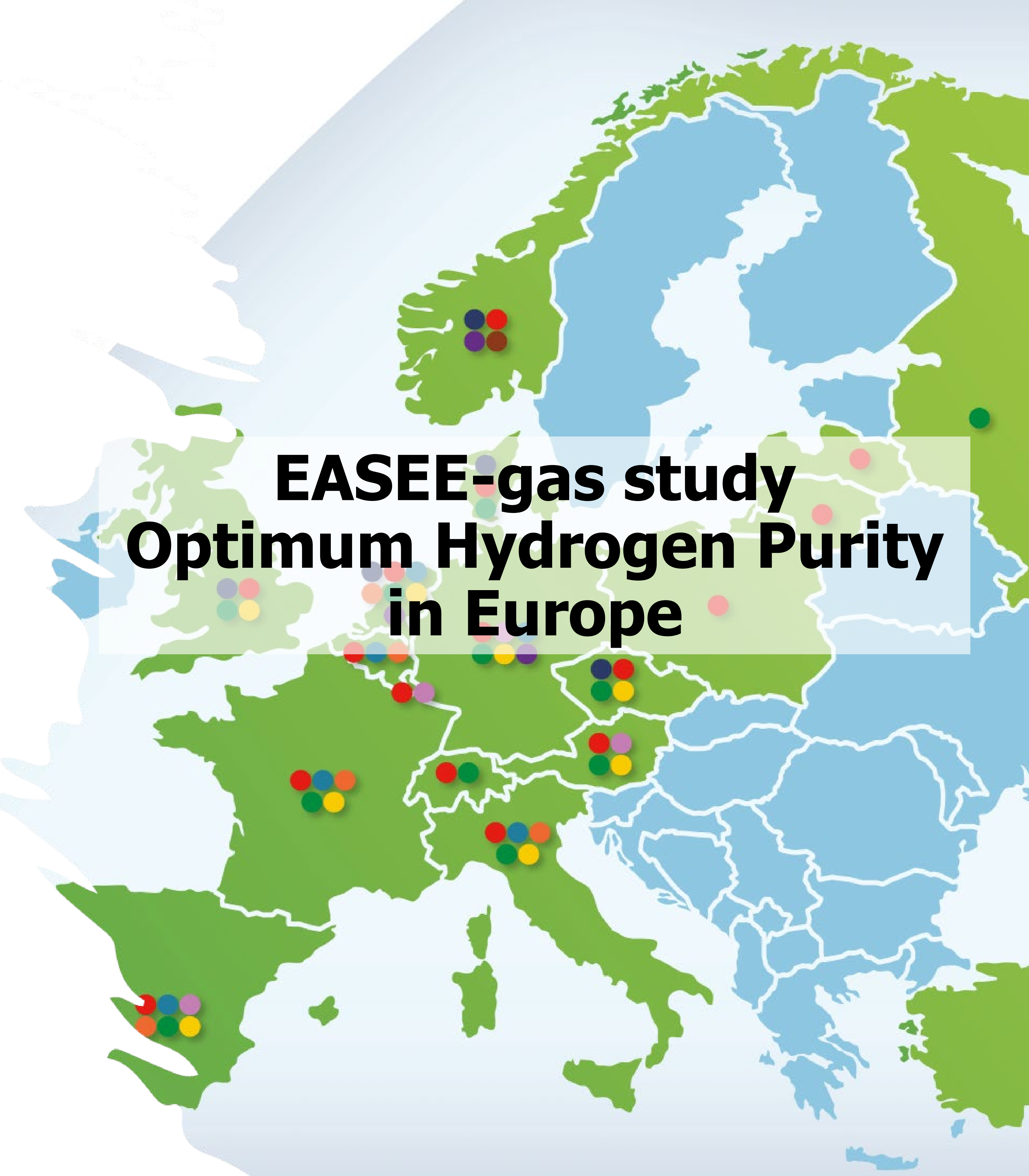

EASEE-gas study Optimum Hydrogen Purity in Europe

Gas Quality Harmonization Working Group
Brussels, 4 February 2026

EASEE-gas

Streamlining the gas business

Summary

The DNV KIWA study presented in this report, investigates the optimal hydrogen purity level for Europe using a techno-economic model. It builds on a previous Dutch study[1] and adapts it to a European context. The goal is to identify the optimum hydrogen purity level that minimizes total system costs across production, transport, storage, and end use. It compares hydrogen purity levels across the hydrogen value chain.

Due to the chosen setup, the study has some limitations that may influence its outcome.

- Purification Technology: The model exclusively uses Pressure Swing Adsorption (PSA) for purification. It does not account for spatial, permitting, or infrastructure constraints that may affect PSA deployment and other technologies for purification.
- Simplified Cost Modelling: The purification cost model is simplified and may not reflect real-world complexity.
- Scenario Sensitivity: The distribution of end-user applications and their specific quality requirements significantly affect the model's outcomes. For example, e-fuel production demands ultra-high purity hydrogen, which may not be adequately captured in the current model.

The EASEE-gas Gas Quality Harmonization Working Group considers it important to highlight these issues as an integral part of this document.

The complete, unmodified DNV KIWA report is presented in Chapter 3 of this document. A summary of the DNV KIWA study can be found on page 9.

[1]) https://open.overheid.nl/documenten/e4c35d40-0888-41bf-bf6f-d59e7269e103/file

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Foreword

The study conducted by DNV KIWA on behalf of EASEE-gas on the optimum hydrogen purity in Europe represents the first European-wide economic perspective on hydrogen, underscoring its significance. The study serves as a starting point for a unified European hydrogen network and encourages further investigation, as noted in the "Recommendations".

Generally, it is important to publish a study as a standalone document to respect its findings and adhere to common practice. However, during the study, it became evident that several stakeholders have significant objections to the underlying assumptions, which have influenced the presented outcomes. These objections are further elaborated in this document. An assessment was made to determine whether the objections could be addressed within the scope of the current study. However, doing so would have required substantial modifications to the study model and design and as a result additional funding. Given the absence of a dedicated budget at the time, it was ultimately decided not to pursue this path. The continuation of this study and a new dedicated budget within EASEE-gas may be considered again at a later stage.

Consequently, the question has arisen whether to proceed with the publication of this study. As the first study of its kind and due to strong external interest during its execution, it was decided to publish the study but to prevent the study results from taking on a life of their own, it has been decided to make the DNV KIWA study an integral part of this document.

Chapter 2 provides an overview of the study's background, outlines the primary assumptions, and offers a concise summary of the methodology. Chapter 3 contains the complete and unmodified DNV/KIWA study report. The limitations of the DNV KIWA study, along with concerns raised by several EASEE-gas members during the study's execution, are discussed in Chapter 4. Finally, Chapter 5 presents recommendations for future research.

EASEE-gas
Streamlining the gas business

1 Introduction

European gas infrastructure operators—including Transmission System Operators (TSOs), Distribution System Operators (DSOs), and Storage System Operators (SSOs)—are working toward the development of an integrated network of national hydrogen infrastructures ("European hydrogen backbone") over the coming decades. This vision closely mirrors the structure and function of the existing European natural gas network.

The objective is to enable the formation of a European hydrogen market by facilitating cross-border hydrogen flows. Such connectivity is critical for ensuring both security of supply and demand, as well as fostering competition among future hydrogen producers.

The hydrogen infrastructure will consist of newly built assets, existing repurposed natural gas assets and underground storage facilities, which connect numerous hydrogen producers (e.g., steam methane reforming, power-to-gas, gasification, pyrolysis) and end-users (e.g. industries, mobility).

Hydrogen quality will be influenced by multiple factors, including the production method, potential contaminants present in repurposed or newly built infrastructure, end-user specifications, and economic considerations such as the production costs and cost of purification method depending on where it is performed (by the producer, TSO, SSO, or end-user). Establishing a robust and harmonized hydrogen quality specification, reflecting the optimum for the whole value chain, will therefore require careful assessment of all these interrelated parameters.

1.1 "Dutch" DNV KIWA study

In 2023, KIWA and DNV have performed a study on behalf of the Dutch Ministry of Economic Affairs with the aim of providing recommendations for the quality requirements for hydrogen in the Dutch National hydrogen backbone. The study included both technical and economical evaluation to arrive at the optimal hydrogen purity specifications. The results of this study were published in August 2023[2] and presented among others at the ENTSOG Gas Quality workshop in November 2023[3]. The focus of the study was on the minimum hydrogen purity in the future Dutch national transport systems and listed each the economic pros and cons of 98% and 99.5%mol minimum hydrogen purity standard. To address the cost impact of '98% vs 99.5% minimum requirement', a hydrogen purity cost model framework was developed in a previous study, resulting in a framework tailored specifically to meet the requirements of the envisaged future Dutch hydrogen system, but not necessarily those of other European countries. The model scope included i.e. suppliers, end users, transport, and underground storages.

1.2 "European" DNV KIWA study

The objective of this European study initiated by EASEE-gas is to find the optimal hydrogen purity level for the entire European Union. In this case optimal is defined as the lowest market costs for the entire hydrogen system. To find this optimum a techno-economic model was used that was created together with Gasunie and the Dutch Ministry of Economic Affairs in a previous study. The model was adapted to suit the specifics of the European Union. Scenarios based on the TYNDP 2024 were used as an input for supply and demand of hydrogen for years 2040 and 2050. The key steps include defining European scenarios, reviewing existing models, gathering feedback, and disseminating findings.

1.3 Similarities and Differences with the Dutch Study

The main differences between the "Dutch" and "European" DNV/KIWA studies, are the broader scope covering the entire European market and the usage of converted natural gas storages (salt caverns and porous ones - depleted or aquifers). The study utilizes a simplified hydrogen purity cost model that was made for the Dutch Ministry of Economic Affairs. It was adapted to fit the European Union. The main change was the use of a European energy scenario instead of a Dutch energy scenario. For this purpose, the TYNDP 2024 scenarios[4], were used. The various TYNDP 2024 scenarios were assessed for the years 2030 (National Trends+), 2040 (National Trends+, Distributed Energy, Global Ambition), and 2050 (Distributed Energy, Global Ambition).

[2]) https://open.overheid.nl/documenten/e4c35d40-0888-41bf-bf6f-d59e7269e103/file

[3]) https://www.entsog.eu/sites/default/files/2023-11/AllPresentations_GQWorkshop2023_FV%2BEC.pdf

[4]) https://2024.entsos-tyndp-scenarios.eu/ These TYNDP 2024 scenarios were drafted from data collected by TSOs and subsequently for their validation, they were submitted to public consultation to take inputs from all the stakeholders of the value chain.

In contrast to the Dutch study, this analysis utilized data from 2040 and 2050, enabling a direct comparison with the TYNDP 2024 scenarios. If the methodology from the Dutch study had been applied, it would have necessitated calculating 2035 data by interpolating between two separate TYNDP scenarios: 2030 (National Trends+) and 2040 (Distributed Energy, Global Ambition). By instead relying on actual data for 2040 and 2050, the findings directly correspond to the TYNDP 2024 information. Additional details about the TYNDP 2024 scenarios referenced are available in Annex A.

The subdivision of the various sectors in the model is based on the sectoral distinctions made in the TYNDP 2024. A differentiation is made between 'energetic' and 'non-energetic' usage. However, after consulting ENTSOG, it became clear that these labels cannot be directly linked to the required hydrogen purity. Therefore, for the purpose of determining the necessary purity levels, the classification used by DNV/KIWA in the Dutch study was adopted. Further details on this approach can be found in Annex A.

The model is based on calculating the total purification costs in the complete value chain from producer to end-user focussing on the optimum hydrogen concentration by optional separation of the main components (inerts and/or hydrocarbons) which can be present in larger amounts. Depending on the type of underground storage, the composition of the stored hydrogen changes and as a result purification is necessary during withdrawal. Other costs such as the price of hydrogen, transportation fees, storage costs, etc. are not included as they remain the same even though a different hydrogen quality is used. In the hydrogen purity cost model, all technical parameters of every step in the value chain are included: production, transport, storage, and end use. Most parameters were reused from the previous study. However, there are major differences.

As stated before, the main alterations are regarding the underground storages. A distinction was made between the different storage techniques, as to which hydrogen purity will leave the storage site. Newly built salt caverns will possibly (but not confirmed, besides for the methane content) produce hydrogen with less contamination than repurposed natural gas ones. For aquifer and depleted storage, the difference will be more significant.

2 DNV KIWA Study report (full and unaltered version)

GT-250064 Report code
3 February 2026

Optimal hydrogen purity for the European market

GT-250064 Report code
3 February 2026

GT-250064
3 February 2026

Optimal hydrogen purity for the European market

Update Januari 2026

Colophon

Title	Optimal hydrogen purity for the European market (update)
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Summary

Having a clear and transparent hydrogen network quality specification is crucial to facilitate market players, guarantee pipeline integrity and to guarantee optimal and safe performance of end use installations. To aid in creating a hydrogen quality specification two main research questions are developed in the start of this study: 1) What is the optimal hydrogen quality specification of European hydrogen system based on current views on the future hydrogen market? 2) What are the key market trends and technical drivers affecting the optimal hydrogen purity and how robust are the findings?

In this study end user hydrogen requirements, hydrogen production quality, storage specifications and purification technologies are used to model the optimal hydrogen purity level for the entire European union. In this case optimal is defined as the lowest market costs for the entire hydrogen system (so called "sweet spot(s)"). To find the cost optimal specifications, a high-level techno-economic analysis of the optimum hydrogen purity level for the European Union hydrogen market was performed, using a hydrogen purity cost model that was developed in a previous study for the Dutch Ministry of Economic Affairs. This model was adapted to include European production/consumption volume scenarios for the years 2040 and 2050 and specifications of the European union hydrogen storage market.

The output of the model is greatly determined by the input parameters. The most important input parameters are: the hydrogen market scenarios, the expected technical parameters of all the parties connected to the hydrogen markets, the specifications of hydrogen separation techniques and the price of hydrogen. Significant effort was made on getting the input parameters as accurate as possible, but the large uncertainty levels in technical specifications resulted in the systemic usage of an "optimistic" and "pessimistic" set of parameters.

For the hydrogen market scenario's, the ENTSOG / TYNDP 2014 scenarios were selected as the base scenario. A particular change for this work compared to previous works, was the integration of storage data in the supply and demand TYNDP 2024 scenarios. The storage send-out requirement of the various TYNDP 2024 scenarios were estimated by comparing the main drivers for storage flexibility services with possible alternative sources of flexibility, information from Guidehouse and EASEE gas members on future storage market composition and technical performance.

The main finding of the cost model is that the 99.5% sweet spot is marginally preferred over 98% in 2040. The main driver of this result is that the bulk of hydrogen end use is e-fuels, requiring high purity hydrogen. However, towards 2050 the 98% sweet spot becomes more attractive and may even be marginally preferred over the 99.5%. This shift is caused due to the increasing role of repurposed natural gas storages in the market scenarios. The main uncertainty is in technical parameter uncertainties: a positive bias makes the 99.5% sweet spot preferable, and a pessimistic parameter bias shifts the preference towards the 98% sweet spot.

It was found that these findings are relatively robust for several key assumptions like market scenarios, future price levels and uncertainties in future usage of hydrogen separation techniques. For example, should the commodity price level (hydrogen, natural gas and CO_2) increase more than expected, the entire cost curve shifts up, but shape of curve remains the same. This means although the absolute costs rise, the location of the sweet spot and their relative merit order tend to remain the same. Other sensitivities have a similar effect, including slight ad hoc small changes in the tilt of the curve, marginally impacting the relative 98% v. 99.5% merit order. However, the overall shape of the curve tends to remain the same.

Identifying the market optimal European standard on hydrogen network quality is a highly challenging topic due to the complex interplay of underlying cost drivers and commercial interests of suppliers, end users, storage operators and transporters. In this study we have brought them together in a simplified cost model to provide first quantitative insights based on TYNDP 2024 market scenarios. These may serve as a valuable input for focussing the market discussions on the key issues, including needs for performing additional analysis and focussed discussions.

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1 Introduction

1.1 Developing a hydrogen market

The implementation of hydrogen in (existing) gas networks in Europe is currently slowly growing. Having a clear and transparent hydrogen quality specification is crucial to facilitate market players, guarantee the pipeline integrity and to guarantee optimal and safe performance of end-use equipment. Large industrial customers, production, storage and import parties will be connected to the hydrogen high-pressure grid, which is expected to consist of newly built and/or reused pipelines.

An important parameter in connecting the numerous customers and hydrogen suppliers is the hydrogen quality. At present no decision is made on the future European hydrogen specification for the gas networks, although the EC is working on a mandate to CEN to develop the hydrogen specification standards. Stakeholders need to understand all sources impacting (incoming and outgoing) hydrogen quality. This work will account for all these sources to find an economic optimum for the entire hydrogen grid.

1.2 Key elements for defining an hydrogen quality specifications

The goal is to find a balanced hydrogen quality standard in which the total market costs are as low as possible, while avoiding unnecessarily strict specifications. When developing a hydrogen specification at least the following elements should be considered:

End-user hydrogen requirements
End-users do not all have the same requirements for hydrogen purity. Some end-users need high purity levels (e.g. >99.9%) and require strict limits on certain trace components (e.g. sulphur containing components), while others can technologically accept even a 95% purity level. The required hydrogen quality strongly depends on the end-user's application.

Hydrogen production
Hydrogen produced with various production technologies (SMR, electrolysis, gasification, and possibly new technologies) will be fed into the gas network. Operators therefore need to understand the composition of (locally) produced hydrogen and the specific trace components. Different hydrogen production technologies may have different profiles for impurities and trace components causing risks for the hydrogen purity/quality in the network.

Storage and cross border trade
A fully functioning hydrogen system requires storage and cross border trade. Hydrogen will need to be stored for short term balancing of intermittent green supply, bridge seasonal supply-demand imbalances and eventually also for security of supply purposes. To this end a mix of line pack, salt caverns, depleted gas fields and aquifers will be used. These storages may be newly built or repurposed natural gas storages. The new salt caverns will likely be able to send out higher hydrogen purity grades. It is expected that hydrogen from new or repurposed aquifers and repurposed depleted gas fields need extra purification.

Purification technologies
In case purity levels need to be increased or trace components removed, purification or filtering technologies can be applied at production sides and/or at end-user locations. Different technologies are available; some are mature while others are still under development. For network operators it is therefore important to understand all (potentially) available technologies for hydrogen purification.

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1.3 Objective of this project

The objective of this project is to find the theoretical optimal hydrogen purity level for the entire European union. In this case optimal is defined as the lowest market costs for the entire hydrogen system. To find this optimum a techno-economic model was used that was created together with Gasunie and the Dutch Ministry of Economic Affairs in a previous study. The model was adapted to suit the specifics of the European union. A scenario based on the ENTSOG / TYNDP 2024 was used as an input for supply and demand of hydrogen for years 2040 and 2050.

