards are adjusted.

If there is limited local application for heat, or a lower cost alternative heat source is available, tail gas will result in a “loss of value”. The “loss of value” in the cost model is defined as the difference between the remaining value of the tail gas when used for heat, versus the value of hydrogen. The value of the tail gas is obtained through benchmarking against the lowest cost alternative, natural gas combined with CO_2 emission rights. The value of hydrogen is based on a 2017 TNO study on predicted green hydrogen prices in the future. [2] The value of green and blue hydrogen is assumed to be the same in this model, but this might not be the case in practice due to policies aimed to stimulate green hydrogen.

The scenarios from Table 1 and Table 2 have been expanded to include the category “import (transmission network)” and “cavern storage”. The Dutch natural gas transportation system currently functions as an important gas transportation hub. Natural gas from Dutch fields, as well as imported natural gas, is transported to the European hinterland. It is possible that a similar position can be assumed for hydrogen transportation. Hydrogen import for transit purposes through pipelines (for example, from Belgium to Germany) would utilize the Dutch hydrogen transmission network and would need to meet the same quality requirements. By adding this category, the model can account for differences in hydrogen quality between the Netherlands and neighboring countries. If higher quality requirements are imposed on the Dutch transmission network compared to its neighboring countries, additional purification steps would need to be added and these costs are included in the hydrogen purity cost model as a sensitivity to the main scenario. Currently, there is no European regulation that sets quality requirements for transmission networks, and it is also unknown what quality requirements neighboring countries will adopt.

3 Model calculations

Introduction to the Hydrogen purity cost model
In the period from 2019-2021 DNV has investigated together with N.V. Nederlandse Gasunie various ways to quantify the market impact of the hydrogen backbone purity standard. This eventually resulted in a “Hydrogen purity cost model”, that aimed to weigh the following factors:

- possible Hydrogen backbone design options & quality specifications.
- volume of future hydrogen suppliers and end users.
- the impact of PSA purification stages.
- total purification related costs per hydrogen quality specification.

The starting point of the model is that appropriate measures will need to be taken along the supply chain, at either the suppliers, end users or even perhaps the system operators to keep system operations within technical limits. The associated costs will be reflected in one form or another in the overall hydrogen price. The key issue is to determine which players are best positioned to take these technical measures to keep the overall purification related costs as low as possible. To this end the following guidelines are considered:

- Minimize the possibility that hydrogen is purified twice, both by the supplier and the end user.
- Minimize possibilities that hydrogen is unnecessarily purified by the supplier, i.e. bulk of the end users could have been supplied with the “unfiltered” hydrogen feed.
- Concentrate the purification measures with the players best equipped to handle this task, with large load factors, economy of scale and direct local application for “tail gas”, i.e. the waste stream of hydrogen containing the impurities.

The original model was considered an internal “proof of concept” model for Gasunie internal policy purposes only. However given the wide interest in this topic by the stakeholders, an fully revised version of the original model was made with the following updates:

- all scenarios provided by EZK;
- all input parameters from public sources or best estimates by KIWA and DNV;
- small revisions on calculation methods;
- market players engaged in the process via workshops.

However please note that the model is still(very) much high level and can only provide guidance in resolving the debate, not settle it.

Model description
The Hydrogen purity cost model is an MS Excel “bookkeeping model”, set up as illustrated in Figure 2, where a calculation engine calculates the hydrogen purity related costs as a function of A) a list of possible Hydrogen backbone purity standards, B) a specific market volume & price scenario and C) a set of technical input parameters, either “best case” or “worst case”.

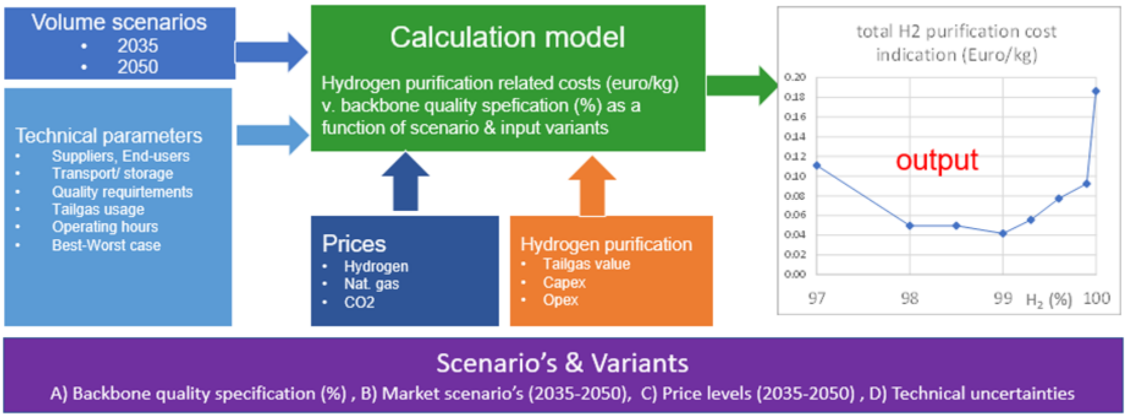

Figure 2: overview of the modules in the Hydrogen purity cost model. Model outputs are the Hydrogen purity costs (euro/ kg) as a function of the Hydrogen backbone quality standard.

The actual model calculation flow is illustrated in figure 3. The model premise is that suppliers and end users are connected to a hydrogen backbone with a specific hydrogen quality standard, ranging from a possibly very low (<97%) to very high (>99.99%) specification. Note that the other specifications are only present to give context to the 98% and 99.5% cases and are not considered as viable alternatives. The model then calculates the system impact of all the individual market player decisions, end users, suppliers, HNOs (hydrogen network operators), storage operators, as they invest in purification measures (PSA systems) in order to be fully compatible with the backbone purity standard. The model assumption is thus that end users will perform hydrogen purification based solely on their compatibility with the backbone specification. The option that end users could make this decision "just in time", based on the actual hydrogen purity arriving at their inlet is not considered.

The overall cost impact is that whenever PSAs are introduced, investments need to be made in PSA systems (CAPEX), operational expenditures will be made (maintenance and electricity) and tail gas, a small hydrogen flow including the filtered impurities, will be produced. The main issue is that tail gas can only be used locally as heat and the associated costs are two-fold:
1. To what extent can a local high temperature heat application be found?
2. What is the value gap between missed hydrogen sales revenue (supplier) or the additional cost of purchasing hydrogen (end users) at hydrogen market prices versus the remaining value of the (high temperature) heat, compared to the lowest cost alternative?

To quantify this "loss of value" the hydrogen heat value is compared to the lowest cost alternative high temperature heat source, assumed to be natural gas + CO_2 emission rights. The model assumption is that producers would ideally prefer to use the lowest cost heat source available (assumed to be natural gas) to maximize hydrogen output, or perhaps burn part of the feed (Ammonia, liquid hydrogen, …), but will now be forced to use some of the production output (tail gas) as a source of heat instead. Note that this is especially an issue in 2035, where hydrogen is considerably more valuable than natural gas, but much less so in 2050, where the value gap between hydrogen and natural gas has closed or perhaps even reversed.

The final step in the model calculation is to re-balance the original market scenario to account for all the tail gas losses. It is assumed that 50% of the supply-demand imbalance is to come from additional ammonia imports and 50% from a reduction of exports (ammonia import is chosen as a balancing supplier as this is the only import source with sufficient volume in all scenarios to perform the scenario corrections).

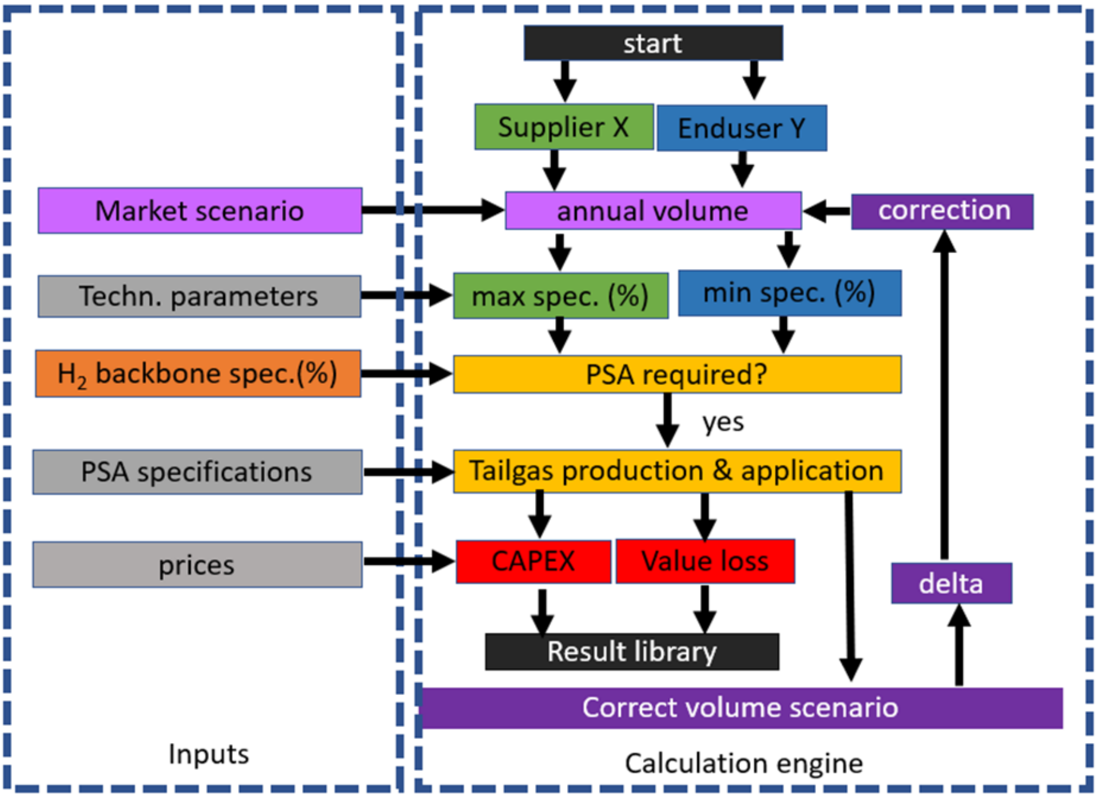

Figure 3: illustration of the model calculation flow. A specific scenario and a Hydrogen backbone specification (%) is selected, along with a set of prices and technical parameters, and then all actors assess their need for a purification stage (PSA) and cost associated for building and operating these systems and find usage for the tail gas. As a last step the input scenario is rebalanced to account for all tail gas losses.

In figure 4 the general model flow is illustrated. The model selects a scenario, a set of technical specifications, a specific backbone purity standard, and assesses the impact on the actors connected to the backbone, depending on their technical abilities to consume or produce low, medium or highly pure hydrogen. The main issue for all actors is whether their supply/demand systems are compatible with the Hydrogen backbone specification or if a PSA system needs to be placed between the backbone and the technical installation (“red dots” in figure 4). The calculation engine then assesses the overall economic impact of the “red dots” as a function of a series of 97% -99.99 % grade backbone standards, market scenarios and a wide range of input sensitivities. Note that “98%” or “99.99%” are labels of generalized backbone quality standard indicators, along with a long list of specifications on allowed impurities, and not numeric values used for performing “gross-net” volume corrections.

Note the hydrogen purity cost model is a simplified techno-economic model and treats all cost factors in the following way:

- annual CAPEX is CAPEX / technical lifetime.
- OPEX (annual maintenance + electric power use) = fixed rate of CAPEX.
- no inflation correction, WACC, interest payments or taxes included.
- Re-use of existing PSA installations are not taken into account as their technical status is unknown, so all investments are considered green field, even in 2050.

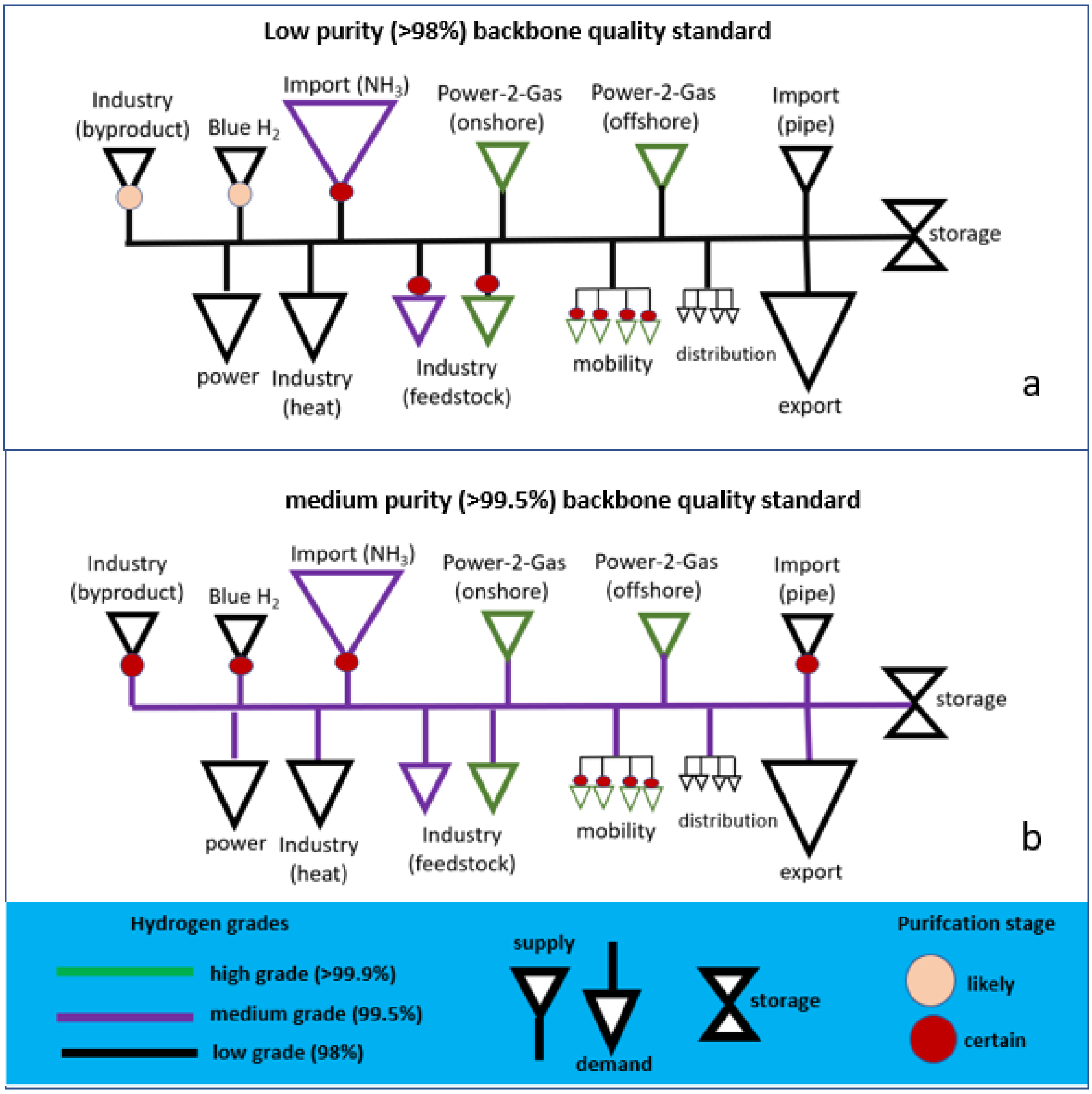

Figure 4: illustration of the consequences of a specific hydrogen backbone purity standard for the main supply/ demand players and their likely or certain requirement to invest in pressure swing adsorption (PSA) purification stages. The purpose of this study is to determine the total system cost impact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

Overview of input parameters

The input parameters are based on a combination of market and literature research, stakeholder feedback and expert estimates. It is important to note that technical parameters have large intrinsic uncertainties. This is due to 1) lumping widely diverse producers and end users, large and small, all in to one main category, 2) large uncertainty in the future performance of new technologies and 3) trying to capture a wide range of technical nuances into one parameter. To address the large uncertainties in the technical values, the ”best” and “worst case” value is introduced. Here “best” and “worst” refer to an optimistic or pessimistic assessment on the abilities of producers to produce highly pure hydrogen, end users to accept impure hydrogen and overall abilities of all parties to find local application for tail gas. Please also note that the parameters ”# locations”, “annual operating hours” have high uncertainties but only have a minor impact on the results, especially compared to “tail gas usage “ and “hydrogen purity”, and are thus rough estimates only.