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2 The hydrogen purity model

In 2023, Kiwa and DNV performed a study on behalf of the Dutch Ministry of Economic Affairs on the “techno-economic optimal hydrogen purity specifications for the Dutch hydrogen system” (Turkstra, JW, 2023; Turkstra, 2023). The focus of this study was on the optimal hydrogen purity in the future Dutch national transport systems and to list the techno-economic pros and cons of “>98%” versus “>99.5%” hydrogen purity standard. To quantify the overall cost impact of “98% versus 99.5% minimum purity requirement”, a hydrogen purity cost model has been created, based on a concept model developed in an (Gasunie internal) previous study, as illustrated in Figure 1, and shared with GERG Members (Jan Willem Turkstra, 2022). In this figure two different hydrogen network specifications are displayed. On the top of the network are the producers and at the bottom the end-users. The dots between the connected parties and the network indicates if purification is needed.

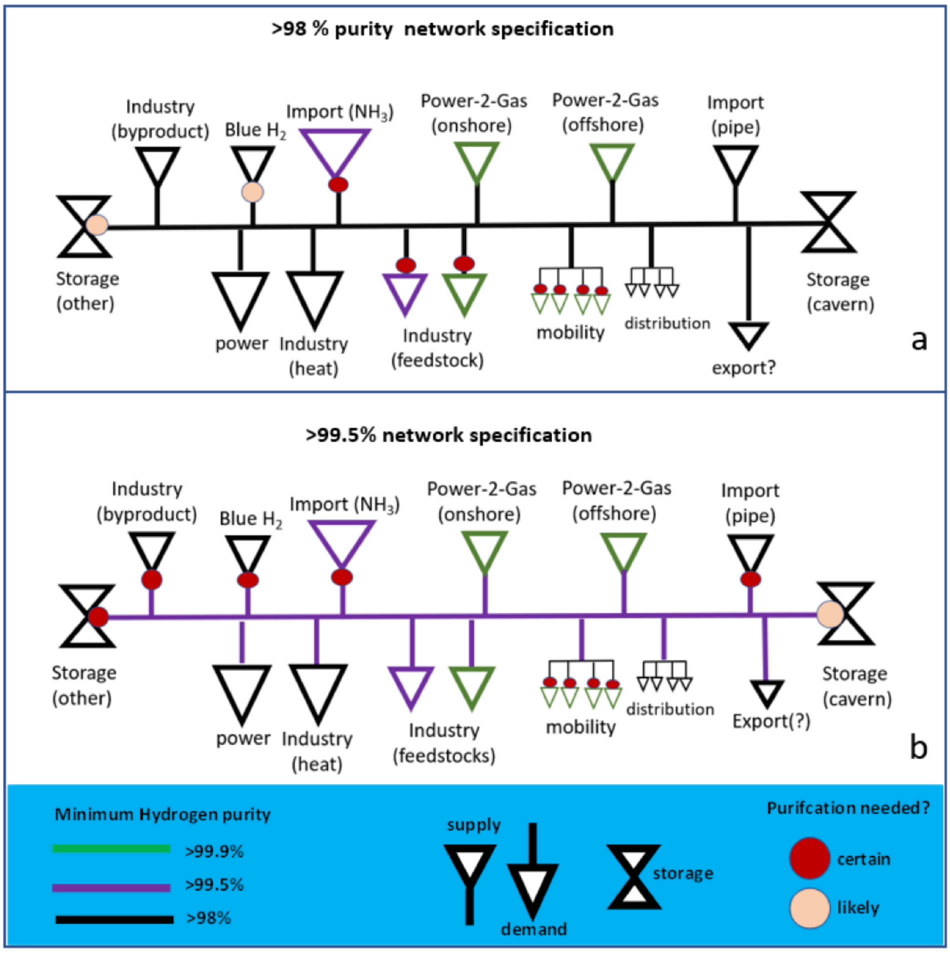

Figure 1: conceptual diagram of techno-economic model: A “red dot “represents a purification stage that needs to be installed to align either an end user or producer with the hydrogen specification of the backbone system.

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In the EZK study, the following model input information have been collected and validated with market stakeholders:

- Alignment on the hydrogen purity model scope concerning suppliers (on shore/ offshore electrolyzers, blue hydrogen, ammonia & LOHC importers), end users (power plants, industrial heat, chemical feedstock, mobility, residentials), hydrogen transport (road transport, pipeline, distribution, transit Belgium/ Germany) and storage (new salt caverns by HyStock).
- Minimum hydrogen purity requirements of current and future end user categories.
- Minimum hydrogen purity abilities of current and future suppliers without additional purification steps.
- A set of 2035 and 2050 hydrogen supply-demand scenarios for the Netherlands, covering the technological range of technologies in scope and future price levels.
- The techno-economic impact of installing and operating "Pressure Swing Adsorption" (PSA) hydrogen purification stages and especially the ability to find useful application for the so-called "tail gas", a small low pressure hydrogen flow out of the PSA's containing the filtered-out impurities (Essen van, Gersen, & Bastiaanse, 2024).

Based on the agreed hydrogen purity model scope and technical parameters, the model outputs a "spectrum of cost curves" for the input scenarios as outlined in Figure 2.

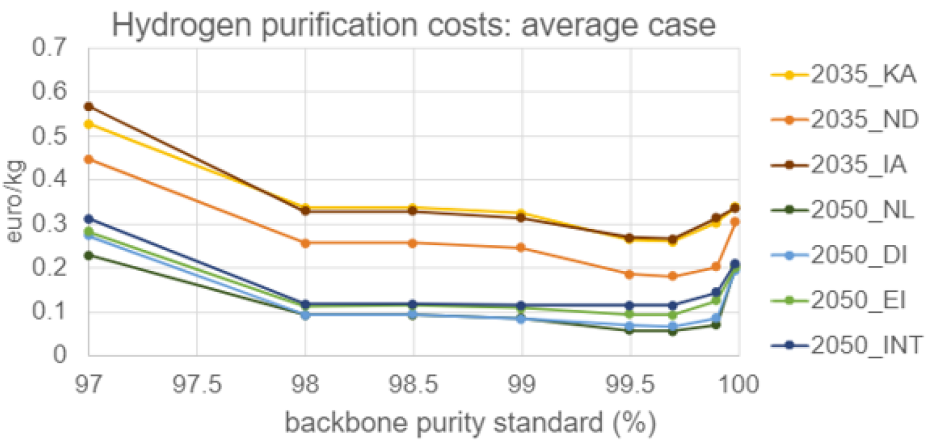

Figure 2: results of the Dutch Ministry of Affairs study: characteristic "curve spectrum" of the hydrogen purity cost model: total hydrogen purity related costs (normalized per kg), as a function of the minimum hydrogen purity requirement of the future hydrogen system.

Based on the "spectrum of cost curves" it is possible to identify cost minima or so-called "sweet spots" in hydrogen purity requirements for the national hydrogen system, including the robustness of these "sweet spot" across a wide range of uncertainties, such as market scenarios and technical assumptions.

The main research questions are as follows:

- From a societal /market perspective, what is the optimal minimal hydrogen content specification of European hydrogen system based on current views about the development of the hydrogen market?
- What are the key market trends, technical drivers driving the optimal hydrogen purity and how robust are the findings?

Note that in this work we will only refer to hydrogen purity specifications in terms of minimal hydrogen content (vol%) as in "98% versus 99.5%" and not go into technical detail on the allowed impurities that make up the remaining 2% or 0.5%. The outcome of this work can serve as a market sider input for the complex task of defining European hydrogen

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entry and exit specifications, also considering the technical limitations of transporting hydrogen through new and re-used pipelines.

For this EASEE-gas study, the hydrogen purity cost model from the Dutch EZK study was used, upon request by EASEE-gas, in mostly unaltered form for the European market modelling. The following approach was chosen:

- We started with conceptual frameworks as outlined in Figure 1.
- We replaced the Dutch scenarios with European ENTSOG/ TYNDP 2024 scenarios and used the same technical specifications for supply / demand where possible. We added the parameters for the new E-fuel fuels category. We discussed with ENTSOG and the EASEE-gas members on scenario interpretation and technical parameters of new and existing salt cavern, depleted gas field and aquifer storage, as the EZK study only involved new salt caverns.
- We created an updated hydrogen purity cost model to include all new information and requirements.
- We aligned the preliminary findings with EASEE-gas members in a workshop session.

2.1 Introducing the hydrogen purity cost model

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

- Possible hydrogen network design options & quality specifications.
- Volume of future hydrogen suppliers and end users.
- The impact of PSA purification stages.
- Total purification related costs for specific hydrogen quality specifications.

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, a fully revised version of the original model was made for the Dutch Ministry of Economic Affairs (“EZK model”). In this work, we used the EZK model again with as few alterations as possible, as requested by EASEE-gas, so the results of the EZK and EASEE-gas studies may be directly compared.

2.2 Model functionality

The hydrogen purity cost model is an “Microsoft Excel bookkeeping model with macro’s”, set up according to the conceptual design illustrated in Figure 3. The calculation engine calculates the hydrogen purity related costs for the following inputs:

- possible hydrogen network purity standards,
- a specific market volume & price scenario,
- a specific set of default technical input parameters,
- alternative datasets to test the robustness of the result for uncertainties in input values.

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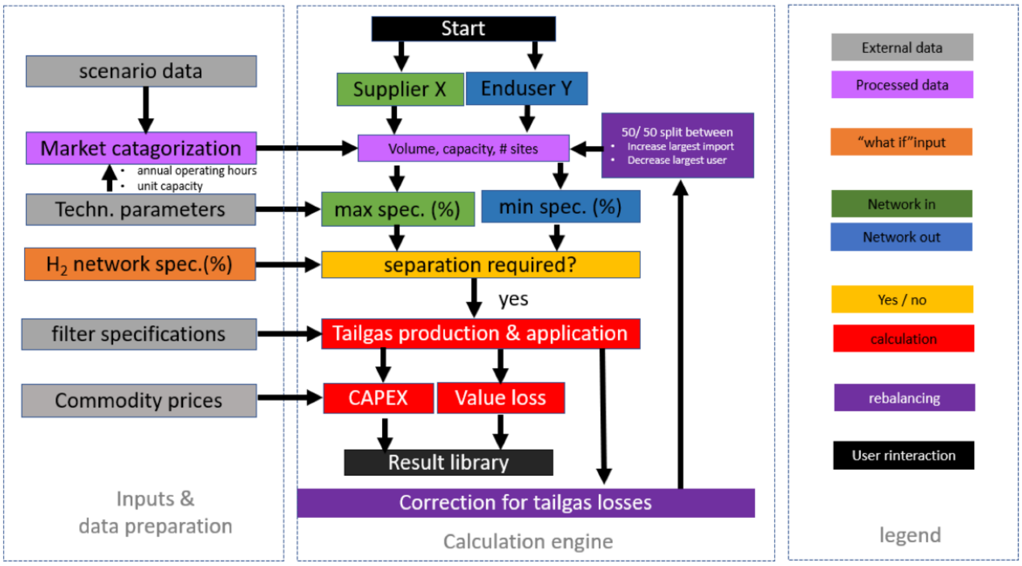

Figure 3: the data flow through the main hydrogen purity cost model.

The main model premise is that all suppliers and end users are connected to "ideal stirred vessel" hydrogen system with a specific minimum hydrogen purity specification, ranging from a low (<95%) to very high (>99.99%) quality specification. These boundaries were chosen so that the regions of interest can be analysed within a broader context. The model then calculates the overall market impact of a specific system purity specification on all individual market segments: suppliers, end users, storage operators and Transmission System Operators (TSO's). These are the stakeholders that need to decide to invest in separation/ purification measures to be fully compatible with a specific purity standard. The final calculation step in the model calculation is to re-balance the original supply-demand scenario to account for all the tail gas losses incurred along the supply, storage to end-use value chain. This is done by equally 50/50 adjusting down the market volume of the largest end user and by adjusting up the largest flexible import source.

The overall purification costs are determined by the model by the introduction of separation/ purification stages at supply, endues and storage sites. The overall costs are built up by CAPEX investments, operational expenditures (maintenance and electricity) and finally the associated hydrogen loss from tail gas. Tail gas is a small hydrogen flow including the filtered impurities. It is assumed that tail gas can only be used locally as a source of industrial heat and thus may represent the following economic loss factors:

- For **suppliers**, tail gas represents a missed opportunity to sell more valuable hydrogen to the market and use an alternative, more cost effective, energy source to meet local heat demands.
- For **end users**, tail gas production implies the purchase of more valuable hydrogen from the market instead of using industrial waste heat or an alternative, more cost effective, energy source to meet local heat demands.
- For **TSO's,** the challenge is to find a local industrial end user for tail gas associated with purifying hydrogen from/ to separate networks sections with different hydrogen specifications, for example on an import/export location, or to/from a regional hydrogen network.
- For **storage** operators, usually there is no local application for tail gas. Special measures may need to be taken like transporting tailgas to a local industrial site or connecting the storage with a dedicated "off spec" pipeline and purifying storage send out nearby industrial end users.

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To quantify these economic "loss of value" associated with tail gas, the remaining heat content is compared to the lowest cost alternative heat source, assumed to be natural gas + CO_2 emission rights. In 2040, it is mainly the price spread between hydrogen vs. natural gas+CO_2 emission rights that drives the overall tail gas associated economic losses. This implies that in 2040, when hydrogen is still considered a premium energy source compared to natural gas, the tail gas economic losses, when measured in €/kg, will be high. In 2050 (or any other moment in the distant future), when hydrogen is expected to be more a direct alternative to natural gas, the tail gas economic losses, when measured in €/kg, will be relatively low. However, due to the increase in the overall hydrogen market volume, the absolute tail gas economic losses measured, are likely to be higher in 2050 when compared to 2040.

The full scope of the model data organization around the hydrogen purity cost model is illustrated in Figure 4.

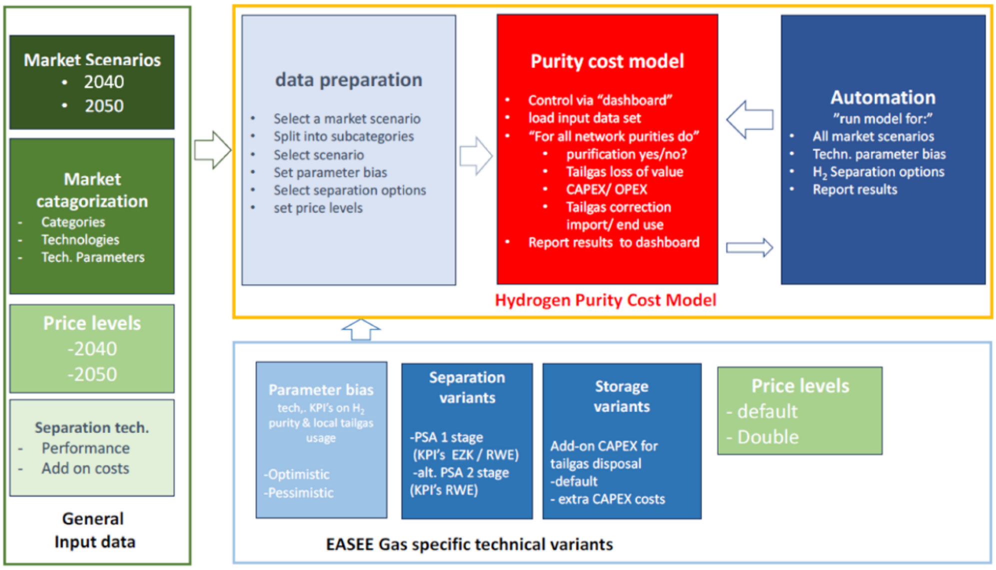

Figure 4: data flow around the hydrogen purity cost model, as outlined in Figure 3, here shown in red.

The model facilities a wide range of possible data input combinations. A full model run may thus comprise the following market narrative: "*calculate the hydrogen purity costs for the TYNDP 2024 Decentralized Energy (DE) scenario, year 2050, apply a "pessimistic bias to the technical parameters", assume the use the default single stage PSA technology include default CAPEX add-on (to address the storage tail gas disposal issue) and assume double price levels"*. Each choice in the model run has a default value and a set of alternatives to test the sensitivity to the uncertainties in that default assumption. The model uses macros to automate the run calculations for all combinations.

The core concept of the model is that appropriate measures will need to be taken somewhere along the supply chain, pre-emptively at the side of the suppliers, or just-in-time by the end users or even halfway the system by TSO or DSO to keep the overall hydrogen system within its specifications. The associated costs made by any party will be reflected in one form or another in the overall hydrogen price. The key issue is to determine which network locations are best suited to take potentially costly technical measures to keep the overall purification related costs as low as possible. The model does not specify which stakeholder is responsible for the CAPEX investments and responsible for tail gas disposal. The hydrogen purity cost model allows for the analysis of the following purification cost drivers intrinsic to the hydrogen system:

- Minimize the possibilities 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 better served with "cheaper lower quality" hydrogen.

- Concentrate the purification measures with the players who are best equipped to handle this purification task with the most economy of scale and with high annual load factors.
- Concentrate hydrogen purification at market parties with a direct use for energy content of the so-called "tail gas" out of the separators, i.e. the "off spec" hydrogen flow containing the filtered-out impurities that will need to be burned locally by a specialized burner.
- The network must be balanced to account for all tail gas losses.

Finally, it important to note that the hydrogen purity cost model is intended as a highly simplified techno-economic market model, giving first insights into the market dynamics concerning hydrogen purity specifications. The model treats cost factors therefore in the following simplified manner:

- Costs only address the hydrogen purification related costs (CAPEX/ OPEX/ tail gas) of the producers, end users, TSO's and storage operators. The costs cover the loss of sales of producers, the extra procurement of hydrogen by end users and storage operators due to tail gas losses minus the remaining value of the tail gas as heat.
- Annual CAPEX of separation stages is defined as CAPEX / technical lifetime.
- OPEX (annual maintenance + electric power use) assumed as a fixed rate of CAPEX (typically ~5% for single stage PSA and 7% for two stage PSA)
- No inflation correction, no interest rates, no commodity price discovery, taxes or subsidies.
- No re-use of existing PSA systems in 2040 or 2050 or other separation installations as their technical status is unknown. All 2040 and 2050 investments are considered green field, even in 2050.
- The model does not include technical limitation of hydrogen transport through new and re-used pipelines as it is a pure market model. However, we will impose external limits on the feasible range of possible hydrogen purities (95% - 99.99%) and mainly focus on the "98%" and "99.5%" regions of interest

The main purpose of the model is thus to provide high level insights into the key market drivers for determining the optimal network specification and the model costs should not be used outside this context. The hydrogen purity cost model, like other models, is a simplification of a real system, which means that hydrogen purity cost model used in this work has limitations. More information on these limitations can be found in Appendix A.

Please note that the original EZK model assumes two distinct moments in time, being near future (2030-2035) and distant future (2050/ 2060/ 2070), effectively starting points and end point of a future scenario. However, in this study we ran into the issue that ENTSOG only had complete data on 2040 and 2050. We thus chose to interpret "2040" as a proxy for the near future and "2050" for a proxy for a distant future scenario end goal.

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3 Input parameters

The hydrogen purity cost model is mainly a “bookkeeping model” and thus the output is greatly determined by the input parameters and mainly:

- The market scenarios including segment breakdown.
- The technical parameters of the market players.
- Techno-economic specifications of hydrogen separation techniques, the PSA systems.
- The price of hydrogen compared to the alternative, natural gas + CO_2 emission rights.

In this section we will discuss the input parameter used.

3.1 European supply & demand scenarios

The starting point for the model inputs are the assumptions on the future European hydrogen market sizes, and the segment break downs in 2030, 2040 and 2050. The TYNDP 2024 scenarios were selected as our main data source because of the following reasons:

1) ENTSOG is tasked by the EU with developing European gas market and infrastructure outlooks (Ten Year Network Development Plans / TYNDP) since 2009.
2) A fairly recent scenario, including EU policy revisions due to the Ukraine crises.
3) Completeness of the scope, documentation and availability of the data.

The TYNDP 2024 scenarios provide market data points for 2030, 2040 and 2050 as shown in Figure 5. However, TYNDP 2024 only provides detailed end user market breakdown for the 2040 and 2050 Distributed Energy (DE) / Global Ambition (GA) scenarios and therefore we will only use 2040 and 2050 DE and GA scenarios in this work. Moreover, the 2040 and 2050 Distributed Energy (DE) scenario will be used as the default scenario and the 2040 and 2050 Global Ambition (GA) is used as the alternative scenario to test the scenario sensitivity of model results. The choice to select the more conservative 2050 Distributed Energy scenario as the default scenario is not of major importance. This because the model results are normalized to “cost per kg transported”, the overall annual market volume cancels out. To the model it is more important on how the various scenarios differ in their underlying market supply, demand and storage technology break downs. The DE and GA scenarios are however rather similar in their views on future market break downs, making the choice not crucial to interpretation of model results.

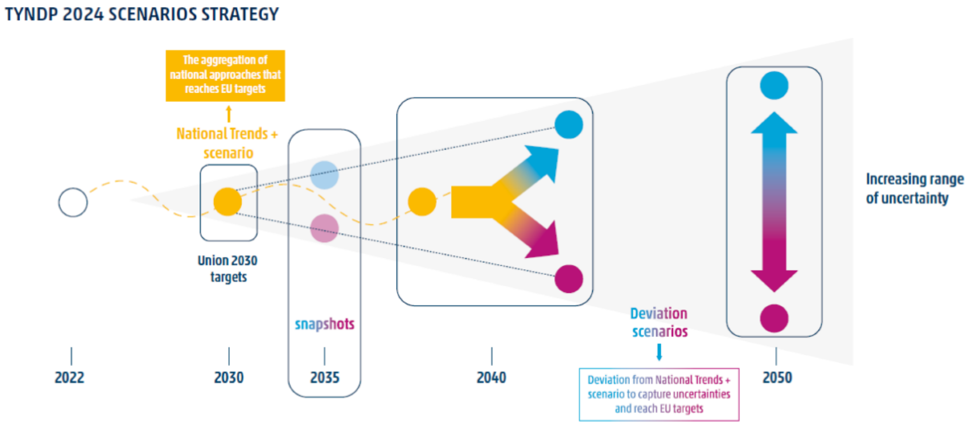

Figure 5: the interrelation between the ENTSOG National Trends -> Global Ambition (blue) & Distributed Energy (red) scenarios.

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In Table 1 the unaltered TYNDP 2024 market supply data is supplied. Some interpretation was needed on the specific technologies that may be used to import the low carbon and renewable hydrogen from outside the EU. We assumed that low carbon implies blue hydrogen likely arriving via pipelines from Norway. Renewable hydrogen is likely imported via bulk carrier from the other contents using, LOHC and Liquid H2 bulk carrier. In Table 2 the TYNDP 2024 demand volumes are shown. Note that the original TYNDP 2024 supply and demand volumes are not perfectly balanced. This is not an issue for the hydrogen purity model and therefore we did not correct for the small discrepancies between supply and demand.

Table 1: ENTSOG supply data (TWh/y). Only the 2040 and 2050 DE and GA will be used in this work.

ENTSOG data	All values in (TWH/y)	Distributed Energy		Global Ambition	
source	**technology**	**2040**	**2050**	**2040**	**2050**
Import	Low Carbon imports	135	111	196	192
Import	Renewable imports	388	318	473	546
Import	Ammonia	135	135	154	244
Grey/Blue	Methane ATR/SMR (+ CCS)	107	0	90	5
Green	Electrolysis	959	1795	1163	2083
Total		**1724**	**2360**	**2076**	**3069**

One of the challenges when using the TYNDP 2024 scenario data is that some industrial end user categories, like “steel”, “refinery”, “ammonia production” use hydrogen both for energy (heat) and feedstock. The TYNDP 2024 does distinguish between “energy” and “non-energy” hydrogen use, however ENTSOG has indicated to us that this distinction is still rather arbitrary. In this work we will continue to use the hydrogen usage interpretation for these sectors as used in the EZK study.

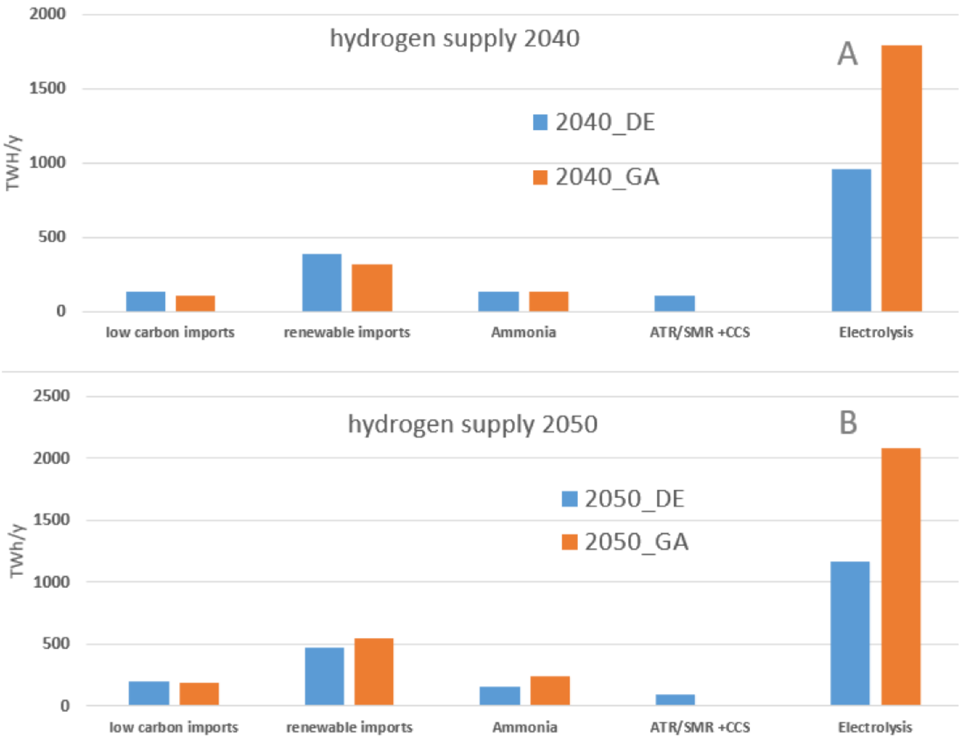

Figure 6: visual representation of the supply scenario data as shown in Table 4.

In both the 2040 as the 2050 scenario, creating hydrogen from electricity (called power to gas (P2G)) is the largest supply of hydrogen. This is more pronounced in 2050, where there is no blue and grey hydrogen production anymore.

Table 2: TYNDP 2024 scenario demand data (TWh/y)

TYNDP supply data	**Distributed Energy**		**Global Ambition**	
All values in (TWH/Y)	**2040**	**2050**	**2040**	**2050**
Residential & Tertiary	75	109	347	391
Transport	139	187	282	448
Industry	376	523	555	741
Agriculture	3	6	12	25
Power Generation	94	82	88	70
Non-energy use	308	402	277	407
Others	0	0	0	0
e-fuels	643	813	500	767
International maritime bunkers*	113	211	129	265
Total	**1750**	**2332**	**2189**	**3114**

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Note that e-fuels (both for aviation as for maritime purposes) are a big demand in these scenarios. This is because the TYNDP 2024 scenarios are modelled to give a net zero CO_2 result in 2050. As these sectors are hard to abate, hydrogen derived e-fuels are used to reach the net zero goal.

Table 3: End use market breakdown (in TWH/y) as used in this work.

Sector	Category	Usage	DE 2040	DE 2050	GA 2040	GA 2050
Industry	Fertilizers	Feedstock	73.0	106.8	55.9	79.4
Industry	Fertilizers	Heat	9.0	11.5	10.2	12.2
Industry	Chemicals	Feedstock	235.4	295.3	221.1	327.9
Industry	Refineries	Feedstock	67.9	107.5	70.0	88.3
Industry	Steel	Feedstock	106.2	159.5	132.7	159.1
Industry	Chemicals	Heat	38.7	45.2	72.5	104.5
Industry	Food, Paper, Others	Heat	153.8	199.0	269.5	377.1
Power	CC-GT	Combustion	94.1	81.9	88.3	70.0
Mobility	Land/Shipping	Fuel cells	134.4	180.6	275.3	444.0
Residentials	Boiler/CHP	Heat	74.7	108.6	346.7	390.5
Agriculture	Total	Heat	3.2	5.6	11.7	24.8
Transport	Planes	E-fuel	4.2	6.5	6.6	4.5
Transport	International shipping	E-fuel	113.1	210.8	128.7	264.9
P2M and P2L	Total	Feedstock	642.6	813.2	499.7	766.9
		Total (TWH/y)	**1750**	**2332**	**2189**	**3114**

The demand side of the scenarios divided over a multitude of different uses, all with potentially different hydrogen quality demands. The largest use of hydrogen will be to create e-fuels, specifically for aviation and shipping. E-fuels are chemically engineered substances (mostly liquids) that can be used as a drop-in replacement for fossil fuels. Hydrogen is the main feedstock for manufacturing these fuels. According to the scenarios, e-fuels dictate the hydrogen demand in 2040 and 2050 in Europe. In 2040 a substantial amount of hydrogen is used for refining purposes, as is also currently (2025) the case. Hydrogen is used in refineries during the breakdown of larger hydrocarbons ("crude oil") into smaller ones (e.g. diesel, petrol, LPG, and so on). Besides this cracking process, hydrogen is also used to lower the sulphur content in the fuel to meet the increasing stringent sulphur regulation and possibly as a source of heat. In 2050 it is expected that fossil fuels are reduced or compensated via underground storage, leading to reduced hydrogen use of this demand sector by 2050. Refineries will likely not disappear but will transform into hubs for sustainable fuels and chemical feedstocks. They will shift from fossil-based production to processes using renewable hydrogen, captured CO_2, and bio-based inputs.

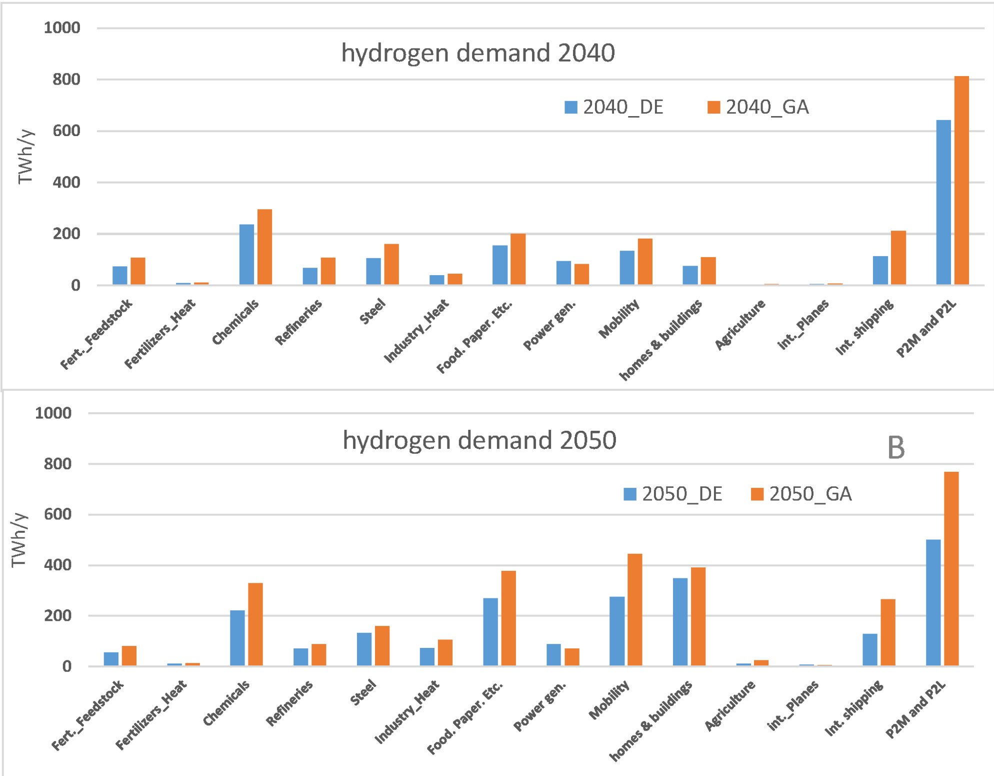

Figure 7: visual representation of the end use scenario data as shown in Table 5.

Although these scenarios may be open for debate as the market expectations evolve continuously, a decisive choice was made not to adjust any of the scenario value since this was not part of the assignment. The TYNDP 2024 scenario gives a well-thought direction that was useful as a starting point for discussion on cost optimal hydrogen specifications.

3.2 Storage modelling

A particular change for this work compared to previous works, was the lack of storage data in the TYNDP 2024 supply-demand scenarios. Towards this end, the storage send-out requirement of the various TYNDP 2024 scenarios was estimated. The main purpose of the storage estimation is to obtain storage send out values for the supply/demand scenarios that align well with the current market expectations on storage volume requirements. Therefore, the main drivers for storage flexibility services were compared with possible alternative sources of flexibility.

Key demand drivers for storage flexibility are:

- **Intermittent hydrogen production**. According to the TYNDP 2024 scenario the main hydrogen supply is that of hydrogen production via electrolysis. It is assumed that this production relies on the availability of excess electricity production, mainly via solar-PV, wind energy and supplemented by nuclear power. It was estimated that to smooth out this intermittent green hydrogen production source, a storage of at least ~25% of the production capacity is required.

- **Seasonal heating demand**. When hydrogen is used for residential and buildings heat demand, both for space heating and hot water, an estimated ~40% of the residential heating market demand must be stored (as for the winter period, the heat demand is larger than in the summer period).
- **Electricity generation**. When hydrogen is used for power production, it will be at moments that power-to-gas production is zero. It is estimated that ~90% of peak gas-to-power demand must come from storage.

The availability of (underground) storages is not the only source of flexibility. Other flexibility suppliers are:

- **Import flexibility**. Import of ammonia, LOHC, liquid H_2 via cargo ships will not be fully baseload but respond to market price signals. These importers have large above ground storage tanks, like LNG import terminals, which can also be used to supply short term flexibility to the market. A conservative 5% flexibility is estimated to come from this source.
- **Industrial alternative fuel**. It is likely that the industry will switch over to alternative heat sources or even decrease production when hydrogen production is low. A conservative 5% flexibility is estimated to come from this source.
- **Transit.** When the European market is widely interconnected, supply and demand mismatches between regions can be smoothed out via transit flows. A conservative 5% flexibility is estimated from this source.

If the intermittent hydrogen production from electrolyzers is offset to the three flexibility suppliers, there is still a gap that requires balancing. This balancing flexibility must be supplied by underground storage, which can be seen in Table 4.

Table 4: estimation of the required storage withdrawal / send-out for the 2040 and 2050 scenarios including the flexibility of users.

Flex drivers (TWh/y)	2040 DE	2050 DE	2040 GA	2050 GA
P2G intermittent	288	539	349	625
Residential	37	54	173	195
Power	85	74	79	63
Import	-77	-56	-91	-99
Industry	-38	-52	-55	-74
European interconnection	0	0	0	0
Storage send-out	**296**	**558**	**455**	**710**

To validate our estimates, we used the storage volume data from the Guidehouse study (Guidehouse, 2021) and discussed our assumptions on storage cycles specifications with the EASEE-gas expert panel. Additionally, the Guidehouse study was used to distribute the storage requirements over salt caverns, depleted gas field and aquifers. The results can be found in Table 5.

Table 5: storage send-out i.e. withdrawal volume (TWh/yr) estimates per storage type as used in the hydrogen purity model

			2040 DE	2050 DE	2040 GA	2050 GA
Caverns new	Peakshaving	Send out	53	44	81	56
Caverns Repurposed	Peakshaving	Send out	53	44	81	56
Depleted gas field	Seasonal	Send out	95	235	146	299
Aquifers	Seasonal	Send out	95	235	146	299
Total (TWH/y)	All	Send out	296	558	455	710

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Table 6: storage characteristics for the average storage site.

	Salt cavern new	Salt cavern repurposed	Depleted gas field	Aquifer
Characteristic volume (TWh)	0.8	0.8	16	4
Estimated # annual cycles	3	3	1	1
Max. send out capacity (GW)	1.2	1.2	8.0	2
Tail gas usage (0-1) (optimistic / pessimistic)	0.5/0.1	0.5/0.1	0.5/0.1	0.5/0.1
Send out purity (vol%) (optimistic/ pessimistic)	99.7/98	99.5/98	98/98	98/98

Table 6 the characteristics of the four types of modelled underground gas storages (UGS) are given. It was very challenging to establish the characteristic performance data of new/ repurposed salt cavern, depleted gas fields, and aquifer in terms of working volume, annual cycles, injection/ withdrawal capacity and minimum hydrogen purities. This is mainly due to that this market is highly divers and still in early stage of development. However, for the model, the important parameter is the total storage send-out / withdrawal volume and this value is derived from the TYNDP 2024 supply/demand outlook. Equally important is the expected minimum hydrogen content of the storage send out, and the uncertainty in this parameter is captured via an "optimistic and pessimistic" range in parameter value, ranging from 99.7% provided by Hystock in the EZK study to 98% in this study. It is assumed that the impurities (the 0,3 Vol% and the 2%) consist of contaminants like N_2, CH_4 , CO_2 etc., as it is assumed that reactive/ corrosive components like H_2S, H_2O ,etc. are removed via Temperature Swing Adsorption (TSA), glycol and/or activated carbon filters, before the gas enters the pipeline. It is also assumed, that reactive components can be filtered out without creating tail gas whereas the removal methods of the "inerts" will always produce tail gas, as we consider membrane technology very challenging for the very large send out flows.

Another highly uncertain parameter is the likelihood that the produced tail gas may find a local usage, due to a) expected lack of nearby industrial end users and b) the intermittent nature of the storage send-out. In the optimistic case we assume that, even after significant additional CAPEX investments, only 50% of the tail gas can find its way to local industrial end-users and in the pessimistic case only 10% of the tail gas can find valuable local application. The additional CAPEX investments may cover a diverse range of technical measures such as off-site PSA installations and/ or dedicated tail gas pipelines.
The typical volume and annual cycles are not directly used by the model, but these numbers are used together with the "max. send out capacity" to estimate the total number of distinct storage sites in Europe. This will lead to the total CAPEX investments that must be made to incorporate PSA systems and dispose of tail gas, which in turn is used in the model to find the financial optimum.