Table 3: overview of the parameters used for the end users. The # locations refers to the estimated number of PSA systems, the best/ worst refers to the best estimate and the possible worst case value. The tail gas usage (0,1) refers to the expected fraction of the tail gas that can be used locally (best effort, worst case)

Category	Technology	# locations (2035/2050)	Annual operating hours (h)	Hydrogen purity (%) (best/worst)	Tail gas usage (0,1) (best/worst)
Fertilizer	Haber-Bosch	2 / 2	8000	98.6 /99.5	1 / 0.8
Oil-refinery	Various	4 / 4	6000	97 / 99.5	1 / 1
Steel	Direct reduced iron	1 / 1	6000	99 / 99.5	1 / 1
Chemical-feedstock	Methanol, peroxides, etc.	5 / 10	6000	99.5 / 99.9	1 / 0.8
Chemical – other	Food, coolant, …	5 / 10	6000	99.5 / 99.9	1 / 0.8
power	Turbine	2 / 2	3000	98 / 98	0.5 / 0.1
Industry- heat	Burner	10 / 100	6000	98 / 98	1 / 1
Mobility (road)	Fuel cell	12 / 12	6000	99.99 / 99.99	1 / 0
Export	Pipeline	3 / 3	4000	98 / 98	0.5 / 0

Table 4: overview of the parameters used for the suppliers. The # locations refer to the estimated number of PSA systems, the best / worst refers to the optimistic estimate and pessimistic parameter value in terms of impact on purification requirements and tail gas "loss of value". The tail gas usage (0,1) refers to the expected fraction of the tail gas that can be used locally (best effort, worst case). Please, note that the annual operating hours / full load hours do not reflect technical capabilities but include flexibility to meet seasonal market dynamics. Ammonia import will also increase operational hours within the model to account for tail gas losses. Special attention will be provided to the Blue Hydrogen specifications in the sensitivity analysis.

Category	Technology	# locations (2035/2050)	Annual operating hours (h)*	Hydrogen purity (%) (best/worst)	Tail gas usage (0,1) (best/worst)
Import (Ammonia)	Ammonia cracking	2 / 2	5000	<95 / <95	1 / 1
Import (liquid hydrogen)	Evaporation	1 / 4	3500	99.9 / 99.9	0.5 / 0
Import (LOHC)	Dehydrogenation	1 / 2	6000	99.7 / 99	1 / 1
Import (pipeline)	New / re-used pipelines	3 / 3	3000	98 / 98	0.5 / 0.1
Power to gas	Electrolysis	5 / 15	3000	99.99 / 99.9	0.8 / 0.5
Offshore wind	Electrolysis	3 / 3	4000	99.9 / 99.9	0.8 / 0.5
Blue hydrogen	ATR / SMR	3 / 3	6000	97* / 95	1 / 0.8
Industrial byproduct	Various	5 / 5	7000	97 / 96	1 / 0.8

Table 5: overview of the parameters used for storage (optional include in the analysis). The '# locations' refer to the number of PSA systems, the best/ worst refers to the best estimate and the possible worst case value. The tail gas usage (0,1) refers to the expected fraction of the tail gas that can be used locally (best effort, worst case).

Category	Technology	# locations (2035/2050)	Annual operating hours (h)	Hydrogen purity (%) (best/worst)	Tail gas usage (0,1) (best/ worst)
Storage injection	Cavern + compressor	1 / 2	2000	98 / 98	0.5 / 0
Storage send-out	Cavern + dehydration	1 / 2	2000	99.7 / 99.5	0.5 / 0

Table 6: overview of the price values used for this study. The hydrogen price data are the upper values of the TNO report "TNO 2021.11.08 Hydrogen cost projections_v2_openbaar" [2]

Item	Unit	2035	2050	Source
Hydrogen	Euro/kg	3.5	2.5	TNO
CO_2 emission rights	Euro/ton	100	100	DNV
Natural gas	Euro/ MWh	30	30	TNO
Tail gas value	Euro/kg	1.5	1.5	Calculated
Boiler efficiency	Heat output (LHV) / H_2 input (HHV)	0.75	0.75	DNV

As price data the 2017 TNO Hydrogen cost projections study was used. [2] That study is from before the recent increase in annual inflation rates. To compensate, the upper limits reported by TNO were used and not the mean values. Green hydrogen is used as the indicator of the hydrogen market price. The hydrogen market is considered as a commodity market where the most expensive source in the merit order (green hydrogen) sets the overall market price. In reality, a more differentiated price structure, including guarantees of origin, may be used. The tail gas "loss of value" is the difference between the hydrogen market value relative to the assumed lowest cost alternative, natural gas price and CO_2 emission rights. The value of green and blue hydrogen is assumed to be equal in this model. Due to policy decisions green hydrogen may become more valuable. It is however possible that in 2050 hydrogen is the lowest cost source of heat. For this to occur, either hydrogen price should drop to 1.5 euro/ MWH, the natural gas price should double to 62 euro/MWH or the CO_2 price should almost triple to 275 euro/ton.

It is assumed that the burner efficiency for hydrogen and natural gas are identical and the latent heat of the water vapor in the flue gasses will not be used.

Table 7: overview of the PSA parameters used for this study (source DNV team analysis, stakeholder feedback)

Item		Unit	Value
CAPEX (fixed)	(Meuro/ unit)	4	
Capex variable	(Euro/kg/h)	250	
OPEX	(% / CAPEX/ y)	5	Ex. tail gas
Efficiency (99.5%)	(%)	89	H_2 out/H_2 in
Efficiency (>99.9%)	(%)	85	H_2 out/H_2 in
Tech. lifetime	(yr)	25	

Finally, our modelling approach includes the key assumption that the market will rely on the proven and scalable Pressure Swing Adsorption (PSA) technique for the required hydrogen purification stages. PSA systems use absorbent beds to “catch” impurities at high pressure and release the impurities at low pressure within the “tail gas”. The main assumptions are:

- When a PSA system is used the hydrogen purity will be >99.5%.
- When hydrogen purity in excess of 99.9% is required the PSA efficiency will decrease.
- When a PSA system is employed, the indicated tail gas production will be unavoidable, regardless of the actual presence of impurities in the feed.
- It is assumed that it is not possible to analyze the incoming feed purity first and then decide to purify it using a PSA or not, as the required analysis methods will not be fast enough.
- It is theorized PSA efficiency could be increased when filtering already pure hydrogen (“tail gas recycling via compressors”), but this will need to be examined further with experts.
- If the tail gas is of sufficient grade and consistency, it could perhaps be used in a higher grade applications, like an engine or turbine based CHP system. This option is not considered in this analysis.
- PSA systems are tailored to specific industrial needs and very challenging to generalize based on publicly available sources. The provided cost estimates are the best estimates based on private conversations.
- Other purification methods are available (membrane, electro-chemical, cryogenic) but mainly focus on filtering out specific components and are less suitable in handling very large volumetric flows.

These model assumptions were validated with market stakeholders during the consultation phase, but it should be noted that it is a simplified approach to a complicated subject matter, and it could be explored further with domain experts in a follow up study, if considered necessary.

4 Model results

The Hydrogen purity cost model translates supply/demand/price scenarios plus a specific set of technical specifications (best-worst case) into total market hydrogen purification costs for a range of possible Hydrogen backbone design standards. In figure 4a the market characteristics for the **2035 Klimaatambitie** scenario are illustrated. The majority of the hydrogen supply produces purities lower than 98% without a PSA stage (Blue, ammonia import), and after all suppliers have taken PSA measures the actual average hydrogen purity in the network will be around 99.6%. The bulk of demand (heat, power, export) requires 98%, a relatively small section of the market is located around 98.5-99.5% (fertilizer, refinery) and 99.5%-99.99% (industrial, mobility, electrolysis). The market average hydrogen purity demand is 98.1%. The effects of hydrogen storage and transit will be considered in a dedicated section, as will the possible situation that Blue hydrogen may be able to meet the 98% grade without PSA stage.
An impression of the purification costs for the 2035 Klimaatambitie scenario can be derived from table 10 that will follow later in this chapter. At a yearly hydrogen energy content of 441 PJ, the total yearly purification costs are 1.16 billion euro for 98.0% hydrogen quality and 0.91 billion euro for 99.5% hydrogen quality, being 14% respectively 7.5% of the hydrogen value transported.

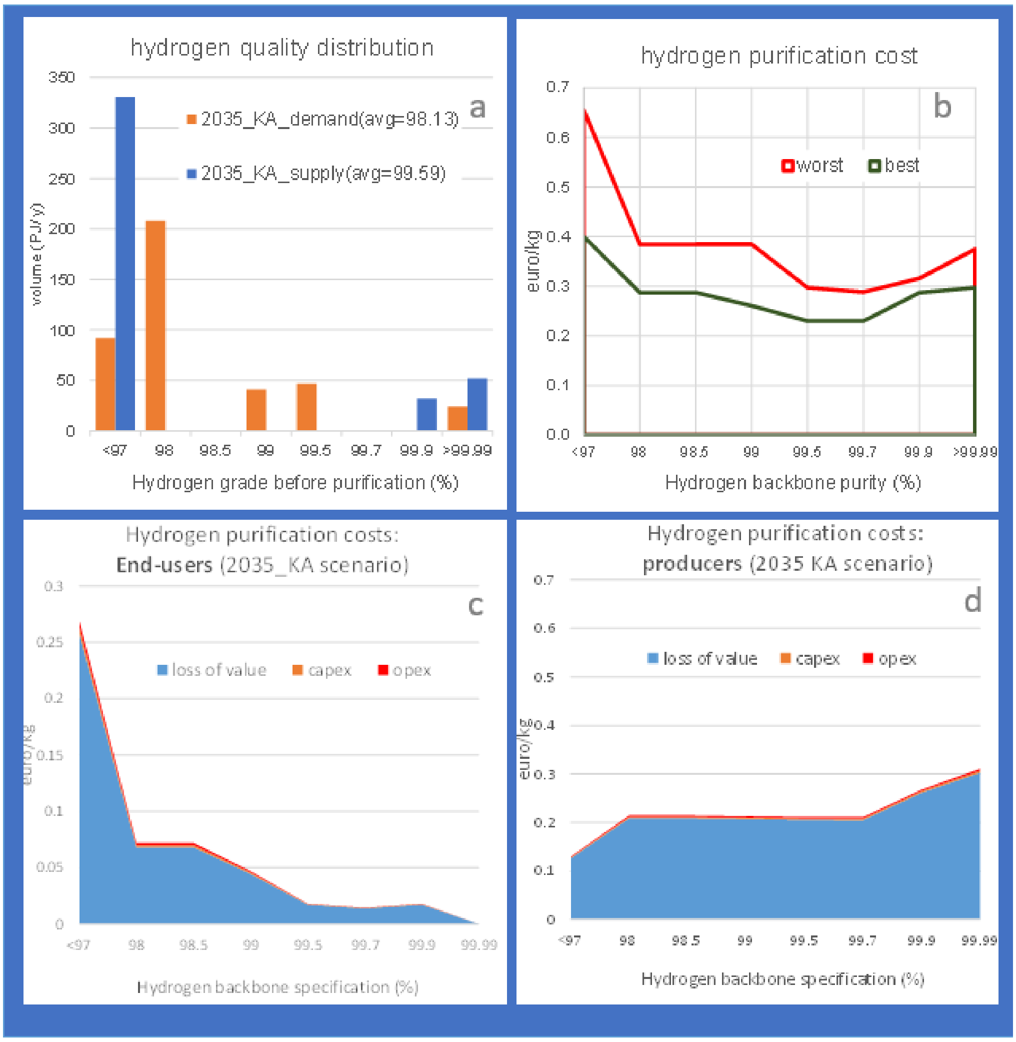

Figure 4: a) analysis of the market supply-demand characteristics (before purification) of the ***Klimaatambitie 2035*** *scenario, b) the system purification costs (euro/kg) for the "best case" technical specifications and the "worst case" estimates, c) the purity cost curve of the end users and d) the purity cost curve of the producers. Note that this cost curve is without the effects of storage and transit.*

In figure 4b the cost characteristics can be viewed going from < 98% to 99.99% both for the "best" and the "worst" case. The following hydrogen purification cost trends can be observed:

- **97-98%:** For hydrogen grades below 98% the hydrogen purification related cost are extremely high as both the bulk of the suppliers (Ammonia, likely Blue H_2) still need to purify, and nearly all of the end users (export, power, heat) would (in principle) still need to purify the hydrogen again. Moreover, the power end users and export have no useful application for the tail gas and in the worst case the tail gas is flared and the value is considered fully lost. Hydrogen grades below 98%, i.e. below the technical capabilities of the bulk of the end user market, are considered academic and in this analysis merely serve to give context to our region of interest (98% v. 99.5%).
- **98-99%**: Around 98% the system purity cost curve stabilizes as a large group of end users (power and heat, export) can now accept the hydrogen from the backbone without further need for purification. The curve may even display a local cost minimum as imports or blue hydrogen may be able to supply the 98% specification with additional purification. Also fertilizer end users may be

able to accept hydrogen in this range. However most of the industrial end users (fertilizer, refinery) would still require hydrogen purification.

- **99-99.5%**: In this region a large fraction of industrial end users (refinery, methanol, steel) can accept the hydrogen from the backbone without additional need for purification, thus further lowering the overall hydrogen purification costs of the system.
- **99.5-99.8%:** At a purity >99.5% nearly all industrial end users can be supplied directly from the backbone. Only the mobility sector still requires PSA purification. The model usually displays a local minimum in this region, although hydrogen grades higher than 99.5% may prove to be too challenging for some of the re-purposed natural gas pipelines in the hydrogen transmission system.
- **99.8-99.9%:** At these hydrogen purity standards the PSA efficiencies of the ammonia import and blue hydrogen PSAs will start to decrease. Also the LOHC or even the liquid hydrogen importers or even the off-shore electrolyzers using repurposed natural gas pipelines may not be able to meet these purity grades. Also salt caverns will not be able to meet this specification. Moreover, these issues are not compensated by a reduction of PSA installation for the mobility sector, as this sector requires even higher grades.
- **>99.9%:** This range of specifications could potentially satisfy all end users, including mobility. However all suppliers except the electrolyzers, will require PSA systems, running at reduced efficiencies, to meet these types of specification. In any case, this range is considered academic as it cannot be transported by the transmission system. This option is merely included to give further context to the region of interest 98%-99.5%.

Hydrogen purification cost breakdown

The Hydrogen purification related costs are composed of both the investment cost in PSA systems and the “loss of value” from the tail gas produced by the PSA purification stages. The “loss of value” is a complex concept: PSA produces a low pressure hydrogen flow including all captured impurities, dubbed “tail gas”. Tail gas cannot be sold by producers to the market, and end users need to purchase additional hydrogen from the market to compensate for the tail gas loss. The sole remaining application of the tail gas is high temperature heat. However the producer or end user may have limited use for this heat, perhaps already have a waste heat supply from another source or would have preferred to use an alternative lower cost heat source. The “loss of value” is the gap between the hydrogen market price and the (perceived) remaining value of the tail gas heat. To calculate the latter, tail gas heat value is compared to the lowest cost alternative, natural gas & CO_2 emission rights. Moreover, it is also assumed that the most valuable hydrogen source (green) will set the hydrogen market price, not conventional grey hydrogen. Since green hydrogen has a higher value than grey hydrogen, it setting the market price results in even more “loss of value” when tail gas is produced, because the value gap between the hydrogen and tail gas is higher.

However, in 2050 the gap between green hydrogen prices and natural gas levels will be substantially smaller and the “loss of value” will decrease substantially. However even then it will be the “loss of value” component that will still dominate the overall hydrogen purification costs, with CAPEX and OPEX (maintenance and electric power) and ad hoc flared tail gas making up the remaining costs. Loss of value makes up 90-93% of the total hydrogen purification costs for the 2035 scenarios and 80-85% of the total for the 2050 scenarios, assuming average case technical parameters.

The relatively high values of these costs are however somewhat misleading as for the largest producers (ammonia import) the “loss of value” will be unavoidable as a PSA system is considered inevitable. Otherwise, (in 2050) part of the ammonia import will be burned to supply heat for the ammonia cracking process, as the market phases out natural gas. Similarly for blue hydrogen producers, PSA purification systems are likely to be inevitable as the 98% purity level will be challenging to achieve or remaining impurities will likely contain unacceptable amounts of carbon and oxygen. However, the situation that Blue Hydrogen can meet the 98% specification without PSA, will be considered in the next section.