3.3 Commodity prices

In addition to market hydrogen production, end use, storage volumes, the hydrogen purity model also requires the commodity prices of hydrogen, natural gas and CO_2 emission rights. These are needed to calculate the cost of the tail gas (i.e. the loss of hydrogen sales by producers, additional procurement of hydrogen by end users with the remaining value of tail gas as a local source of heat). To determine the cost of heat, it is compared to the presumed lowest cost alternative: natural gas plus carbon emission rights. A key issue with the price levels as used in the EZK study however is that they originate from before the 2022 ban on Russian gas imports and the associated energy price inflation and general uncertainties of future price levels.

The hydrogen prices as used in the TYNDP 2024 study are mostly based on the 2022 Guidehouse study (GuideHouse, 2022). However, the values stated in the Guidehouse study are also still pre-Russian invasion in Ukraine and it is mentioned in the report that energy prices forecasts are highly uncertain. Table 7 indicates that the values used at the EZK study are at the upper range of the Guidehouse estimates. This is more in line with the currently price level in

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Europe. As a sensitivity test, we will also test the model sensitivity to an overall increase in hydrogen and natural gas prices, as Europe has experienced since 2024.

Table 7: commodity prices as used by GuideHouse and as used in the hydrogen purity cost model (EZK 2023).

Prices	**2030 (GH)**	**2035 (EZK)**	**2040 (GH)**	**2050 (EZK)**
Hydrogen (€/kg)	2.1/3.8	3.5	1.4/ 2.8	2.5
CO_2 (€/tonne)	130	100	205	100
Natural gas (€/MWh)	28	30	13	30

3.4 Technical assumptions

If the market volume scenarios, the category splits and the commodity prices are known, the next key step for the model is to quantify the impact of a network wide hydrogen purity standard. The model calculates this for each supply, demand, storage category. In the EZK study a list of key technical parameters was made for suppliers and end users, which we will also use in unaltered form in this study. Storage in re-used salt caverns, aquifers and depleted gas fields and e-fuels were not included in the EZK study and added in this work using EASEE-gas member expertise.

The technical parameters have the following assumptions and subsequent roles in the model:

- There are uncertainties associated with key technical parameters like minimum hydrogen purity for industrial end uses and maximum purity of hydrogen production techniques. Also, the future possibilities for market players to find local tail gas applications is largely unchartered territory. The uncertainty range will be captured using the “optimistic and pessimistic” parameter range and the default model result will be the average value between these estimates.
- The annual full load hours are used to calculate the capacity of the end use connections, and the CAPEX of the hydrogen purification stages.
- The average size (MW) parameter is used to calculate the total number of distinct production or end user sites in future hydrogen system.
- We assume that the full load hours for future industrial hydrogen application will be somewhat lower than currently used for natural gas as industries will need to become more flexible in their energy usage, assisting in network balancing and hydrogen price stabilization.
- The full load hours for mobility primarily refer to the regional distribution hubs filling the tube trailers that in turn will supply the filling stations, not to the actual full load hours of cars and trucks.

The technical parameters as used in the model are shown in Table 8 for end users and in Table 9 for the producers. The parameters are given including optimistic/ pessimistic range in minimum hydrogen purity specification. Also, the assumed possibility to utilize tail gas as a local heat source is given in a scale from 0 (= no feasible local application) to 1 (= full time local application). The number of sites is calculated by dividing the total market capacity by the unit capacity per category.

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Table 8: List of key technical parameters for the hydrogen end users in minimum hydrogen purity specification, as used for all scenarios.

Sector	Application	Technology	Tail gas Usage (0-1) optimistic	Tail gas Usage (0-1) pessimistic	Unit capacity (MW)	# sites 2040 (DE)	# sites 2050 (DE)	annual hours	Min. H_2 content (%) optimistic	Min. H_2 content (%) pessimistic
Industry	Fertilizer	Feedstock	1	0.8	1000	9	13	8000	98.6	99.5
Industry	Fertilizer	Heat	1	1	100	9	13	8000	98	98
Industry	Chemicals	Feedstock	1	0.8	500	59	74	8000	99.5	99.6
Industry	Refinery	Feedstock	1	1	1000	11	0	6000	97	99.5
Industry	Steel	Feedstock	1	1	1000	18	27	6000	99	99.5
Industry	Various	Feedstock	1	0.8	100	65	75	6000	98	99.5
Industry	heat	Combustion	1	1	50	513	663	6000	98	98
Power	CCGT	Combustion	0.5	0.1	500	63	55	3000	98	98
Mobility	Road	Fuel cell	1	0.5	50	448	602	6000	99.9	99.99
Residential	Heat	Boiler	1	0.5	50	747	1086	2000	98	99
Residential	Heat	CHP	1	0.5	50	0	0	2000	98	99
Agri-culture	Heat	CHP	1	0.5	50	32	56	2000	98	99
Export	Pipeline	Pipeline	0.5	0.1	500	0	0	4000	98	99.5
Mobility	Aviation	E-fuel	1	0.8	500	216	273	6000	99.5	99.9
Mobility	Shipping	E-fuel	1	0.8	500	38	70	6000	99.5	99.9

We have performed multiple studies into the hydrogen specifications issue, including surveys and interviews, and the result remains that many industry hydrogen specifications are still ambigous. As for example the refinery endusers, they may now typically receive 99.5% from SMR's and thus one may assume the hydrogen backbone must meet the same standard. However the 99.5% may perhaps also be the result of SMR's + PSA systems be able to easily produce 99.5% and thus refineries are likely now tuned to this specification. However, from a strict technical and chemical perspective, the required purity may vary. Depending on whether the hydrogen is used for cracking long hydrocarbon chains, providing process heat, or for fuel desulfurization, a purity level of around 97% could be sufficient for certain processes. The challenge to distinguish between technically required hydrogen purity specifications for complex industries like refinery, steel, etc. can only be made by the end users themselves once it becomes clear what the extra cost will be for providing 98%-99.5% hydrogen specifications from the backbone. This is the aim of this study and to this end we include the range of reported hydrogen specifications used in the specific sectors via "optimistic" and "pessimistic" values.

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Table 9: List of key technical parameters for the hydrogen producers, as used for all scenarios.

Sector	Application	Technology	Tail gas Usage* (0-1)	Tail gas Usage (0-1)	Unit capacity (MW)	# Sites 2040	# Sites 2050	Annual operational hours	Min. H_2 content (%) optimistic	Min. H_2 content (%) pessimistic
Industry	Various	Byproduct	1	0.5	100	0	0	5000	99.6	98
Green	Biomass	Gasification	1	1	10	0	0	7000	97	95
Green	Electrolysis	Onshore	1	0.9	100	1370	2564	4000	99.99	99.99
Green	Electrolysis	Offshore	0.8	0.5	5000	0	0	4000	99.9	99.9
Import	Pipeline	Norway/ UK/ Africa	0.8	0	10000	3	3	4000	99.9	99.5
Blue	CH4 reforming	ATR/SMR	1	1	1000	18	0	6000	97	95
Import	Ammonia	Cracking	1	1	1000	23	23	6000	95	95
Import	LOHC	Dehydro-generation	1	1	500	129	106	6000	99.7	99.5
Import	Liquid H2	Evaporation	1	1	500	0	0	6000	99.99	99.9
storage	withdrawal	New cavern	0.5	0.1	2000	13	18	2000	99.7	98
storage	withdrawal	Re-used cavern	0.5	0.1	2000	13	18	2000	99.5	98
storage	withdrawal	New/ re-used gas field	0.5	0.1	8000	6	8	2000	98	98
storage	withdrawal	New/ re-used Aquifer	0.5	0.1	3000	15	21	2000	98	98

3.5 Hydrogen separation technologies

The main assumption of the hydrogen purity model is that all connected parties (end users, producers, TSO's / DSO's and storage operators) should be able to apply purification technologies to meet the required hydrogen purity specifications. It is important to note that this study only focusses on the purification costs for separating out non-corrosive components like CH_4, CO_2, N_2, etc. and not the separation of corrosive components like H_2S, H_2O *which must be taken out in any situation as they may damage transport infrastructure*. It is assumed that Pressure Swing Adsorption (PSA) will be the main separation technology of choice for removing impurities like CH_4, CO, CO_2 and N_2 from the hydrogen feed. Corrosive components can be separated out using Temperature Swing Adsorption (TSA). Membrane technologies are mainly relevant for small scale applications up to now and in this model, we focus on large scale market players. However, there are indications that membranes may be used in the future for storage send out, but there is insufficient information available on this subject to be included in this work. For the removal of more reactive/corrosive pollutants like O_2, H_2O, H_2S, etc. other technologies are more suited (e.g. glycol washing and activated carbon filters). These technologies are highly efficient in capturing the reactive contaminants and do not produce tail gas. In addition, the EASEE-gas technical committee emphasized the likely use of Temperature Swing Adsorption (TSA) technology to remove H_2S from the hydrogen storage send-out, as this can be done without tail gas losses.

This work focuses on the separation of components like CH_4, CO_2, CO, N_2, etc., which is expected to be most of the pollutants. For these components PSA systems is the optimal technology that can separate these components out at the required (very) large flows. However, as these contaminants are hard to filter out, it does imply that part of the hydrogen feed, typically 12% in a single stage PSA, is discarded, the so-called tail gas. As tail gas losses pose a financial loss, the key part of the model is on how to mitigate tail gas losses and to find the optimal network specification where overall market cost costs are lowest.

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In Table 10 the single stage PSA parameters as used in the EZK study and alternative single and two-stage parameters, as provided by EASEE-gas members for the purpose of this study, are given. The EASEE-gas values are interpretations of detailed proprietary information received to suit the scope of the hydrogen cost model. Compared to the EZK study, an extra storage CAPEX is included for PSA retrofit by satellite installation to be able to address the technical challenge to add a PSA system to storage sites (more on this in sensitivity section). The PSA data from the EZK study has been used as a basis in this study. The new EASEE-gas insights on alternative PSA strategies, both “1 stage PSA” or “2 -stage PSA“ have been used to perform a sensitivity analysis on the model results.

Table 10: PSA parameters as, used in this study (EZK) and the new EASEE Gas information used for a sensitivity analysis. See figure 8a for more information on recovery efficiency.

Parameter (source)	**1-stage (EZK)**	**alternative 1-stage (EASEE-gas)**	**2-stage (EASEE-gas)**	**Unit**
CAPEX fixed	4	4	5.2	Mln €
CAPEX Variable	250	250	325	€/ kg H2/hour
OPEX	5	5	7	%/CAPEX/year
Recovery (<99.8%)	0.88	0.96-0.88	0.97	H2 out/in
Recovery (>99.8%)	0.85	0.88	0.94	H2 out/in
Technical lifetime	20	20	20	years
Storage satellite extra CAPEX	25	25	25	Mln €

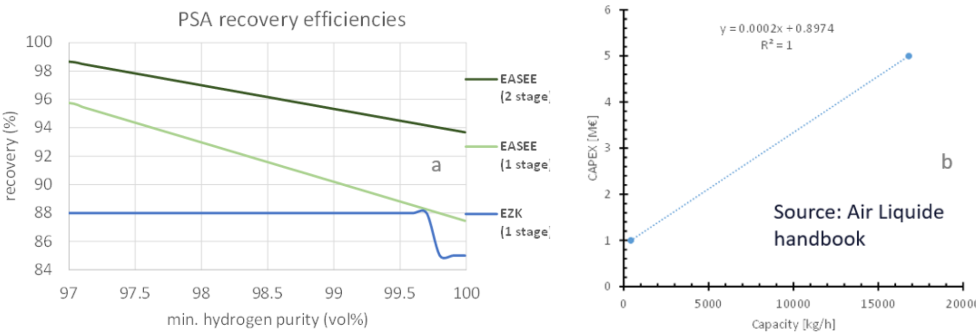

Figure 8 : a) hydrogen recovery efficiency of conventional (EZK) and alternative (EASEE gas) 1 stage and 2-stage PSA systems. b) the PSA curve used as a basis for the fixed and variable CAPEX cost.

Since the 2023 EZK study, new information and insights are gained by market players on PSA separation technology, and particularly the challenge of removing 0.5-2% of components from a hydrogen stream. EASEE-gas member shared their latest insights on expected PSA recovery rates in case of the standard single stage PSA application, and for a possible two-stage approach. In a two-stage system, the tail gas is recompressed and purified again. The latter option was discussed in the EZK study but there was no information yet available on feasibility, efficiency and costs. The main premises of this study was to re-run the EZK model with European market scenario but with the parameters of the EZK study. However, we will also re-run the model with updated PSA information on efficiencies, and for single and double stage PSA systems, to test the impact of these new insights of the main model findings.

4 Results

In this section the main findings of the hydrogen purity study are presented. The findings are based on the European 2040 and 2050 scenarios, as discussed in the previous chapter. In the next chapter the robustness of the model findings is explored.

4.1 Interpreting the model results

In Figure 9 an output of the hydrogen purity model is shown for the 2040 Distributed Energy (DE) scenario using "technical assumptions with a positive bias" as listed in Table 8 and Table 9. Figure 9A shows the overall system costs related to controlling the N_2, CH_4 and CO_2 impurities, normalized per kg transported. Figure 9B shows the cost break down, in absolute values, split out over producers (light/ dark green, cyan), end users (light/ dark blue) and storage (light/ dark purple). The dotted lines indicate additional system factors that will impose upper and lower limits to the hydrogen specification.

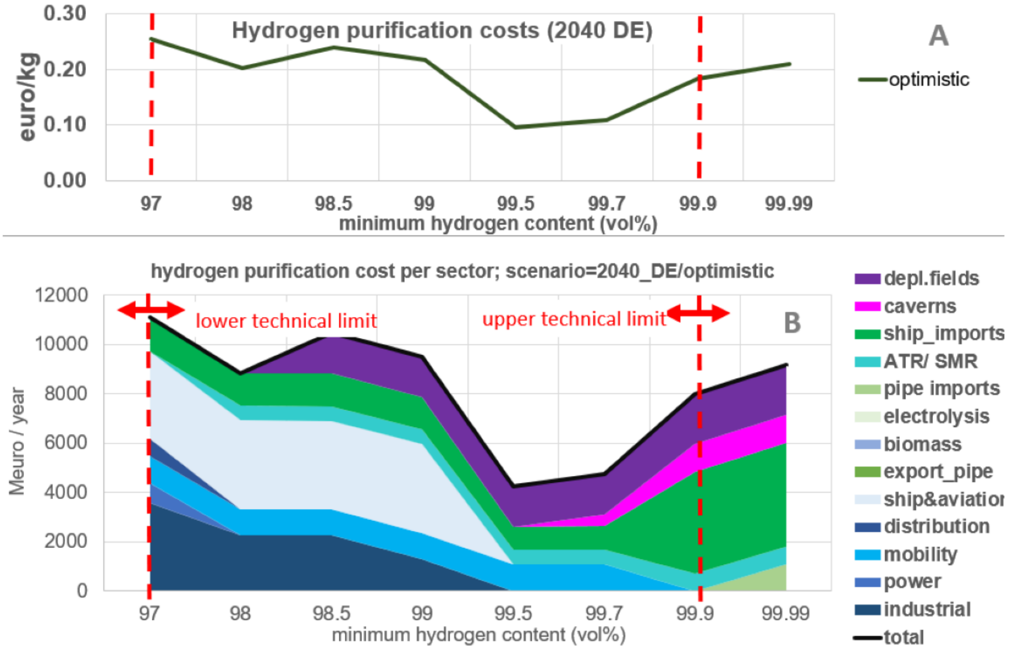

Figure 9: results for the TYNDP 2024 2040 Distributed Energy scenario. A) total normalized market costs, B) absolute costs per segment.

The "hydrogen purification cost per kg", can be rather ambiguous in the context of the hydrogen purity model. A transported volume hydrogen may have been purified twice or even three times, once at the producer's side, once at end-users' side and perhaps even once during the storage send-out. For the analysis of market specific impacts, the "total cost per segment" (Figure 9B) is the only unambiguous KPI. Thus the "market purification costs per kg transported" (Figure 9A) is the most intuitive KPI and thus will be used as the default model result.

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Figure 9B mainly illustrates how to interpret the output from the hydrogen purity cost model:

- **Hydrogen grades below 98%.** At hydrogen grades below 98%, effectively the entire end user market will need to make investments in PSA systems and find applications for tail gas. This will be challenging for the gas-to-power users, mainly combined cycle gas turbines, as they need stable combustion properties with hydrogen purities >98% and likely have challenges in finding a local use for the intermittent tail gas flows. Small scale industrial and residential heat applications will also struggle with specifications below 98%. The challenge for these market segments would be the installation small scale PSA systems by the TSO/DSO between the high-pressure network (with grades <98%) and the low-pressure distribution hydrogen networks with grades (>98%). Hydrogen grades below 98% would in theory benefit the hydrogen producers including storage operators. But the bulk of the hydrogen production is via highly pure electrolysis and LOHC imports, with minor roles for less pure hydrogen production via ammonia cracking, blue hydrogen (ATR/ SMR) and biomass gasification. The bulk of the producers therefore have no benefit for specifications below 98%. Storage operators are thus expected to be the only party that would greatly benefit from hydrogen specifications below 98%. They indicate that they will need to take out corrosive components like O_2, H_2O, H_2S via Temperature Swing Adsorption, molecular sieves, etc. and the resulting hydrogen specifications would be ~98%. Higher grades would require PSA purification techniques and finding local tail gas applications will be very challenging.
- **Hydrogen grades between 98% and 98.5 %.** At specifications > 98% up to 98.5% the end user markets using hydrogen for combustion (boilers, turbines and engines) are now able to directly use the hydrogen from the network, creating a dip in the cost curve. However, in the TYNDP 2024 scenarios these market segments are less prominent and this minimum around 98% is therefore relatively shallow. At specifications >98%, however the storage operators are expected to require hydrogen purification. Storage operators will struggle with finding tail gas applications due to a) the intermittent nature of storage send out volumes and b) geographical distance to large industrial clusters able to utilize the tail gas. Therefore, the costs rise again at specification >98%. This creates the first "sweet spot" around 98% for hydrogen purity specifications. The bulk of the end use market (feed stock, mobility end users) still requires hydrogen purification whether the specification is 98% or 98.5%.
- **Hydrogen grades between 98.5% and 99.7%.** At hydrogen specifications in the range of 98.5% to 99.5% it is expected (in the optimistic case) that the less critical industrial feedstock end users (E-fuel, Refinery, Ammonia, Methanol and steel) will now to be able to use hydrogen without purification. n the pessimistic case this will only happen at 99.9% for E-fuels. For specifications higher than 99.7%, it is expected that some of the imports (LOHC, pipeline imports) will struggle to meet these strict specifications and require purification. These factors combined, results in a second "sweet spot" in the hydrogen purity cost curve around 99.5%.
- **Hydrogen grades > 99.7%.** For specifications higher than 99.7%, it is expected that some of the imports (LOHC, pipeline imports) require purification to meet these strict specifications. They will struggle to meet these high purity grades and tail gas production is expected to rise rapidly at a quality specification exceeding 99.7%. However, at >99.9% specifications, it is expected that all sectors including the mobility sector using fuel cells is finally able to use the hydrogen from the network directly, thus eliminating their need for hydrogen purification. All these factors combined can result in a potential third sweet spot at >99.9% in pessimistic cases where e-fuels require >99.9% hydrogen purities. However, hydrogen purities higher than ~99.7-99.9% are also expected to be infeasible to transport using (partly) repurposed natural gas infrastructure and we will not include them in our analysis. This is indicated with the red lines in Figure 9.