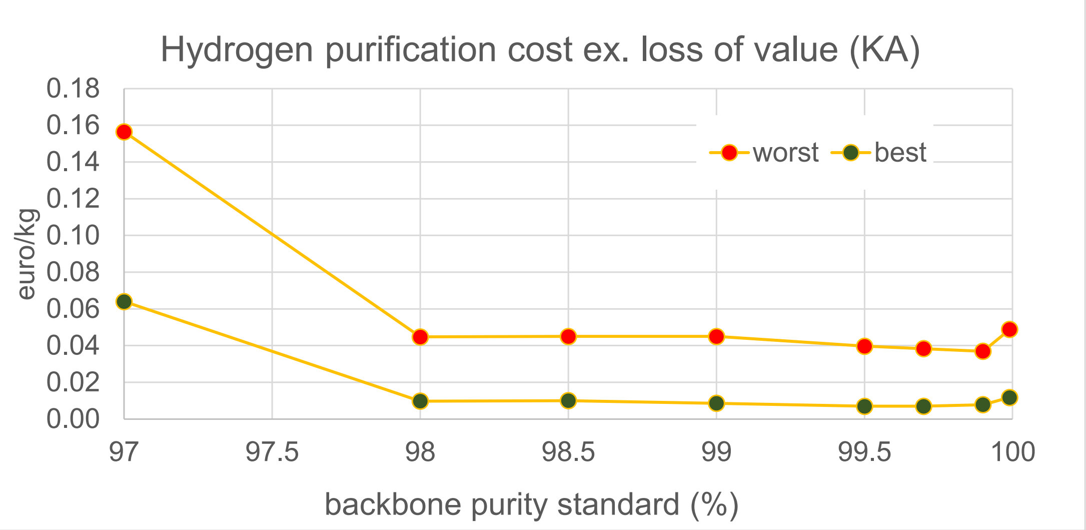

Figure 5: overall hydrogen system purification costs for the 2035 Klimaatambitie scenario, excluding the dominant "loss of value" contribution, both for "best and worst case" technical specifications.

Figure 5 shows the results of the analysis if the "loss of value" contribution is removed from the overall cost. In the best case the costs are now determined by the PSA CAPEX, maintenance and other running costs, which are very low when compared to the tail gas "loss of value". In the worst case however part of the tail gas may not be able to find a useful local heat application and would be flared. This is not likely to occur in reality, but the model also covers these hypothetical situations merely to provide context to the region of interest.

In any case, it is important to note that for the bulk of the producers the hydrogen purification costs may be considered an inevitable part production process and the purification process is not considered a real issue. However, for some smaller hydrogen producers and end users the hydrogen purification aspect can pose a real business issue, especially if there is limited use for tail gas. As only overall system costs are considered in this study, some of these finer nuances tend to be lost in the process.

The next step in the analysis is to extend the findings of the **2035 Klimaatambitie** (KA) to all other 2035 and 2050 scenarios. From figure 6 it is clear that:

- all scenarios have similar cost trends as they are primarily determined by the intrinsic technical limitations of producers and end users and to a lesser extent by their volumes;
- the **2035 Nationale Drijfveren** (ND) cost curve is lower than the other 2035 scenarios due to the relative large contribution of (highly pure) green hydrogen from electrolysis in this scenario instead of ammonia import;
- the 2050 scenarios all trend lower, as the value gap between hydrogen market price and the alternative heat source (natural gas) has strongly decreased.

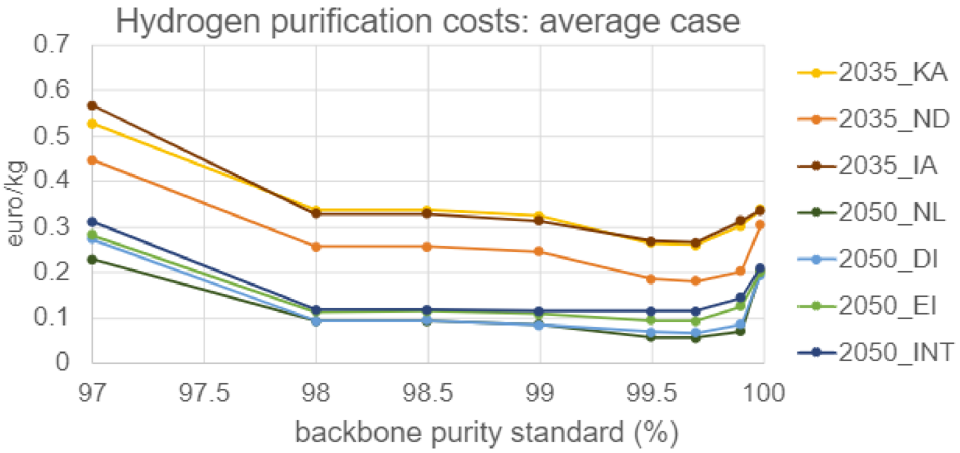

Figure 6: overall hydrogen system purification costs for all scenarios, for the average of the "best and worst case" technical specifications.

From figure 6 it can be concluded that the narrative outlined for the **2035 Klimaatambitie** (KA in Figure 6) scenario can be considered representative for all scenarios, although for most scenarios the overall cost levels will be lower due to 1) higher percentages of electrolysis vs. ammonia import and 2) a smaller value gap between hydrogen and natural gas + CO_2 emission rights.

Scenario sensitivity

Sensitivity to technical specifications

In figure 7 the further examination of the impact of the technical specifications ("best and "worst") on the scenarios is visualized. The main finding is that for the worst case, the end users have stricter requirements and more challenges in finding useful applications for the tail gas. These factors combined results in more elevated overall cost level for the worst case and a pronounced cost minimum around 99.5%. The only stand-out result is the 2050 International Handel. This scenario is characterized by a very large export volumes at 98%, marginalizing the cost benefits of industrial end users in the 99.5% region.

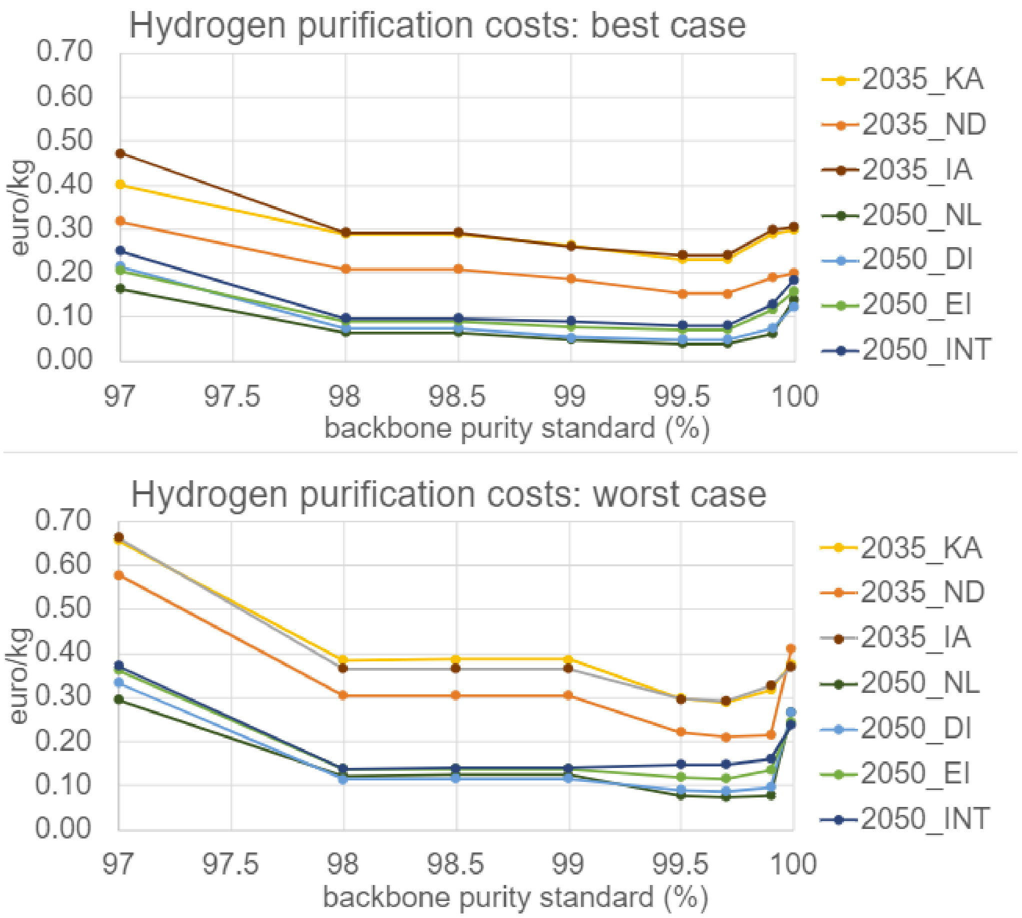

Figure 7: for all 2035 and 2050 scenarios the system purification costs (euro/kg) for the “best” and “worst” case technical specifications.

Storage and import sensitivity

All hydrogen supply-demand scenarios assume the Netherlands will import hydrogen from the North Sea and via ammonia, LOHC and liquid hydrogen bulk carriers and then become a net exporter of hydrogen via pipeline interconnections with Germany and Belgium. (For the 2050_INT scenario, also LOHC and methanol are included). However also to be taken into account is the likelihood that the hydrogen backbone will facilitate ad hoc hydrogen imports/exports/ transits between Belgium and Germany and flows from storage in German salt caverns. In the sensitivity analysis we have assumed that the hydrogen gas quality spec in Germany and Belgium will be 98.0%.

Table 8: additional transit and storage volumes to test the sensitivity of the main findings to the impact of transit and storage. The ad hoc transit volume is estimated as a fraction of the import (10%). The storage volumes are based on the Netbeheer Nederland study II3050. [1]

	2035			2050			
PJ/yr	Klimaat Ambitie	Nationale drijfveren	Inter-nationale Ambitie	Nationaal Leider-schap	Decentrale initiatieven	Europese integratie	Inter-nationale Handel
Transit	36	11	77	40	36	81	161
Storage	9	26	23	30	40	35	55

To test the impact of the main findings with additional contributions of transit and storage, additional supply (pipeline import, storage send out) and demand players (pipeline export, storage injection) have been added to the model, such that cancel out in annual volume. Table 8 shows the assumed annual volumes, storage from the scenario and transit is estimated as a fraction from export (approx. 20%), as listed in Table 1 and 2. Figure 8 illustrates the impact of transit and storage on the cost curves, for both the “best and worst case”, both assuming that the European hydrogen specification will be set at 98% specification. The overall impact is that now the 98% specification becomes more attractive, reducing the cost difference with the 99.5% minimum, and in a few scenarios (**2050 Internationale Handel**) almost closing the gap. This is because at 98% specification the ad hoc transit imports do not require additional purification stages and the challenge of finding a local tail gas application.

Storage resulted in no effect on the loss of value in the 98-99.5% region. Because storage caverns are expected to not require additional purification steps for 99.5% purity compared to 98%, there is no increased costs for a higher purity requirement. Storage does have an effect on purification costs in the 99.8-99.99% region. The result is that the total costs in this region increase more sharply. This is because salt caverns would require PSA systems to meet these specifications (which they do not need for a purity level below 99.8%) and it will be challenging for them to find a local tail gas application. Due to the large uncertainty in annual utilization of the caverns, the results found for the region above 99.5% should be taken with a pinch of salt.

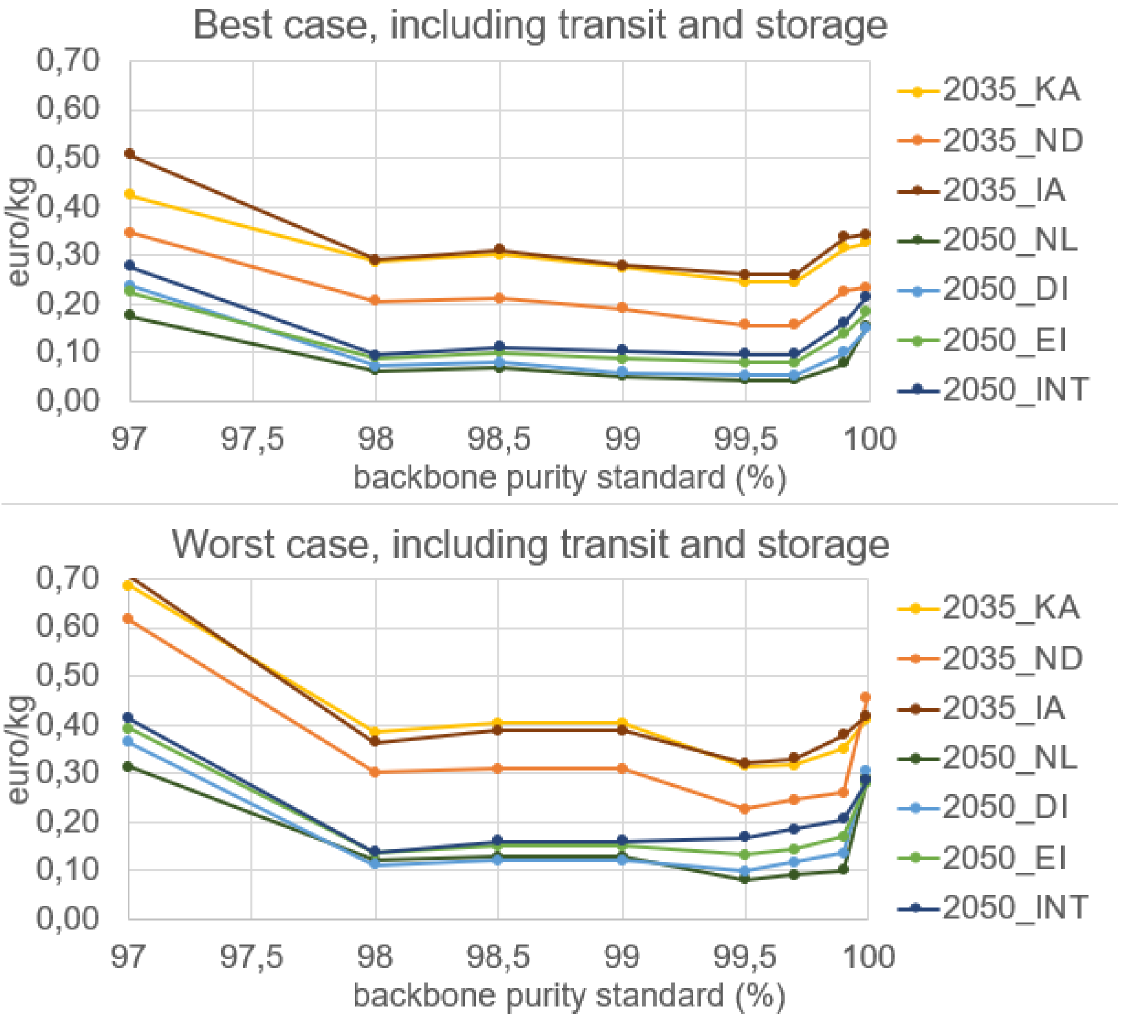

Figure 8: the system purification costs (euro/kg) for the "average" and "worst" technical specifications for all 2035 and 2050 scenarios, now including the transit and storage contributions, as listed in table 1 and 2.

Alternative blue hydrogen specifications

An important but challenging technical specification is the characterization of the hydrogen purity output of future blue hydrogen production facilities. The established grey hydrogen technologies are mainly based on steam methane reforming and produce industrial grade hydrogen (>99.5 -99.999%) to a wide range of customers using PSA stages. The envisaged future blue hydrogen production facilities will however likely be based on Auto Thermal Reformer (ATR) technology enhanced with special stages ("CO shift") to further increase hydrogen purity. The technology is still in an experimental stage although all signals indicate it will be successfully deployed. The main uncertainty is whether or not the ATR technology could be fine-tuned to such an extent that the 98% specification can be reached without PSA. [3] [4]

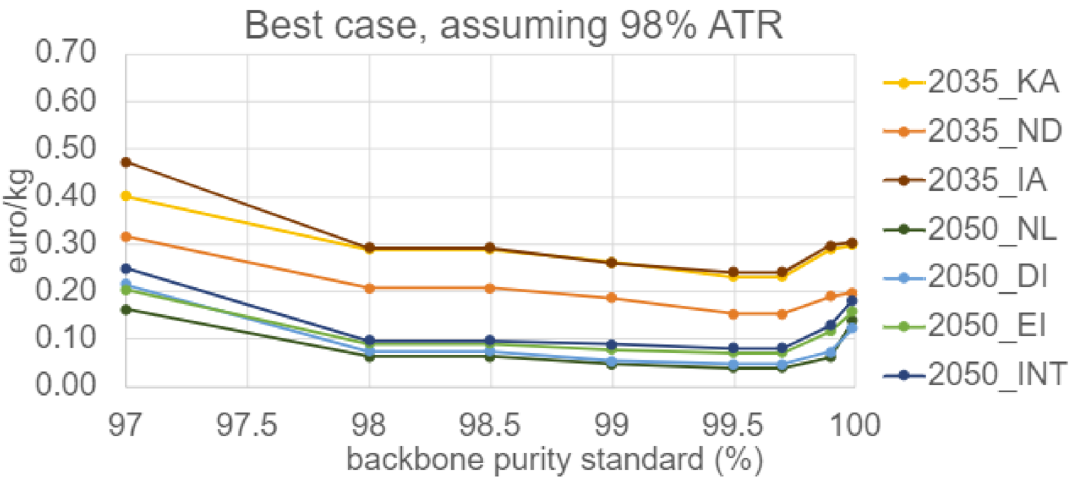

Figure 9: the system purification costs (euro/kg) should future blue hydrogen systems be capable of meeting the 98% specification without PSA stage.