These factors result in local minima in the cost spectrum, so called "sweet spots". In this example, the 2040 DE optimistic parameters case, the 99.5% wins out over the 98% sweet spot, but this depends on the combination of scenario and technical assumptions, as we shall see in the next section. Total market purification costs of around 0.1 €/kg, amount to ~3% of the commodity price of ~4 euro/kg, which is significant, but not to the extent that the hydrogen purification costs will disrupt the assumptions underlying the hydrogen supply-demand scenario.

4.2 2040 and 2050 Distributed Energy results

In Figure 10 we see the main model results for the 2040 and the 2050 Distributed Energy scenario, for the “optimistic”, “pessimistic” and the “neutral” parameter bias. Figure 11 shows the break down in underlying market drivers. The large uncertainty in key technical parameters is captured in “pessimistic” and “optimistic” bias when refers to the estimated abilities of the producers, end users and storage operators to supply or use hydrogen with PSA systems of being able to find local applications for tail gas. The neutral bias is calculated as the average of the optimistic and pessimist parameter bias results. Note that the model results include the >99.99% hydrogen purity option, but this option is only feasible for regional networks with new pipelines and considered infeasible option for international hydrogen backbones including re-used natural gas pipelines.

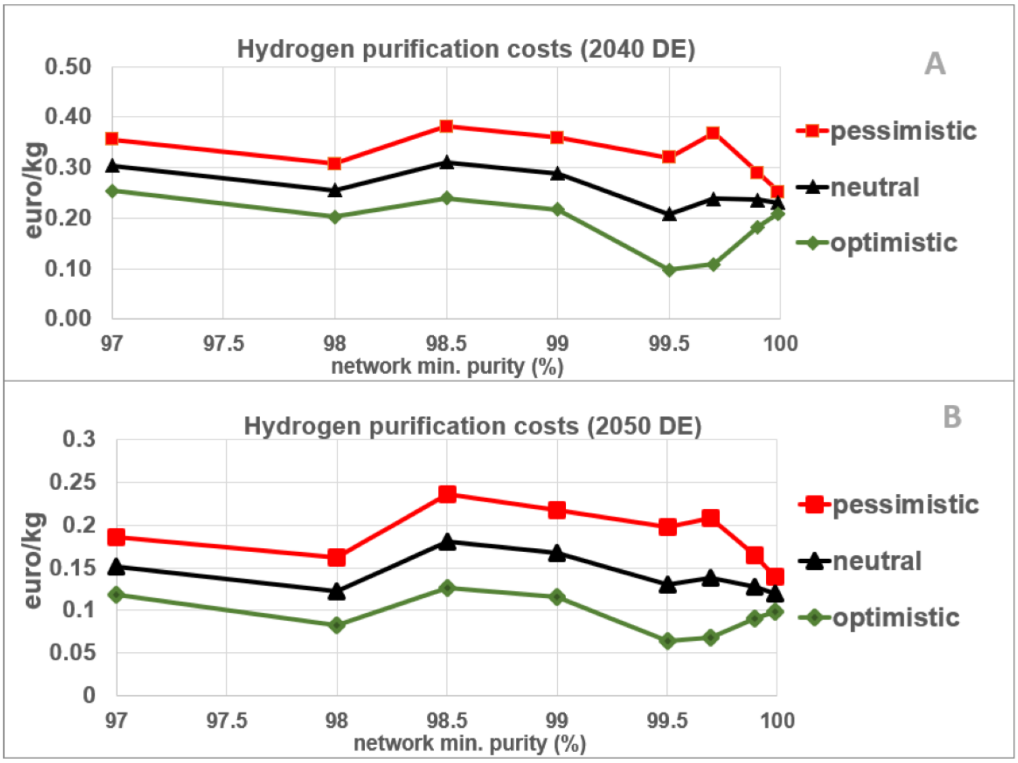

Figure 10: results of the hydrogen purity cost model for the 2040 and 2050 Distributed Energy scenario. The 2040 and 2050 Global Ambition scenarios are shown in Figure 12.

The main observations from Figure 10 (the main cost curves), and from Figure 11 (the underlying cost drivers), are:

- Applying a “pessimistic bias” erase the relative advantage of the 99.5% sweet spot, due to the uncertainty if the large e-fuels market can be satisfied with the 99.5% purity (optimistic) or require a 99.9% minimal hydrogen purity (pessimistic bias).
- From 2040 to 2050, the relative costs of hydrogen purification decrease as the cost spread between hydrogen tail gas and natural gas combined with carbon emission rights is set to disappear.
- Towards 2050 the small relative advantage of the 99.5% sweet spot over 98% sweet spot effectively disappears as the cost impact of repurposed natural gas storages, depleted gas field and aquifer, starts to add up.

- The biggest impact of the uncertainties in technical parameters is in that the overall level of the hydrogen purification costs curve shifts up or down entirely and the small advantage of the 99.5% sweet spot over the 98% sweet spot is reduced. In the neutral bias the preference of the 99.5% over the 98% is effectively diminished.
- The EASEE-gas curves match the cost curves observed for the EZK study in terms of general shape and levels. This is slightly surprising as the underlying scenarios are completely different. The main distinction is that the European curves have a more pronounced 98% sweet spot, and the relative difference with the 99.5% sweet spot is decreased.
- Figure 11 illustrates the relative contributors to the overall shape of the curves. The #1 contributor is e-fuels followed by storage (depleted gas fields & salt caverns), industry and ship import (LOHC) in comparable amounts.
- At >99.99% network specification all demands can be met (including mobility), both for optimistic or pessimistic bias, and all suppliers (except electrolysis) will need to purify, either optimistic or pessimistic bias. The >99.9% sweet spot thus arises as there is no longer any double purification along the value chain, i.e. hydrogen purified both by suppliers and again by critical end users like mobility.

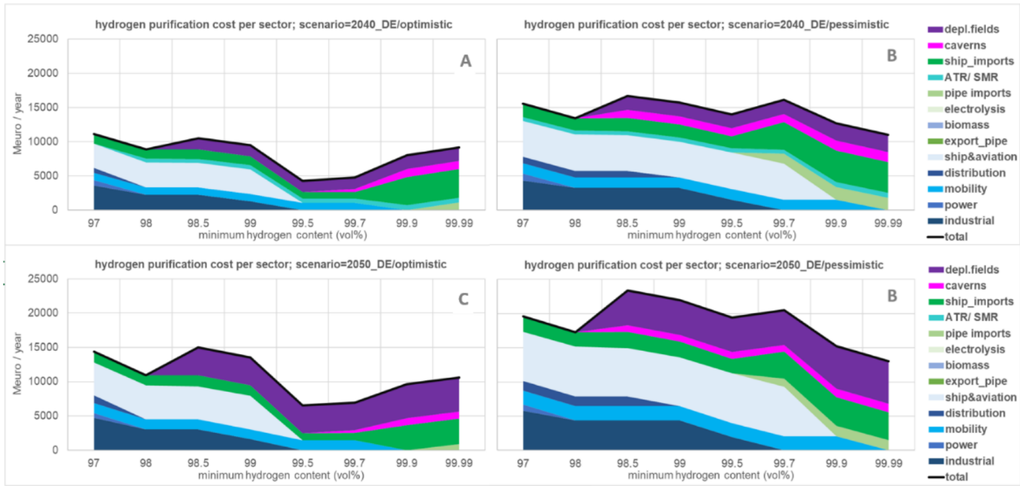

Figure 11: breakdown hydrogen purity output into market segments for the 2040 DE and 2050 DE scenarios, optimistic and pessimistic parameter bias.

In conclusion, the general findings are:

- The results indicate two technically feasible sweet spots at 98% and at 99.5% in which the total market purification costs are the lowest. The 99.99% sweet spot is considered technically infeasible to transport and is thus not considered in more detail in this work.
- The 99.5% sweet spot tends to be marginally preferred by the model in 2040 but the difference vanishes towards 2050. In 2050 the 98% sweet spot is preferred in the pessimistic parameter bias.
- The #1 contributor to the hydrogen purity costs is e-fuels closely followed by storage, industry and ship import (LOHC) in comparable amounts.
- The relative advantage of the 99.5% sweet spot disappears when the parameter bias changes from optimistic to pessimistic and the 98% sweet spot is even slightly preferred.
- The results of this study are in line with the cost curves from the EZK study. This is not straight forward as the differences between the used scenarios are considerable. The main difference is that the 98% sweet spot is

more pronounced and the difference with the 99.5% sweet spot is smaller and in the pessimist case, the 98% is even slightly preferred.

5 Sensitivity analysis

The hydrogen purity cost model has many uncertainties in assumptions about the future European hydrogen market. Most uncertainties are addressed by the key model uncertainties via the "optimistic" and "pessimistic" technical parameter bias approach. In this chapter, we will test the sensitivity of the main model for several remaining uncertainties:

- **Alternative market scenarios.** The model will be tested with the Global Ambition TYNDP 2024 scenarios.
- **Future commodity prices**. With the Covid19 pandemic and the Ukraine invasion, inflation has risen, and energy prices have doubled compared to previously set long term price levels. The long-term impact of the recent price spikes is highly uncertain. The impact will be tested by commodity price doubling.
- **Storage CAPEX add-on.** The EASEE-gas expert group indicated that there are technical challenges on installing PSA systems on new and existing storages. There may not be sufficient space on site and special measures should be taken to address the tail gas issue. The chosen approach in this study is to include a one-off ~25 M€ CAPEX add-on investment for either installing PSA systems on every storage site or having a dedicated transport line to a site where the gas can be purified. The size of this one-off investment is however highly speculative, and we will test the impact of increasing this one-off value.
- **Two Stage PSA systems**. The EASEE-gas expert group provided insights on the possibility of a two-stage approach on hydrogen purification. Since the hydrogen impurity levels are relatively low (<2 vol%) it becomes feasible to recompress and purify the tail gas a second time. This technical option was discussed in the EZK study, but no information was available at that time on price, performance and technical maturity. However, with the provided information by EASEE-gas experts the impact of two-stage PSA systems is explored.
- **EASEE-gas PSA efficiencies**. In addition to the two-stage PSA option, the EASEE-gas expert panel also provided more insight in their information on PSA efficiencies as a function of output purity. The model was rerun with the insights provided by the EASEE-gas expert group.
- **Check on storage tailgas valorisation**. A Major unknown will be to what extend tailgas from storage send out purification may be recovered even after 25-to-75-million-euro extra investment per site. In the best case tailgas may be transported to an industrial site 50-100 km away or in the worst case a PSA installation will be placed on a satellite location with local tailgas application. In this work we assume that even after these extra investments only 10-50% of the tailgas value may successfully be recovered. We will examine the impact of these conservative estimates by testing what would happen if in an ambitious case 50-90% of the tailgas may be recovered after the extra investments.

5.1 2040 and 2050 Global Ambition results

In Figure 12 the model results are shown for the alternative Global Ambition TYNDP scenario. The impact of alternative GA scenarios on interpretation of the hydrogen purity cost curve is minimal. In the Global Ambition (GA) scenarios the relative order between the 98% and 99.5% sweet spots is the same and they mainly become more pronounced. The main reason for the similarity that the TYNDP 2024 scenarios are quite similar in relative market break down as all scenarios rely heavily on power-to-gas and on the creation of e-fuels. Also, the hydrogen purity cost model normalizes cost per kg transported and thus the model is insensitive to differences in overall market volumes. The differences in cost curves between the scenarios are therefore well within the overall uncertainty margins of the model parameters.

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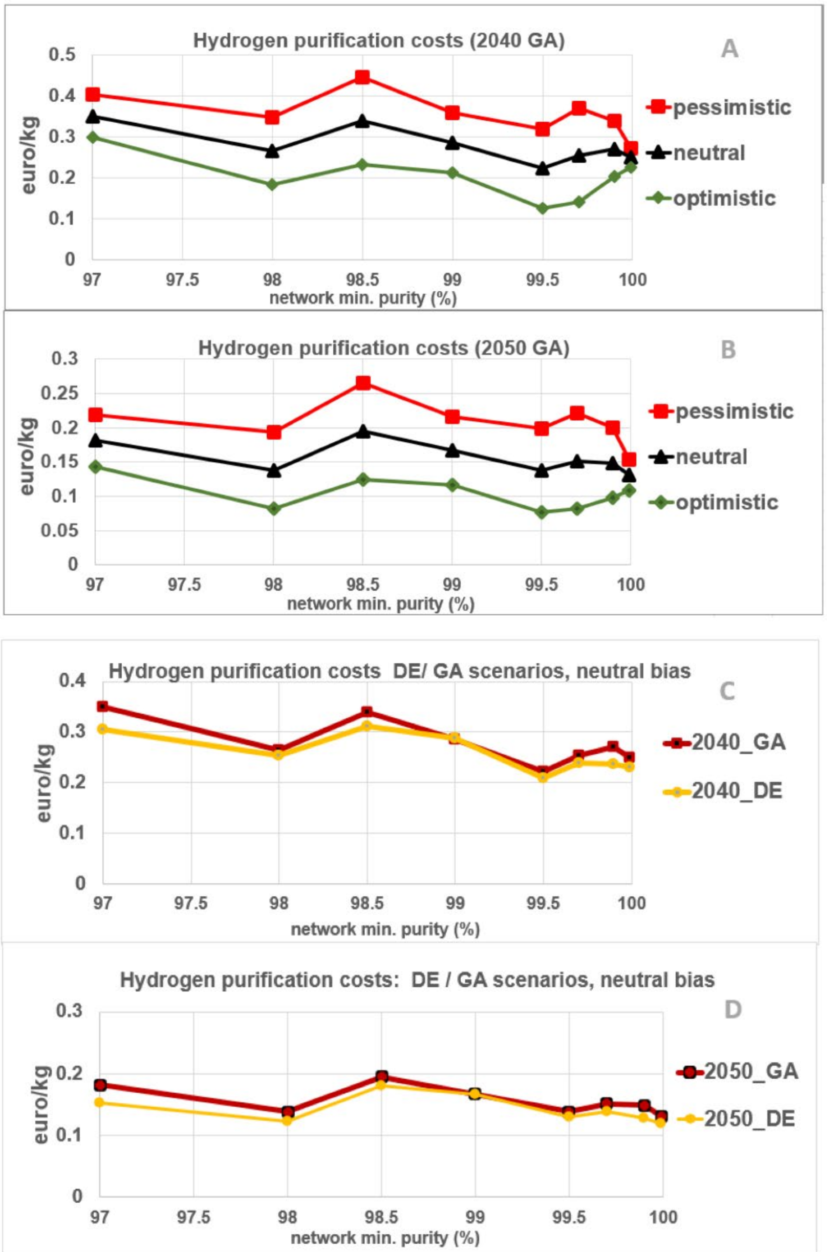

Figure 12 the Global Ambition (GA) results and a direct comparison of DE and GA results (neutral parameter bias).

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5.2 Future commodity prices

Due to the current large uncertainties in future energy price levels, the model was rerun with the hydrogen and natural gas prices and the CO_2 emission rights doubled, see Table 11.

Table 11: testing the impact of doubling energy prices with CO2 emission rights remain unchanged or also doubled.

Prices	2040 default	2040 double	2050 default	2050 double
Hydrogen (€/kg)	3.5	**7**	2.5	**5**
CO_2 (€/tonne)	100	**200**	100	**200**
Natural gas (€/MWh)	30	**60**	30	**60**

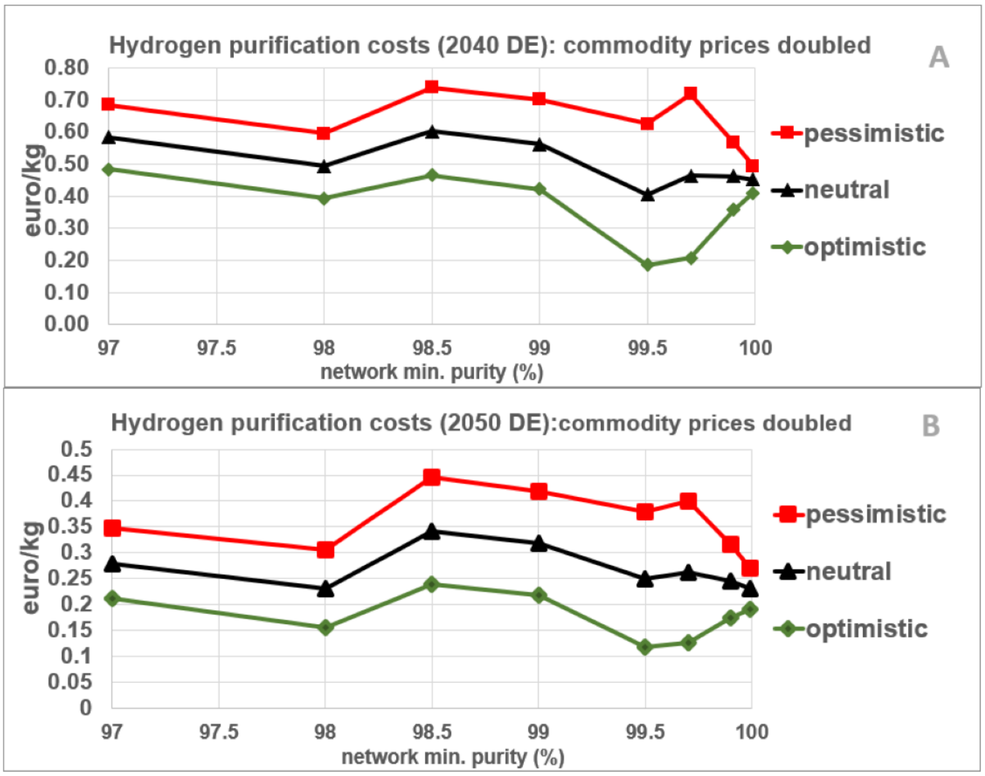

Figure 13 the output of the hydrogen purity model with the hydrogen and natural gas price levels and CO2 emission right prices doubled.

The main impact of doubling all commodity prices is that the overall level of the hydrogen purification cost also effectively doubles, but the shape of the curve and main findings, remain largely unaffected. The main finding is thus robust against the large uncertainty in future energy prices, if hydrogen, natural price and CO_2 prices remain coupled and move higher or lower in similar direction.