Figure 9 shows the results of a sensitivity analysis in which no purification is required for the production of all blue hydrogen. The main impact is that the 98% specification becomes relatively more attractive, especially in 2035, even to the extent that for some scenarios it is more attractive that the 99.5% specification. However in 2050, with the value gap between hydrogen and natural gas closing this effect is diminished.

Summary

In this chapter the main findings are presented of the Hydrogen purity cost model for the scenarios, hydrogen prices and technical specifications from market consultations and public sources discussed in previous chapters. The impact of the uncertainties in the technical specifications have also been examined, ranging from “best” to “worst” case and the inclusion of transit and storage and the possibility that ATR systems may be able to produce 98% without PSA stages. The key findings are:

Focus on ”loss of value” associated with tail gas.
The main driver for hydrogen purification costs is the “loss of value” per kg hydrogen associated with the tail gas produced by using Pressure Swing Adsortion (PSA) purification systems. Tail gas is essentially a low pressure hydrogen flow containing all impurities that can only be used as a local heat source. The tail gas volume increases when purification to a higher purity is required. The subsequent “loss of value” is the gap between the hydrogen market value and the remaining value of the tail gas, benchmarked against the lowest cost heat alternative (natural gas + CO_2 emission rights). In other words, the key driver of hydrogen purification costs is the reduction of hydrogen sales by producers and the additional hydrogen procurement by end users to account for the tail gas losses of the purification stages. The expected “loss of value” of this process makes up 90-93% of the total purification costs for the 2035 scenarios. Note that it is assumed that the hydrogen produced by cracking imported Ammonia, LOHC, liquid hydrogen and blue hydrogen, can all be valued at the price set by the last producer in the merit order, being green hydrogen from electrolysis. The remaining costs are for installing, maintaining and running the PSA systems. See Table 4c and 4d for a division of the costs for end-users and producers.

Costs are not shared equally across market players
The loss of value due to tail gas will not be experienced equally by individual suppliers and end users (see Figure 4c and 4d). For some producers the “loss of

value" can be considered as inevitable, because for most hydrogen production methods (Ammonia, Blue H2, LOHC, liquid hydrogen), heat must be applied to release the hydrogen gas. This heat will need to come from either burning natural gas, from part of the feedstock (ammonia, natural gas) or tail gas. For some end users, industrial end users with already excess heat supply, or a requirement for a purification stage on a pipeline import, local tail gas applications are limited and the "loss of value" is a very real technical economic challenge for the parties involved. For this study however, only the total market purification costs have been considered and focus is put on the overall trends using graphs. The finer nuances of hydrogen purification cost tend to get lost in this process.

Strong decrease in purification cost from 2035 to 2050 due to closing of the hydrogen-natural gas price gap.

The dominant factor for hydrogen purification costs is the "loss of value" associated with tail gas production. However, with the expected ~40% decrease in the hydrogen production costs in 2050, the large 2035 price gap between the hydrogen and natural gas will almost close in 2050. The result is that the hydrogen purification costs are set to decrease by a much larger factor of 3 to 4. Moreover, hydrogen could become the lowest cost source of heat in 2050 if either 1) hydrogen prices would reach 1.5 euro/kg, 2) natural gas prices would reach 65 euro/ MWH or 3) CO_2 emission rights would exceed 275 euro/ton.

Hydrogen purification cost indicators (normalized per kg)

Table 9: overview of the main hydrogen purification costs, averaged over the best and worst case technical parameters, for both the supply-demand scenario excluding and including transit contributions for 99.5% purity. For 98% purity, transit has no influence on the cost/kg, as hydrogen from neighboring countries is assumed to have a 98% purity. Storage did not effect the cost/kg for either 98% or 99.5%.

Year	Scenario (see Chapter 2)	Cost (€/kg) for 98% purity	Cost (€/kg) for 99.5% purity	Cost (€/kg) for 99.5% incl. transit
2035	Klimaatambitie	0.34	0.26	0.28
2035	Nationale drijfveren	0.25	0.19	0.19
2035	Internationale ambitie	0.33	0.27	0.29
2050	Nationaal Leiderschap	0.092	0.057	0.063
2050	Decentrale Initiatieven	0.093	0.068	0.076
2050	Europese Integratie	0.11	0.094	0.11
2050	Internationale Handel	0.12	0.011	0.13

Hydrogen purification cost indicators (absolute)

Table 10: overview of the absolute hydrogen purification costs (in billion euro/year), averaged over the best and worst case technical parameters, excluding transit and storage contributions. Hydrogen prices are assumed to be 3.5 euro/kg in 2035 and 2.5 euro/kg in 2050. Natural gas prices are 30 euro/ MWh and CO_2 emission rights are 100 euro/ton. At the bottom the total value of the hydrogen market for each scenario is included.

Costs (billion euro)	**2035 Klimaat ambitie**	**2035 Nationale drijfveren**	**2035 Internationale ambitie**	**2050 Nationaal leiderschap**	**2050 Decentrale initiatieven**	**2050 Europese Integratie**	**2050 Internationale Handel**
<97%	1.82	1.42	3.11	1.54	1.31	1.93	2.82
98%	1.16	0.81	1.79	0.62	0.45	0.77	1.06
98.5%	1.16	0.81	1.79	0.63	0.45	0.77	1.06
99%	1.11	0.78	1.71	0.57	0.40	0.73	1.03
99.5%	0.91	0.59	1.46	0.38	0.33	0.64	1.03
99.7%	0.89	0.57	1.45	0.37	0.32	0.63	1.03
99.9%	1.04	0.64	1.71	0.46	0.41	0.85	1.30
>99.99%	1.16	0.96	1.83	1.36	0.93	1.37	1.90
Total value of market	**12.1**	**11.2**	**19.2**	**16.9**	**12.0**	**17.1**	**22.8**

Relatively small cost differences between 98%-99.5% due to the technical characteristics of major suppliers and end users
A key observation is the relatively identical shape of the curves across all scenarios and the relatively small cost differences across the 98-99.8% range. This is caused by the following factors:

- the bulk of the producers in the scenarios are set to supply >99.5% hydrogen either via electrolysis, LOHC or cryogenic hydrogen import or via technologies that require purification in any case (e.g. Ammonia import);
- all scenarios assume net export through the pipes, the majority of import is in the form of ammonia or other carriers in ports, i.e. the domestic producers are set to determine the actual hydrogen quality in the backbone;
- the bulk of demand, i.e. heat, power and export, can already accept 98% specifications and has no stake in the hydrogen purity debate;
- The difference makers in 98% v. 99.5% purification costs are the industrial end users, transit and possibly future blue hydrogen (ATR), which are represented with relatively small volumes compared to other categories.

Short/medium term 99.5% cost optimum determined by industrial end users
Although the hydrogen purification costs for 98% are 99.8% are similar, there is a cost minimum in the 99.5%-99.8% region in nearly all 2035 scenarios, The reason is that with a requirement of 99.5% the largest industrial end users (fertilizer, refinery) can then accept the hydrogen from the backbone without PSA systems and avoid the associated CAPEX and tail gas loss of value. Above 99.8% the loss of value will increase due to loss of efficiency of the PSAs of the Ammonia importers and Blue H2 producers and challenges of salt caverns, LOHC importers or perhaps even the off-shore electrolyzers with these specifications. In any case, the purities exceeding 99.5% are not considered feasible for now as there is no guarantee that the repurposed natural gas pipelines and salt caverns can handle these specifications.

Longer term parity between 98%-99.5% cost optima when including transit, storage and future ATRs
When transit and storage are included in the scenario analysis and the possibility that ATR based blue hydrogen may achieve 98% without PSA stages is assessed, that the 98% specification becomes relatively more cost attractive. This effectively diminishes the cost difference between the 98% and 99.5%, depending on the scenario. Here it is also important to note that any requirement for the HNO (or a third party) to purify ad hoc import flows from Belgium and Germany and find a local application for the tail gas would present significant techno-economic and legal challenges that require further investigation.

5 Gas Quality parameters

The economic effects of setting the gas purity specification to 99.5% compared to the 98% advised in previous work have been investigated in the previous chapters. This chapter will go more in depth on the technical feasibility of a 99.5% hydrogen specification.

Two interviews have been held with important stakeholders regarding storage and reuse of the existing natural gas infrastructure. One with Hynetwork Services (HNS), the company responsible for the development and management of the hydrogen backbone, which is a subsidiary of Gasunie. The other one with Hystock, another subsidiary of Gasunie, which is developing and managing the first salt caverns for storage of hydrogen in the Netherlands. Additionally, other stakeholders have been asked for their input on the model parameters and regarding the currently proposed specifications.

Pressure
Hynetwork Services expects operating pressures for the hydrogen backbone to be between 30 and 50 bar once the backbone is put into operation. Due to the number of announced projects for hydrogen production, they expect these operating pressures to become insufficient for the required capacity. HNS expects to raise the pressure up to the maximum operating pressure of 66.2 bar(g).

Hystock currently has plans for four caverns for hydrogen storage at Zuidwending, the first of which is expected to be operational by 2027. The caverns have a volume of 1 million m^3 and will be operated at pressures between 80 and 180 bar.

Contaminations
Research by DNV commissioned by HNS parent company Gasunie [5] has indicated that the amount of contaminants left in reused natural gas pipes is well below the levels as advised by Kiwa and DNV in the previous study when following the Gasunie cleaning protocol.
Most compounds left behind were non-volatile, which are more likely to stay behind on the pipe wall instead of being absorbed by the hydrogen. The exceptions are aromatic compounds and the odorant THT, which were mostly flushed out of the pipe through multiple rounds of nitrogen purging.

HNS does not expect problems with the solid materials that are released during cleaning of used piping [6], as the amounts released are relatively small compared to the gas volumes transported and the compounds are not expected to be soluble in hydrogen. HNS will make use of filters at exit locations to ensure no solids can impact the gas quality.
Mercury in natural gas is absorbed by the pipe surface. There is currently no indication that large quantities of mercury are released into hydrogen under the conditions to be used for transport.

When hydrogen is stored in salt caverns, it is saturated with water, so the hydrogen needs to be dried at the exit of the caverns.
For the general case of storing hydrogen in caverns, the gas can be contaminated by carbohydrates in the oil used to protect the cavern ceiling during construction. This is not the case for Zuidwending, because nitrogen was used as a protector. The remaining sources of contaminants are geothermic and biochemical reactions. For salt caverns, reactions with anhydrite can result in H_2S contamination, while microbes can produce H_2S or methane.

Both HNS and Hystock have indicated a hydrogen purity of 99.5% to be possible. Both indicated their main concern to be a stricter sulfur limit than the previously proposed 3 ppm, at which point extra purification steps would be required.

Temperature

The current temperature range for natural gas in the transport network is 5-30 °C. In principle the network can handle temperatures of up to 50 °C [7], but the current range is set and based on three factors:

a. Soil temperature. Higher temperatures of the gas will result in more heat transfer to the surrounding soil. A high soil temperature can potentially damage crops or natural plant life and is strictly limited in permissions issued to the network operator.
b. Length of the pipeline from entry point to the nearest exit point. This also limits the upper temperature range. Sufficient length is required for cooling of the gas before arrival at an end user;
c. Coatings used in the pipe. Temperatures below 0 °C can damage the coatings used in pipelines [7]. The effect of high temperatures on coatings is unknown, but temperatures up to 50 °C should have no negative impact.

Relevance for hydrogen:

The temperature range for natural gas is taken as a basis for that of hydrogen. The same factors still apply to some extent:

a) The soil temperature again limits the upper limit of the range. The molar heat capacity, the amount of heat that can be added to a mole of the gas to raise its temperature by 1°C, for hydrogen is 80% that of methane. This means that all else being equal, hydrogen will cool down faster than natural gas. Unfortunately, it is not that simple. Heat transfer is dependent of an array of factors, such as the temperature difference, type of soil, velocity of the gas through the pipe, pressure inside the pipe and type of coating. This makes it very difficult to generalize the effects of a higher upper limit.
b) For the temperature at the nearest exit point, the same arguments apply as for a). It is not possible to say that a temperature limit above 30 °C can be implemented before evaluating on a case by case basis.
c) The coatings enforce the same lower limit of 5 °C that is currently used for natural gas. Due to a lack of knowledge on the effects of high temperatures on the coatings, the temperature range is limited to at most 50 °C.

Hystock expects the hydrogen stored in the caverns to reach a temperature of 40 °C, which would mean an exemption is required or cooling equipment needs to be installed. Other stakeholders have also indicated their preferences for a higher upper limit, to reduce the costs associated with cooling green hydrogen produced by electrolyzers.

Some stakeholders advocate for a higher upper temperature, since hydrogen produced by electrolysis should be cooled before injection and therefore extra costs would be involved when cooling to 30 °C.

Conclusions

A hydrogen purity of 99.5 mol% is technically feasible. Both Hynetwork Services and Hystock have indicated this purity is achievable with current methods. The limit of sulfur should not be lowered further beyond the currently proposed 3 molppm limit, since leftover odorant in reused natural gas pipes and chemical reactions in storage caverns do not allow for it without the introduction of additional purification steps.

HNS prefers a temperature range of 5 – 30 °C. Kiwa and DNV also advise a temperature range limit of 5 – 30 °C, as is currently the range for natural gas.
An exception can be made for a higher gas temperature up to a maximum of 50 °C if following three criteria are met:

- no impact on the surrounding area at the entry point;
- no exceedance of the temperature range for the nearest exit point;
- no impact on connections and pipeline infrastructure.

Note: HNS argues in a comment to this advice that the evaluation of an exception to the upper temperature range, based on the local conditions, can only be performed if a legal assessment framework is arranged, assuring a non-discriminatory assessment.

6 Specifications for a 99.5% hydrogen quality

In case of a gas quality specification of at least 99.5% hydrogen, the gas quality specifications in Table 11 are proposed.

Table 11: proposed specifications hydrogen in the transport grid for entry- as well as exit-points (momentarily basis)

Parameter	**Unit**	**Value**
Wobbe number	MJ/m^3(n)	45.99-48.35 ^{A}
Hydrogen	mol%	≥ 99.5
Inerts	mol%	≤ 0.5 inert N_2, Ar, He
Hydrocarbons	mol%	< 0.5 incl. CH_4
Hydrocarbon dewpoint	°C	≤ -2 at 1 – 70 bar(a)
Water dewpoint	°C	-8 at 70 bar(g)
Oxygen	mol ppm	≤ 10
Carbondioxide	mol ppm	≤ 20
Total S content (incl. H_2S)	mol ppm	≤ 3
Halogen compounds	mol ppb	≤ 50
Carbon monoxide	mol ppm	≤ 20
Formic acid	mol ppm	≤ 10
Ammonia	mol ppm	≤ 10
Formaldehyde	mol ppm	≤ 10
Dust particles (> 5 µm)	-	^{B}
Temperature (entry)	°C	5 - 30 ^{C}
Temperature (exit)	°C	5 - 30 ^{C}

A. The volume in m^3(n) is defined at 0°C (measurement conditions) and 1013.25 mbar. The energy in MJ is derived from the thermodynamic values between 25°C (combustion conditions) and 0°C and at 1013.25 mbar according to ISO 6976.
B. The hydrogen may not contain any solid particles, liquids or gaseous components which could affect the integrity of the gas network or gas application.
C. The maximum temperature may be deviated from depending on the situation on site (types of materials, requirements of customers).

Compared to the proposed specifications in the previous advice (report (Kwaliteitseisen voor waterstof t.b.v. het transportnet, May 2022), that was based on a 98.0% hydrogen specification, the following parameters have been changed:

- the lower limit of the Wobbe number, based on higher heating value, has increased since the quantity of trace components that may have an impact on the Wobbe number, is lower, leading to a lower band with;
- the number of inert components as well as hydrocarbons are both maximized to 0.5 mol%, but from the ≥ 99.5 mol% hydrogen specification, it is obvious that the sum of all non-hydrogen compounds should never exceed 0.5 mol%.

7 References

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