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5.3 Storage CAPEX add-on

One of the key assumptions of the hydrogen purity cost model is that every connected party can install a PSA system in order to be compatible with the networks hydrogen purity specification. The latter presumes that the connected party is located on a large industrial site, uses heat for hydrogen production or end-use, and should have local options for the tail gas disposal. This assumption is not valid for storage locations which are nearly always located in remote rural areas and storage sites do not require heat. Also installing PSA systems on new and existing storage sites could be challenging due to lack of space and noise concerns. Therefore, this key-assumption might be too theoretical, but it is currently the best way to model purification stages.

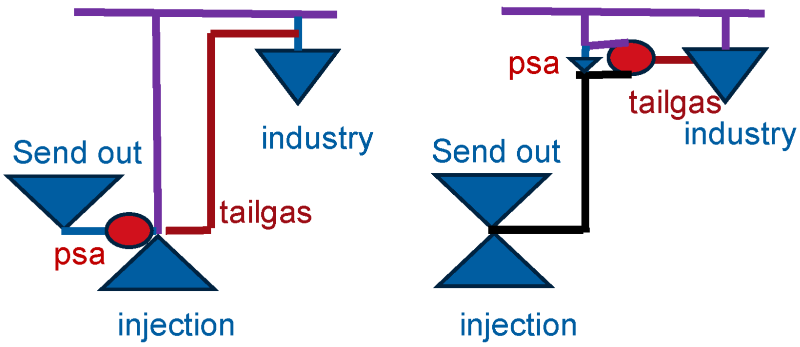

Figure 14: technical options to address the tail gas issue or installing the PSA on a remote site and connecting the storage to a 98% subnetwork.

The chosen approach in this work was to include a one-off additional CAPEX add on investment for installing PSA systems on every storage site, estimated at 25 M€. The one-off investment can be used to install a small tail gas pipeline to a local industrial end use site or to install the PSA system on a remote site and connect the storage site to a 98% sub-network, see Figure 15. However, the size of this one-off investment is highly speculative and the impact of this one-off value on the hydrogen purity cost curve is tested. The model was rerun with a 3 times larger storage capex addon (75 M€) per site.

The impact of the storage CAPEX add-on is shown in Figure 15. The main impact is that the 98% sweet spot becomes slightly more attractive than the 99.5%. The main reason the relatively small impact of the storage CAPEX in 2040 is that the model distributes the extra storage CAPEX over a long technical lifetime (20 years) and over a very large market volume. However, in 2050, with a significant increase in the number of depleted gas field and aquifer storages, the extra CAPEX costs make a more noticeable impact.

So although these add-on investments would be very challenging for an individual party (storage operator or the TSO), when considered over the overall market volume and technical lifetime of the technical measures, the impact does not significantly impact the overall the shape or height of the hydrogen purity cost curve in 2040, but does make the 98% sweet spot more attractive in 2050.

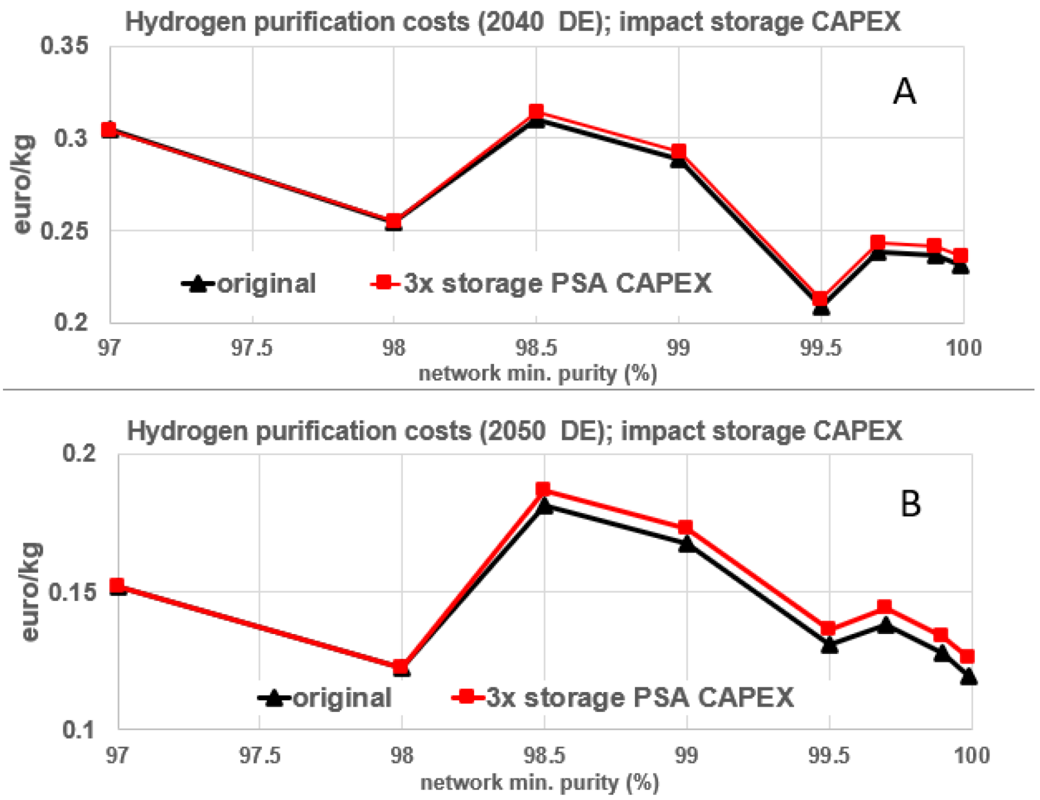

Figure 15: impact of the storage CAPEX add-on, default value and 3 times the value.

5.4 Two Stage PSA systems

The EASEE-gas expert group provided new insights on the possibility of a two-stage PSA approach on hydrogen purification. Since the PSA's only need to alter hydrogen impurity levels in relatively low (<2 vol%) margins, it becomes feasible to recompress and purify the tail gas a second time. This technical option was discussed in the EZK study, but no information was available at that time on price, performance and technical maturity.
With the provided information by EASEE-gas experts, summarized in Table 10, the impact of two-stage PSA systems was explored. Due to the confidential nature of the information, the information cannot be used to replace our original assumptions, only the impact of the information on our main results can be tested.

The result of switching from one stage to a two stage PSA system approach is shown in Figure 16. The main impact is that the overall cost levels decrease with ~35% but the shape of the cost curve and the merit orders between the sweet spots remain largely the same. The >99.9% sweet spot now becomes even more prominent for a 2-stage PSA as producing a >99.9% specification is highly inefficient with a one stage PSA solution and less so with a 2-stage approach. This third sweet spot is however out of scope as the transmission systems are unlikely to transport these high hydrogen grades even in 2050.

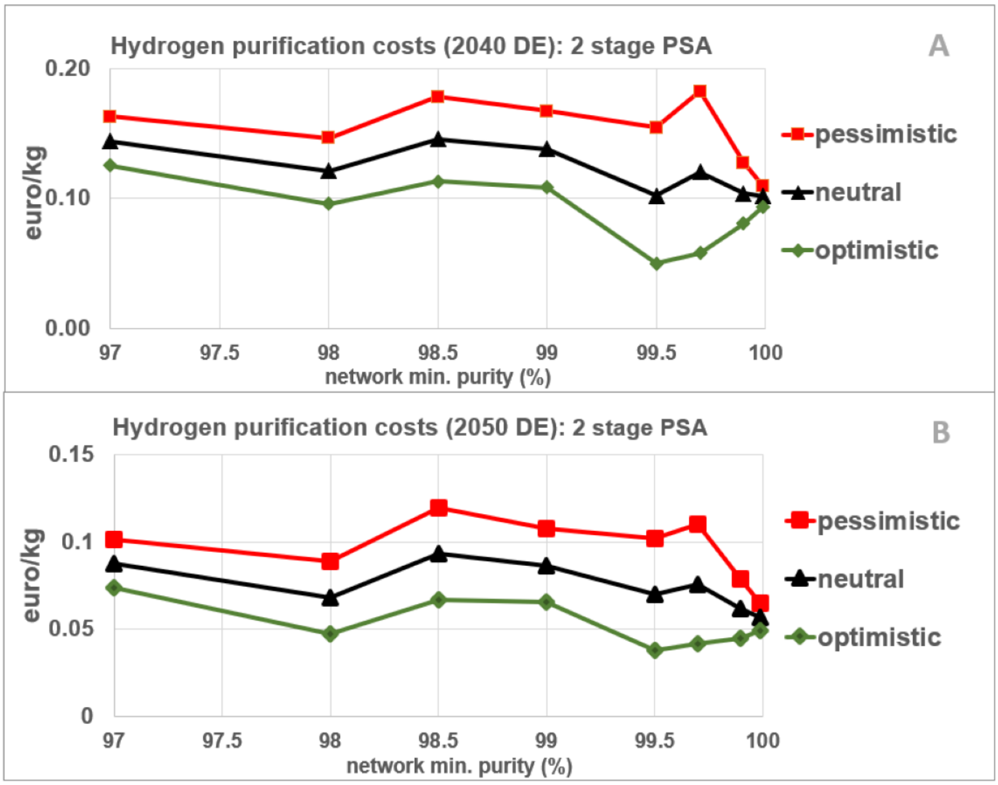

Figure 16: the hydrogen cost curve using the information received on two-stage PSA approach.

5.5 Alternative 1 stage PSA efficiencies

In addition to the two-stage PSA option, the EASEE-gas expert panel also provided more insight in the information on expected PSA efficiencies as a function of hydrogen output purity. A known issue in the model is that on many occasions, PSA systems do not need to purify the hydrogen feed to the best of their technical abilities but only need to take out some of the CH_4, N_2 and CO_2 to exactly meet network or end use specifications. The PSA's could thus operate in a "filter out just enough" mode, part of the hydrogen flow may bypass the PSA, and thus produce less tail gas. However, only information on PSA systems running at the best of their abilities was available during the development of the model and could not include this nuance in the model.

With the information provided by EASEE-gas expert group, as shown in Figure 8, the effect of PSA systems tuned to the required hydrogen specification, i.e. "doing just enough", can be included. Figure 17Figure 17 shows that the main effect of the tuning of PSA to the required hydrogen purity reduces the difference between the 98% and 99.5 % sweet spot. This is mainly because the PSA systems now produce less tail gas at lower network specifications, making the lower network grades slightly more attractive. The flattening of the cost curve does not significantly alter the main conclusions concerning the "98%" versus "99.5%" sweet spot but do make the differences smaller, especially in 2040.

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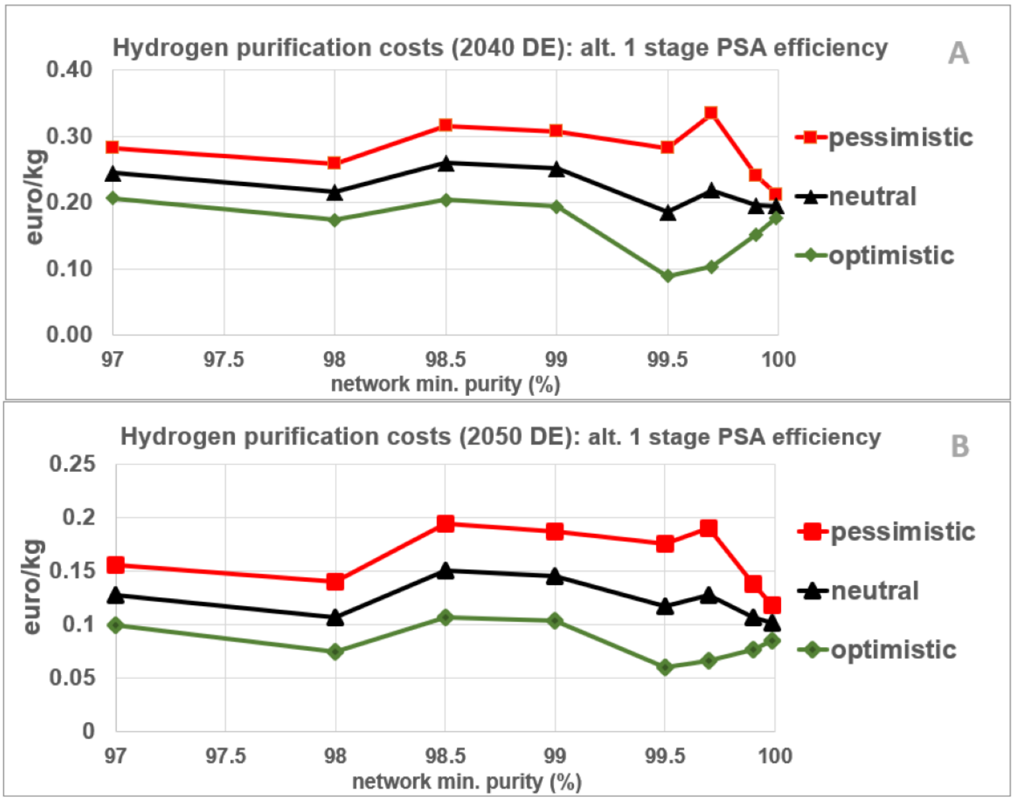

Figure 17: the hydrogen cost curve using the information received on single stage PSA efficiencies at lower output purities.

5.6 Improved storage tail gas utilization

In this work we have put more emphasis on the issues related to storage send-out purification when compared to the original EZK study. This because for the Netherlands only a new salt cavern storage is foreseen.as for Europe, the bulk of hydrogen storage is expected to take place in repurposed depleted gas fields or aquifers natural gas storages. For the latter send out purification is required to meet network specifications higher than 98%. However, placing PSA systems on these existing sites and finding a local tailgas application will be near impossible and thus we have added an extra 25 (best case) or even 75 Million Euro (worst case) extra CAPEX investment, to either build a dedicated tailgas pipeline to a nearby industry or (worst case) place the PSA at a remote satellite location and connect the storage with a dedicated 98% pipeline. However, even with these extra CAPEX investments it is uncertain what the eventual tailgas utilization / value recovery may be.

In this work we use conservative estimates and assume that in the optimistic case only 50% of the tailgas value can be recovered and in the pessimistic case still only 10%. To test the impact of these assumptions we also performed a model run with much more ambitious 90% storage tailgas utilization (optimistic) and 50% utilization (pessimistic). See Figure 18.

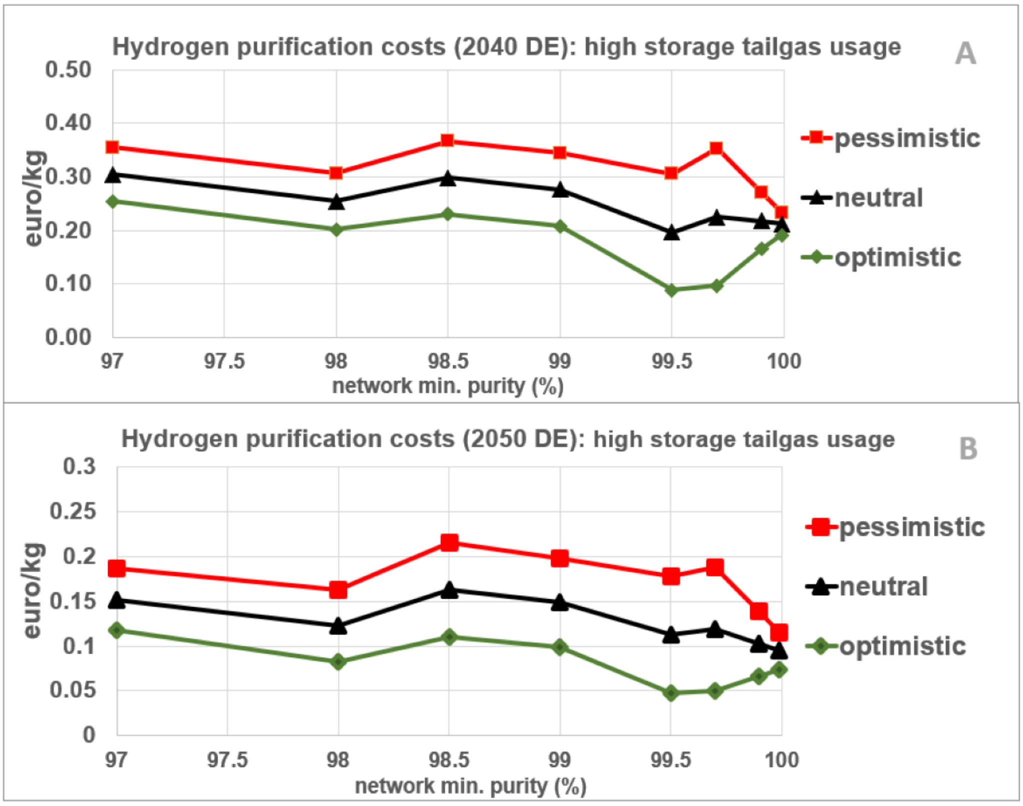

Figure 18: results for the 2040 and 2050 DE scenario in case the tailgas from the storage may be improved to 80% (optimistic) and 50% pessimistic due to the extra 25 to 75 million euro CAPEX investment.

The main conclusion of this extra check is the large uncertainly concerning storage tailgas utilization only marginally impacts the 2040 model results and only have a significant impact in 2050. The main impact would be a ~10 % lower overall costs level and a marginal shift in merit order tin favour of the 99.5% sweet spot, in neutral bias. For a pessimistic bias, the 98% sweet spot remains preferred.

5.7 Main findings sensitivity analysis

In conclusion, we have tested the impact of following uncertainties on the main findings from the hydrogen purity cost model:

- The findings do not significantly change when the alternative TYNDP 2024 GA scenario is used.
- The findings do not significantly change when future commodity price is doubled, provided hydrogen, natural gas and CO_2 emission rights will move in the same direction.
- The size of the additional CAPEX investments to retrofit PSA systems to storage sites and dispose of tail gas do not significantly impact the cost curve from an overall market point of view in 2040 but do make the 98% more attractive towards 2050. This because of the long technical lifetime of the extra CAPEX combined the spreading of the extra costs over large market volumes dominate model results in 2040, but the large amount of repurposed natural gas storages do start to make an impact on the cost curves in 2050

- Switching to a two-stage PSA approach would bring overall cost levels significantly down and even slightly increase the gap between "98%" and "99.5%" sweet spot, even towards 2050.
- When the increased PSA efficiency is changed so that they "filter just enough", the gap between "98%" and "99.5%" sweet spot, decreases and effectively disappears towards 2050, even for the optimistic and pessimistic parameter bias.

It is concluded that the main model findings are robust. There are indications, concerning the real-world use of PSA systems for hydrogen purification, either in two-stage approach or "do just enough" approach, that deserve further attention. This given the very large future market volumes, which represents a significant value for a future 1000 to 3000 TWH/yr hydrogen market.

6 Conclusion

A techno-economic analysis of the optimal hydrogen purity level for the future European hydrogen system was performed. The study is a follow up of a similar study for the Dutch hydrogen market as performed for the Dutch ministry of economic affairs in 2023. The model developed for this study was adapted to fit the future hydrogen market of the European union. For this purpose, the ENTSOG / TYNDP 2024 hydrogen scenarios were used to provide 2040 and 2050 market supply and demand volumes and information on the European storage market was obtained from a Guidehouse scenario study combined with model calculations and EASEE-gas member inputs on storage performance expectations.

The model is developed for calculating the total hydrogen market purification costs. Other costs such as the price of hydrogen, transportation fees, etc. are not included as they are expected to remain the same even though a different hydrogen quality is used. In the hydrogen purity cost model, all technical parameters of every step in the value chain are included: production, transport, storage, end use, purification technology and usage of tail gas. Most parameters were reused from the previous study, including the use of an uncertainty range captured via an "optimistic and pessimistic parameter bias".

However, there are some differences between the EZK and EASSEE gas study. The main alterations are on including different hydrogen storage solutions. A distinction was made between the different storage techniques, new & repurposed salt caverns, depleted gas fields and aquifers, expected to only be able to meet a >98% hydrogen minimum hydrogen purity. Moreover, storage operators will be greatly challenged to finding a valuable application for the so-called "tailgas", a small hydrogen flow with filtered out impurities produced by the Pressure Swing Adsorption (PSA) separation stages. Another alteration is additional information on PSA purification techniques from EASEE-gas members. New insights provided different technical parameters on the purification techniques, which were incorporated in the model as sensitivities.

The main model finding is that there are two technically feasible "sweet spots" for minimum network purity, one around 98% and one around 99.5%. The main driver for a >99.5% purity preference and is the large-scale e-fuels production requiring >99.5% pure hydrogen even in the optimistic case. The main driver for >98% sweet spot are the storage operators using repurposed salt caverns and depleted gas fields and aquifers, as they will need to purify hydrogen send-out for specifications higher than 98%. Note that there is third theoretical sweet spot around >99.99% where all end user purity needs, including mobility, can be met and eliminating any possible double hydrogen purification by both producers and end users. However, the transport of ultra pure hydrogen with repurposed natural gas infrastructure is however not technically feasible and thus the third sweet spot is not considered.

Table 12 gives a complete overview of the all the findings in this work and illustrates how variations in input assumptions affect the relative 98% v. 99.5% merit order. The main finding is that the 99.5% sweet spot is preferred in 2040 in the neutral bias case, but this advantage becomes smaller towards 2050 or ad hoc even flips to a small preference to the 98% sweet spot. When an optimistic parameter bias is applied, the 99.5% sweet spot becomes more pronounced, but when a pessimistic bias is applied the relative advantage shifts towards the 98% sweet spot.

Several sensitivity studies were made to analyse the impact on key techno-economic assumptions. If the commodity price (of hydrogen, natural gas and CO_2) changes, the main impact will be that the entire cost curve shifts up, but shape of curve and the relative merit order of sweet spots will remain the same. Other sensitivities show a similar result, the curve shifts or slightly tilts, but the conclusion on the lowest costs points only make marginal shifts.

Table 12: overview all 98% v. 99.5% sweet spot merit orders listed in this work. (Scoring: +++=large advantage, ++ small advantage, + marginal advantage). – not modelled.

scenario	variant	figure	Optimistic bias		Neutral bias		Pessimistic bias	
			98 %	99.5%	98 %	99.5%	98 %	99.5%
2040 DE	default	10a		+++		++	+	
2050 DE	default	10b		++	+		++	
2040 GA	default	12a		+++		+		+
2050 GA	default	12b		+				
2040 DE	Double prices	13a		+++		++	+	
2050 DE	Double prices	13b		++	+	-	++	
2040 DE	Extra storage CAPEX	15a	-	-		+	-	-
2050 DE	Extra storage CAPEX	15b	-	-	+		-	-
2040 DE	2 stage PSA	16a		+++		++	+	
2050 DE	2 stage PSA	16b		++			++	
2040 DE	Alt 1 stage PSA	17a		+++		+	+	
2050 DE	Alt 1 stage PSA	17b		++	+		++	
2040 DE	higher tailgas valorisation storages	18a		+++		++		
2050 DE	higher tailgas valorisation storages	18b		++		+	+	

Identifying the market optimal European standard on hydrogen quality is a challenging topic due to the complex interplay of underlying cost drivers and commercial interests of suppliers, end users, storage operators and transporters. In this study we have brought them together in a simplified cost model to provide first quantitative indications based on TYNDP 2024 market scenarios. These may serve as a valuable input for focussing the market discussions on the key issues, including needs for performing additional analysis.

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Appendix A: known limitations of the model

The model used in this work has the following known limitations:

- The model is “static”. It uses annual volumes and does not include hourly dynamics on hydrogen supply, demand, storage and other interactions. This is a deliberate choice as it would seriously affect the model performance.
- The model does not include interactions of the hydrogen with pipeline walls, causing the transported hydrogen to pick up impurities along the way or after a significant period of no flow.
- The model assumes “continuous stirred vessel” operation assuming random scattering of suppliers and end users along the network.
- The model only concerns with the bidirectional high pressure section of the international transport networks. It assumes identical entry and exit specifications in terms of minimum required hydrogen content.
- The model only deals with the minimum hydrogen content (vol%) of the hydrogen in the network with respect to trace compounds like N_2, CO_2, CH_4 and CO. As these compounds are relative inert, they do not directly impact pipeline integrity, but they are challenging to filter out using chemical techniques like activated carbon. The model requires that corrosive trace compounds, like H_2O and H_2S, have all been filtered out. These reactive compounds are easier to separate out with TSA systems, glycol filters, molecular sieves and other techniques to very low concentrations, and these techniques do not produce tail gas.
- The model models economics (CAPEX, OPEX and hydrogen values losses) in a highly simplistic manner. There are no inflation corrections, taxes, levelized costs of capital etc. as this is outside the scope of the modelling approach.
- The model assumes a green field investment approach to the required PSA systems both in “2040” and in “2050”, i.e. there is no re-use of existing installations.
- The efficiency of PSA’s in separating out impurities strongly depends on the type of impurity and depth of purity required. Impurities containing carbon (CH_4, CO,…) filter out well whereas impurities like nitrogen, argon, helium are very challenging to filter out. Also achieving purities above 99.7% becomes disproportionally more challenging. These issues are included in the purity modelling but in a highly simplified manner.
- The scenario data includes a large amount of P2G via electrolyzers, either produced onshore or offshore on energy hubs. In either case the produced hydrogen is assumed to highly pure (99.9 -99.99%). The only issue could be if the offshore P2G use repurposed methane pipelines to transport the hydrogen onshore. As these pipelines will be long, and the hydrogen flow may be variable, the offshore pipelines may affect the original P2G hydrogen purity. As this situation is not discussed in the TYNDP scenarios, we did not include it in the P2G specifications and thus we assigned all P2G in the scenarios to the default high purity standard.
- The model assumes two moments in time representing A) the hydrogen market in the near term, dubbed as “2040”, based on the currently announced investment plans and B) a market situation dubbed “2050”, representing a fully mature market. It is however possible that the “2040” situation is already reached in 2037 or perhaps delayed to 2043. In a similar manner, the final market end situation may also be delayed to 2060. The model is not sensitive to these types of market delays, as it treats these moments in time as independent market situations, and is insensitive to the actual time elapsed between the “2040” and “2050” market situations.
- The model assumes that all the hydrogen purity related costs may be considered as “small add on costs” to the significantly larger hydrogen commodity cost. Purification costs must be paid by “someone somewhere along the value chain”, and become part of the overall hydrogen price, just as network fees, compression costs, storage costs, etc. In the real world, these costs could significantly impact individual suppliers, storage operators and end users. This could challenge the assumptions underlying the market supply-demand scenarios.

- A significant part of the hydrogen purity cost is associated with tail gas production of PSA separation stages. PSA systems split an incoming hydrogen stream into a purified stream and a "tail gas" stream including hydrogen and the impurities, this tail gas may represent an economic loss. Firstly, tail gas directly results in lower hydrogen sales for producers or an extra hydrogen procurement requirement for end users. Secondly, the tail gas still represents a remaining value as a source of heat, but only if producer or end user has a local (ideally on site) industrial use case for this heat. This will be challenging for storage operators and thus we have included a 25-million-euro extra CAPEX for a tail gas pipeline to a nearby industrial site or even a 75-million-euro extra CAPEX for placing the PSA on a remote/ satellite location to explicitly include address this issue. The model calculates the remaining tail gas values after these CAPEX investments for all producers, storage operators and end user segments by comparing it to the presumed lowest cost alternative source of heat, natural gas and CO_2 emission rights. The model thus inherently assumes that even in 2050, natural gas (combined with CO_2 certificates) may still be considered as an economic alternative to market.
- For suppliers, installing and operating a PSA system is relatively straight forward as the composition of their hydrogen feed is known. Supplier PSA system can be tailored and operated to always exactly meet network specification. Storage operators mainly have the challenge of installing PSA systems on site and finding tail gas applications. We thus must assume extra CAPEX investments are needed and tail gas valorisation will still be challenging and a conservative 10%-50% value recovery is assumed, even after the extra CAPEX investment. For end users, the challenge is different. Especially at lower network purity grades, their PSA systems must be able to separate out a wide range of impurities, that may or may not be present in the feed. They will thus have a larger challenge in a) how to design their PSA systems for varying impurities in the feed and b) how to operate their PSA system in an efficient manner. It might be that A) PSA CAPEX costs are underestimated for end users and storage operators or B) the tail gas production is overestimated at end user sites as they may receive much cleaner hydrogen for prolonged periods of time, during which the PSA stage may be bypassed.
- There will be a wide range of additional factors that influence the eventual optimal network hydrogen specification that are outside the scope of the hydrogen purity cost model. On the low side (<97%) there may be issues will calorific content billing to small scale consumers, especially if the hydrogen content fluctuates strongly. Also, the Wobbe value of hydrogen is very sensitive to (heavy) impurities, that might result in combustion instabilities in boilers and engines, and these may be an additional limiting factor. Here is the Wobbe time variations that are of higher concern that the actual Wobbe value. On the upper side (>99.5%) there will be various issues in transporting hydrogen over longer distances or in stagnant pipeline sections due to wall outgassing of impurity infiltration from the environment. The exact definition of the limits is outside the scope of this study.

3 Limitations/Concerns

As stated before, the study assignment provided to DNV KIWA is based on their approach previously implemented in the Dutch study. This approach utilized simplified modelling to gain insights into the optimal hydrogen concentration at which the total costs for the entire hydrogen chain are minimized. In Annex A of the DNV KIWA study (see page 47 and 48), the limitations and concerns addressed by DNV KIWA are listed.

3.1 Purification technique used

DNV KIWA utilized only publicly available information and focused exclusively on Pressure Swing Adsorption (PSA)-purification, consistent with the methodology of the Dutch study. During the execution of the study, several EASEE-gas members raised concerns regarding this simplified approach. The primary concerns are outlined below:

- The study's exclusive reliance on PSA technology, to the exclusion of other purification methods such as Temperature Swing Adsorption (TSA) in combination with other adsorbent-methods — frequently cited during meetings as a cost-effective alternative, with higher efficiency and significant lower amounts of tail gas[5]—represents a notable limitation.
- The study only considered the optional separation of non-corrosive components in larger amounts, as it focused on determining the optimum hydrogen concentration. It did not address the mandatory separation of corrosive components such as H_2S and H_2O.[6]
- The publicly available input (Air Liquide Handbook, p. 24[7]) regarding PSA is insufficient for further investigations. Additional inputs are needed to make a more accurate estimate of CAPEX and OPEX costs, considering the effect of increasing amounts of tail gas at higher hydrogen purities.
- The study does not account for the limitations related to feasibility for utilizing PSA at storage sites namely, the permitting challenges, technical feasibility constraints, limited physical space at existing facilities, and the absence of infrastructure for tail-gas handling and utilization.
- The simulations are based on TYNDP 2024 scenarios, which project that a significant portion of hydrogen demand in 2040 and 2050 will be allocated to the production of e-fuels. According to ENTSOG, this demand is expected to stem predominantly from large-scale e-liquid production via the Fischer-Tropsch (FT) process. Fischer-Tropsch synthesis, including the production of e-liquids, typically requires hydrogen with a minimum purity of 99.99% to 99.999%. Therefore, it is essential to assess in detail the differences in capital expenditure (CAPEX) and operational expenditure (OPEX) when the hydrogen feed purity is at 98% or 99.5%, especially considering that further purification will be required regardless.
  Moreover, it is important to note that e-liquid production facilities are expected to resemble modern refineries. As such, their number will likely be limited, with each site designed to support large-scale, centralized production capacities.

3.2 Impact of Gas Storage Facilities on hydrogen purity

The DNV KIWA study suggests 99.5% hydrogen purity may be slightly more cost-effective by 2040 due to dominant feedstock use, though the advantage fades by 2050 as storage gains importance. These results show that gas storage facilities are highly influencing the minimum hydrogen concentration required within the network. This issue is especially critical for repurposed natural gas storage sites, though it is also relevant for newly developed hydrogen storage facilities because the composition of hydrogen withdrawn from a storage can differ significantly from that which was originally injected, potentially necessitating costly purification steps to meet high downstream quality requirements.

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[5]) The off-gas stream released during the regeneration or separation phase of gas purification processes. It primarily contains the removed impurities—such as CO_2, H_2S, N_2, H_2O, and residual hydrocarbons—that are not recovered in the purified product stream.

[6]) The hydrogen produced from an underground storage will be saturated with water. This is why the TSA process is preferred for dehydration. It is necessary to reduce the corrosive compounds upstream of the TSA, otherwise, the TSA would be inoperative. This treatment chain allows for an efficiency of over 95% at porous rock/aquifer storages an 98% at cavern storage sites

[7]) https/engineering.airliquide.com/sites/engineering/files/2022-09/technohandbook11oct.pdf

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3.3 Scenarios used

While various scenarios have been used to assess the sensitivity of outcomes to minor changes in assumptions and to examine the robustness of conclusions, caution is still warranted when interpreting definitive results—especially in cases where the difference between the identified optima is marginal, as observed in this study at the European scale. The table below shows the effect of different assumptions on the hydrogen purity at production and demand.

Table: Position of "Sweet spot" depending on the scenario and case used (base case)

	Case		
Scenario	**Pessimistic**	**Neutral**	**Optimistic**
DE 2040	98% **+**[1]	99.5% **++**	99.5% **+++**
DE 2050	98% **++**	98% **+**	99.5% **++**
GA 2040	99.5% **+**	99.5% **++**	99.5% **+++**
GA 2050	-	-	99.5% **+**

[1]) Scoring **+++**: large difference, **++**: small difference, **+:** marginal difference, - no difference

4 Conclusions and recommendations

In the context of developing a European hydrogen quality standard—or potentially multiple standards tailored to different use cases—it is important to recognize that factors beyond achieving the lowest cost play a critical role. These include technical feasibility, infrastructure constraints, end-user requirements, and regulatory considerations.

Therefore, this study should be regarded as a valuable input to the broader discussion on European hydrogen standardization, while keeping in mind the inherent limitations in its scope and assumptions.

The knowledge of this study shows a follow-up study is worthwhile to further elaborate on the limitations mentioned in this report.

To support a constructive dialogue on this issue, it would be valuable to initiate complementary studies exploring the hydrogen purity range between 98 mol% and 99.5 mol%. Such studies would enable a comparative assessment of the corresponding purification pathways, including alternatives to PSA, along with their associated costs, technical challenges, and scalability potential. They should also consider the actual demand profiles, including the required purity levels as well as the number and geographic distribution of end users for each purity specification.

A Annex "Overview of TYNDP Hydrogen Scenarios 2024"

A.1 Introduction

The ENTSOs Ten Year Network Development Plan (TYNDP) uses entry and exit scenarios to model how gas (including hydrogen) enters and leaves the European network. Information on the TYNDP 2024 can be found here: [ENTSO-E and ENTSOG TYNDP 2024 Draft Scenarios Report](). The scenarios are combined in simulations to test whether the network can meet demand under various conditions.

Each scenario is defined by assumptions regarding hydrogen demand, supply sources (domestic production versus imports), infrastructure expansion, regulatory environment, and technological advancements. The scenarios are used to assess network needs, investment priorities, and the potential for hydrogen to support Europe's energy transition.

In the DNV KIWA study, the following TYNDP 2024 hydrogen scenarios are typically considered:

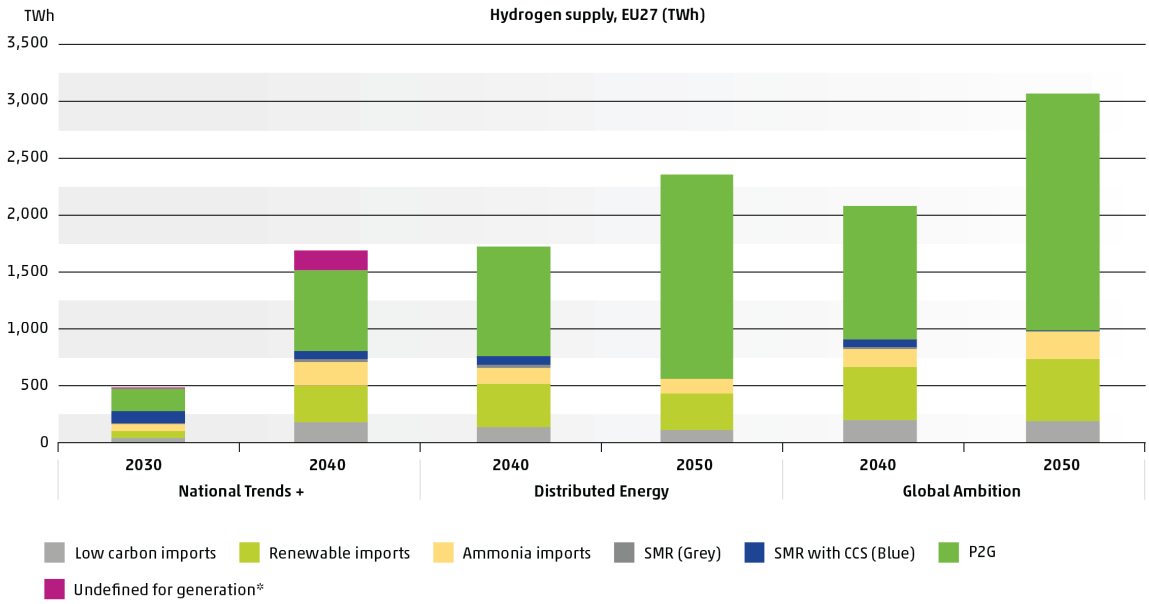
Distributed Energy Scenario: This scenario imagines a future where hydrogen production and consumption are decentralised, with significant local generation (often via electrolysis powered by renewables) and limited cross-border hydrogen trade. It focuses on regional self-sufficiency and flexibility.

Global Ambition Scenario: Here, hydrogen is produced at scale and traded extensively across European borders. Large-scale infrastructure investments enable the formation of a pan-European hydrogen market, with significant imports and exports, reflecting strong policy coordination and market integration.

The DNV KIWA study employs these scenarios to evaluate the feasibility and impact of different hydrogen pathways, guide infrastructure planning, and support decision-making for stakeholders. By comparing scenario outcomes, the study identifies opportunities and challenges for hydrogen integration in the European energy system.

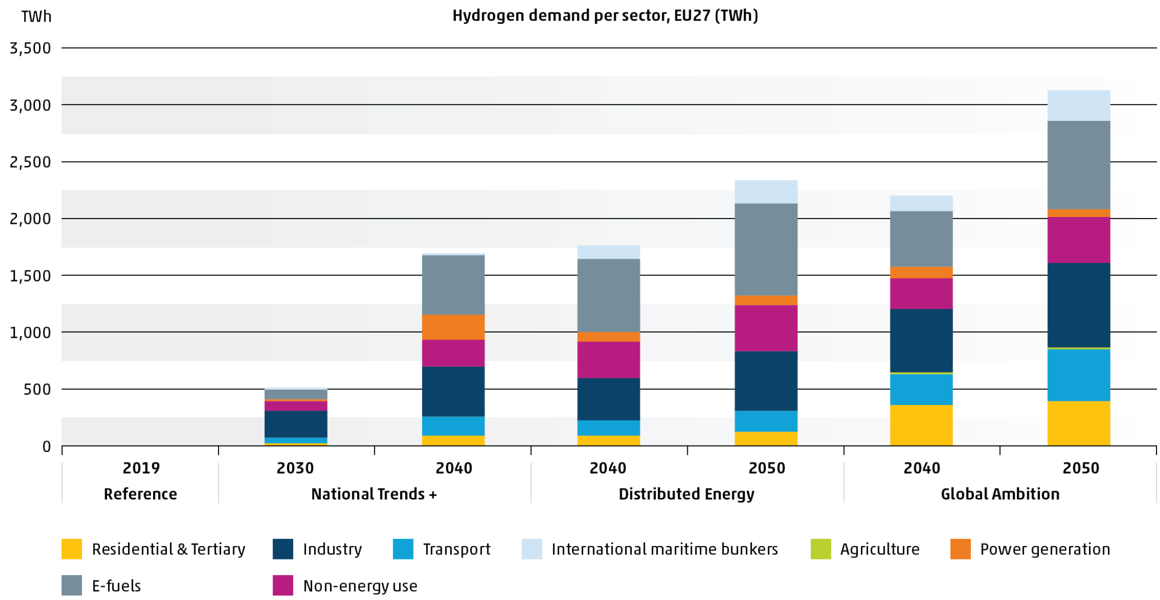
A.2 Overview TYNDP 2024 Demand and Supply

The graphical representation of the supply and demand for the various scenarios is originating from the TYNDP //2024 Scenarios Report (Download | ENTSOs TYNDP 2024 Scenarios).



The accompanying data can be found in worksheet "33" of the TYNDP 2024 Scenarios Report Data Figures (https://2024.entsos-tyndp-scenarios.eu/wp-content/uploads/2024/05/TYNDP_2024-Scenario-Report-Data-Figures_240522.xlsx)

TYNDP 2024	Current	NT+		Distributed Energy		Global Ambition	
Hydrogen Supply	**2022**	**2030**	**2040**	**2040**	**2050**	**2040**	**2050**
Undefined for generation*		10	174				
Low carbon imports	0	45	179	135	111	196	192
Renewable imports	0	62	326	388	318	473	546
Ammonia imports	0	60	206	135	135	154	244
SMR (Grey)	226	9	24	22	0	15	0
SMR with CCS (Blue)	0	105	69	85	0	75	5
P2G	1	193	710	959	1795	1163	2083
Bi product	22.56441						
Total	**249**	**484**	**1688**	**1724**	**2360**	**2076**	**3069**



The accompanying data can be found in worksheet "10" of the TYNDP 2024 Scenarios Report Data Figures (https://2024.entsos-tyndp-scenarios.eu/wp-content/uploads/2024/05/TYNDP_2024-Scenario-Report-Data-Figures_240522.xlsx)

TYNDP2024	REF	NT+	NT+	Distributed Energy		Global Ambition	
Hydrogen Demand	**2019**	**2030**	**2040**	**2040**	**2050**	**2040**	**2050**
Built environment	-	10.4	72.1	74.7	108.6	346.7	390.5
Industry energetic	-	185.7	377.8	307.8	415.2	484.9	652.9
Industry non energetic	-	91.0	244.5	308.4	402.1	277.0	407.3
Transport	-	54.7	181.2	138.6	187.1	281.7	448.4
Agriculture	-	0.3	2.0	3.2	5.6	11.7	24.8
Others	-	-	-	-	-	-	-
Energy	-	46.0	53.5	67.9	107.5	70.0	88.3
Transport int shipping	-	2.7	14.5	113.1	210.8	128.7	264.9
e-fuels	-	76.8	529.6	642.6	813.2	499.7	766.9
Power generation	-	15.9	212.9	94.1	81.9	88.3	70.0
Total	**-**	**483**	**1688**	**1750**	**2332**	**2189**	**3114**

A.3 Supply scenarios

The information in the table below is originating from the Supply Tool (https://2024-data.entsos-tyndp-scenarios.eu/files/scenarios-outputs/20240518-Supply-Tool.xlsm.zip) using worksheet "Supply figures". The data provided in the table below is identical to the information given in the table above.

Hydrogen supply (TWh)		NT+		Distributed Energy		Global Ambition	
Production Technique	**Current**	**2030**	**2040**	**2040**	**2050**	**2040**	**2050**
Undified for generation		10	174				
Low carbon imports	0	45	179	135	111	196	192
Renewable imports	0	62	326	388	318	473	546
Ammonia imports	0	60	206	135	135	154	244
SMR (Grey)	226	9	24	22	0	15	0
SMR with CCS (Blue)	0	105	69	85	0	75	5
P2G	1	193	710	959	1795	1163	2083
Bi product	22.5						
Total	**249**	**484**	**1688**	**1724**	**2360**	**2076**	**3069**

A.4 Demand scenarios

The information in the table below is originating from the Demand Scenarios TYNDP 2024 After Public Consultation (https://2024-data.entsos-tyndp-scenarios.eu/files/scenarios-inputs/Demand_Scenarios_TYNDP_2024_After_Public_Consultation.xlsb.zip) using worksheet “3_Demand_Output” with country selection EU and energy carrier Hydrogen.

Hydrogen demand ETM-Output (TWh)			Reference	Distributed Energy		Global Ambition	
Sector	**Subsector**	**Energy Type**	**2019**	**2040**	**2050**	**2040**	**2050**
Households	*Space heating*	*Energetic*	*0.0*	*34.0*	*47.6*	*125.2*	*130.4*
Households	*Hot water*	*Energetic*	*0.0*	*14.9*	*25.0*	*58.8*	*67.3*
Households	**Total**	**Energetic**	**0.0**	**48.9**	**72.6**	**184.0**	**197.7**
Buildings	*Space heating & hot water*	*Energetic*	*0.0*	*11.4*	*13.9*	*39.3*	*46.2*
Buildings	**Total**	**Energetic**	**0.0**	**11.4**	**13.9**	**39.3**	**46.2**
Industry	*Chemicals*	*Energetic*	*0.0*	*38.7*	*45.2*	*72.5*	*104.5*
Industry	*Fertilizers*	*Energetic*	*0.0*	*9.0*	*11.5*	*10.2*	*12.2*
Industry	*Food*	*Energetic*	*0.0*	*3.8*	*5.7*	*20.3*	*23.5*
Industry	*Others*	*Energetic*	*0.0*	*124.3*	*159.0*	*205.1*	*295.9*
Industry	*Paper*	*Energetic*	*0.0*	*25.7*	*34.3*	*44.1*	*57.7*
Industry	*Refineries*	*Energetic*	*0.0*	*67.9*	*107.5*	*70.0*	*88.3*
Industry	*Steel*	*Energetic*	*0.0*	*106.2*	*159.5*	*132.7*	*159.1*
Industry	**Total**	**Energetic**	**0.0**	**375.7**	**522.7**	**554.9**	**741.3**
Industry	*Chemicals*	*Non-energetic*	*0.0*	*235.4*	*295.3*	*221.1*	*327.9*
Industry	*Fertilizers*	*Non-energetic*	*0.0*	*73.0*	*106.8*	*55.9*	*79.4*
Industry	**Total**	**Non-energetic**	**0.0**	**308.4**	**402.1**	**277.0**	**407.3**
Agriculture	**Total**	**Energetic**	**0.0**	**3.2**	**5.6**	**11.7**	**24.8**
Transport	*Cars*	*Energetic*	*0.0*	*43.9*	*56.1*	*118.1*	*157.7*
Transport	*Busses*	*Energetic*	*0.0*	*9.9*	*15.5*	*14.0*	*29.0*
Transport	*Trucks*	*Energetic*	*0.0*	*54.1*	*68.4*	*83.5*	*152.4*
Transport	*Vans*	*Energetic*	*0.0*	*7.4*	*11.5*	*38.6*	*69.6*
Transport	*Passenger trains*	*Energetic*	*0.0*	*3.4*	*3.6*	*4.7*	*6.4*
Transport	*Freight trains*	*Energetic*	*0.0*	*2.2*	*2.3*	*2.7*	*3.1*
Transport	*Ships*	*Energetic*	*0.0*	*13.5*	*23.2*	*13.7*	*25.8*
Transport	*Planes*	*Energetic*	*0.0*	*4.2*	*6.5*	*6.6*	*4.5*
Transport	**Total**	**Energetic**	**0.0**	**138.6**	**187.1**	**281.7**	**448.4**
Transport	**International shipping**	**Energetic**	**0.0**	**113.1**	**210.8**	**128.7**	**264.9**
Total			**0.0**	**886.3**	**1203.9**	**1348.6**	**1865.6**

A.5 Simulation results

The information in the table below is originating from the the Supply Tool (https://2024-data.entsos-tyndp-scenarios.eu/files/scenarios-outputs/20240518-Supply-Tool.xlsm.zip) using worksheet “DE Total” and “GA Total”

A.5.1 Distributed Energy

Supply (in TWh)		2040	2050	Comment
Import (EU)	Balance	5	36	Residual value (Mix of storage. curtailed energy. ENS)
	Imports non EU	658	564	PLEXOS
Domestic production (EU)	SMR	22	0	PLEXOS
	SMR+CCS	85	0	PLEXOS
	P2G	959	1795	PLEXOS
	Balance UK. No and CH	-5	-28	PLEXOS
Total		1724	2367	

Demand (in TWh)	2040	2050	Comment
Total Energy Demand (including demand for conversion)	1714	2296	Total
Final Energy Demand (inclusive district heating)	1053	1456	PLEXOS
For Electricity generation	3	6	PLEXOS
H2 Demand for P2M and P2L	643	811	PLEXOS
For hybride heating	15	24	Calculated

A.5.2 Global Ambition

Supply (in TWh)		2040	2050	Comment
Import (EU)	Balance	3	41	Residual value (Mix of storage. curtailed energy. ENS)
	Imports non-EU	823	981	PLEXOS
Domestic production (EU)	SMR	15	0	PLEXOS
	SMR+CCS	75	5	PLEXOS
	P2G	1163	2083	PLEXOS
	Balance UK. No and CH	15	-29	PLEXOS
Total		2094	3081	

Demand (in TWh)	2040	2050	Comment
Total Energy Demand (including demand for conversion)	2088	2999	Total
Final Energy Demand (inclusive district heating)	1514	2143	PLEXOS
For Electricity generation	1	2	PLEXOS
H2 Demand for P2M and P2L	500	767	Derived from P2M demand
For hybride heating	74	88	Calculated

A.5.3 Hydrogen Demand Subdivision

In this chapter the information from the overall simulation results is compared to the detailed information available for the different segments.

TYNDP2024	Distributed Energy		Global Ambition	
Hydrogen Demand	2040	2050	2040	2050
Built environment	74.7	108.6	346.7	390.5
Industry energetic[8]	307.8	415.2	484.9	652.9
Industry non energetic	308.4	402.1	277.0	407.3
Transport	138.6	187.1	281.7	448.4
Agriculture	3.2	5.6	11.7	24.8
Energy[1]	67.9	107.5	70.0	88.3
Transport int shipping	113.1	210.8	128.7	264.9
e-fuels	642.6	813.2	499.7	766.9
Power generation	94.1	81.9	88.3	70.0
Total	1750	2332	2189	3114

[8]) The sum of the categories Industry energetic and Energy is in perfect agreement with the category Industry energetic given in Hydrogen demand ETM-Output

Industry. Transport and Agriculture segments

The table above compares Hydrogen demand ETM-Output with the overall simulation results. Demand categories highlighted in green indicate exact matches.

E-fuels segment

The amounts presented for e-fuels can directly be found in the simulation results labeled as "H2 Demand for P2M and P2L" and are highlighted in purple in the table above.

Households & buildings segment

Compared to the results of the "Hydrogen demand ETM-Output" and even after correction for the amount allocated in the simulation to Hybride Heating the simulation results show higher values for the hydrogen amount used in the Built environment. These values are highlighted in the table above in orange. The table below shows the differences between the overall simulation. ETM-Output data. and detailed simulation results.

TYNDP2024	Distributed Energy		Global Ambition	
Hydrogen Demand	2040	2050	2040	2050
Built environment	74.7	108.6	346.7	390.5
Households (ETM-Output)	-48.9	-72.6	-184.0	-197.7
Buildings (ETM-Output)	-11.4	-13.9	-39.3	-46.2
Hybride Heating (Simulation)	-15	-24	-74	-88
Difference	**-0.6**	**-1.9**	**49.4**	**58.6**

Power Generation segment

The Power generation segment exhibits higher values across all scenarios when comparing the data from the overall simulation with the corresponding amounts from the detailed simulations. This information is presented in the table below.

TYNDP2024	Distributed Energy		Global Ambition	
Hydrogen Demand	2040	2050	2040	2050
Power generation	94.1	81.9	88.3	70.0
For Electricity generation (Simulation)	-3	-6	-1	-2
Difference	**91.1**	**75.9**	**87.3**	**68.0**

A.5.4 Final scenarios

The final scenario amounts are derived from the overall simulation and are divided according to ETM-Output and detailed simulation results. If these subdivisions do not match the breakdown used in the overall simulation, the figures from the latter will take precedence. The suggested allocation is shown in the table below.

Proposed Subdivision Hydrogen Demand (TWh)		Distributed Energy		Global Ambition	
Sector	**Subsector**	**2040**	**2050**	**2040**	**2050**
Households & Buildings	Total	74.7	108.6	346.7	390.5
Industry	Chemicals	38.7	45.2	72.5	104.5
Industry	Fertilizers	9.0	11.5	10.2	12.2
Industry	Food	3.8	5.7	20.3	23.5
Industry	Others	124.3	159.0	205.1	295.9
Industry	Paper	25.7	34.3	44.1	57.7
Industry	Refineries	67.9	107.5	70.0	88.3
Industry	Steel	106.2	159.5	132.7	159.1
Industry	Chemicals (non-energetic)	235.4	295.3	221.1	327.9
Industry	Fertilizers (non-energetic)	73.0	106.8	55.9	79.4
Agriculture	Total	3.2	5.6	11.7	24.8
Transport	Cars	43.9	56.1	118.1	157.7
Transport	Busses	9.9	15.5	14.0	29.0
Transport	Trucks	54.1	68.4	83.5	152.4
Transport	Vans	7.4	11.5	38.6	69.6
Transport	Passenger trains	3.4	3.6	4.7	6.4
Transport	Freight trains	2.2	2.3	2.7	3.1

Proposed Subdivision Hydrogen Demand (TWh)		Distributed Energy		Global Ambition	
Sector	Subsector	2040	2050	2040	2050
Transport	Ships	13.5	23.2	13.7	25.8
Transport	Planes	4.2	6.5	6.6	4.5
Transport	International shipping	113.1	210.8	128.7	264.9
Power Generation	Total	94.1	81.9	88.3	70.0
H2 Demand P2M and P2L	Total	642.6	813.2	499.7	766.9
Total		**1750.3**	**2332**	**2188.9**	**3114.1**

A.6 Input used for the DNV KIWA study

The subdivision above is used as input for the DNV KIWA study. which also requires assigning minimum hydrogen quality to each segment. As ENTSOG states that TYNDP's Energetic/Non-energetic classification does not indicate hydrogen quality. the study will use minimum hydrogen quality data from the previous Dutch DNV KIWA study.

Proposed Subdivision Hydrogen Supply (TWh)				H2 Quality	Distributed Energy		Global Ambition	
Type	Sector	Subsector	Category	(best / worst)	2040	2050	2040	2050
Supply	Import	Low Carbon Import	NO/UK/Africa	98 / 98	135	111	196	192
Supply	Import	Renewable Import	Dehydrogenation	99.7 / 99.0	388	318	473	546
Supply	Industry	Ammonia imports	Cracking	< 95 / < 95	135	135	154	244
Supply	Grey/Blue	Methane	ATR/SMR	97.0 / 95.0	107	0	90	5
Supply	Green	Electrolyse	Onshore	99.99 / 99.9	959	1795	1163	2083
Total					**1724**	**2360**	**2076**	**3069**

Proposed Subdivision Hydrogen Demand (TWh)				H2 Quality	Distributed Energy		Global Ambition	
Type	Sector	Subsector	Category	(best / worst)	2040	2050	2040	2050
Demand	Industry	Fertilizers	Feedstock	98.6 / 99.5	73.0	106.8	55.9	79.4
Demand	Industry	Fertilizers	Heat	98.0 / 98.0	9.0	11.5	10.2	12.2
Demand	Industry	Chemicals	Feedstock	99.5 / 99.9	235.4	295.3	221.1	327.9
Demand	Industry	Refineries	Feedstock	97.0 / 99.5	67.9	107.5	70.0	88.3
Demand	Industry	Steel	Feedstock	99.0 / 99.5	106.2	159.5	132.7	159.1
Demand	Industry	Chemicals	Heat	98.0 / 98.0	38.7	45.2	72.5	104.5
Demand	Industry	Food. Paper. Others	Heat	98.0 / 98.0	153.8	199.0	269.5	377.1
Demand	Power	CC-GT	Combustion	98.0 / 98.0	94.1	81.9	88.3	70.0
Demand	Mobility	Land/Shipping	Fuel cells	99.99 / 99.99	134.4	180.6	275.3	444.0
Demand	Residentials	Boiler/CHP	Heat	98.0 / 98.0	74.7	108.6	346.7	390.5
Demand	Agriculture	Total	Heat	98.0 / 98.0	3.2	5.6	11.7	24.8
Demand	Transport	Planes	E-fuel	99.5 / 99.9	4.2	6.5	6.6	4.5
Demand	Transport	International shipping	E-fuel	99.5 / 99.9	113.1	210.8	128.7	264.9
Demand	P2M and P2L	Total	Feedstock	99.5 / 99.9	642.6	813.2	499.7	766.9
Total					**1750.3**	**2332**	**2188.9**	**3114.1**