Introduction

Underground Hydrogen Storage (UHS) will become important in the Netherlands, to balance demand and supply in the future hydrogen chain. At the same time, it will balance the energy system where wind and solar power are becoming major, albeit intermittent sources of sustainable energy. Furthermore, timely availability of hydrogen storage will enable increased energy security.

The Dutch government has stated the importance of the development of hydrogen storage, in the national roadmap for energy storage (EZK, 2023) and in national energy system outlook reports such as NPE (EZK, 2024). A pilot for UHS in a gas field was set as a goal for 2028 and the first four UHS salt caverns storing ~1 TWh should be operational around 2030, in line with national goals for the development of offshore wind. Development of hydrogen storage can also be seen as offering potential for economic growth by enabling an international hydrogen hub. Few case studies for UHS in Dutch gas fields were published, e.g. NAM (2022) and Yousefi et al. (2022).

Current storage of natural gas in the Dutch subsurface amounts to 25% of the final energy demand in the Netherlands (CBS, 2022), which equals ~140 TWh (AGSI, Gas Infrastructure Europe). The estimates of how much UHS is needed for the Netherlands in the coming decades vary, depending on many assumptions, scenarios and choices which are made in (national and EU) climate and energy policy. But all estimates, e.g. from TNO/EBN (2019, 2021) and from the II3050 (2023) report are in the order of at least tens of TWh[1]. Estimates of UHS need for Europe amount to 50 TWh in 2030 to 260 TWh in 2050 (HyUSPRe, 2024), in line with results from Peterse et al. (2024) estimating 45 TWh of required hydrogen storage in 2030.

It is clear that timely clarity on the technical, techno-economical and societal feasibility of UHS in salt caverns and depleted gas fields, onshore and offshore, is crucial for adequate policy and decision making for the development of the hydrogen value chain in the Netherlands for public and private stakeholders. As the Dutch state company in energy production and storage and advisor to the government, EBN initiated a programme to develop and disseminate public knowledge on UHS. The goal is to enable timely development of UHS in a safe and sustainable manner.

Screening the Dutch subsurface for UHS potential

The Dutch subsurface is ideally suited for storing energy in new salt caverns and in existing depleted gas fields. Joint screening studies by TNO and EBN indicate the potential for storing over 200 TWh in salt caverns and over 550 TWh in gas fields, onshore and offshore (TNO/EBN (2019, 2021, 2022)).

The continuous screening of gas fields (including existing natural gas storages) and salt bodies, shown in figure 1, is linked to the potential development of hydrogen valleys or ‘use cases’ in the Netherlands. One example is UHS as a buffer for fluctuations in future offshore hydrogen production. Other use cases link to industrial and harbour areas such as Rotterdam or the province of North Holland (Amsterdam region). UHS will act as a buffer between supply from import and local production on one hand, and usage in power plants and industry, e.g. refineries or steel production, on the other hand.

EBN is evaluating the Dutch subsurface by screening gas fields and salt bodies on suitability for UHS (pilot) projects. A tool is developed to screen and rank, using a wide range of screening parameters (subsurface, infrastructure, wells, location, distance to other mining activities or other usage of space, etc.) and considering insights from different research programs. The tool enables discussions with stakeholders and government.

[1] BCM1 TWh = 3,6 PJ = 0,1 bcm natural gas or 0,3 bcm hydrogen

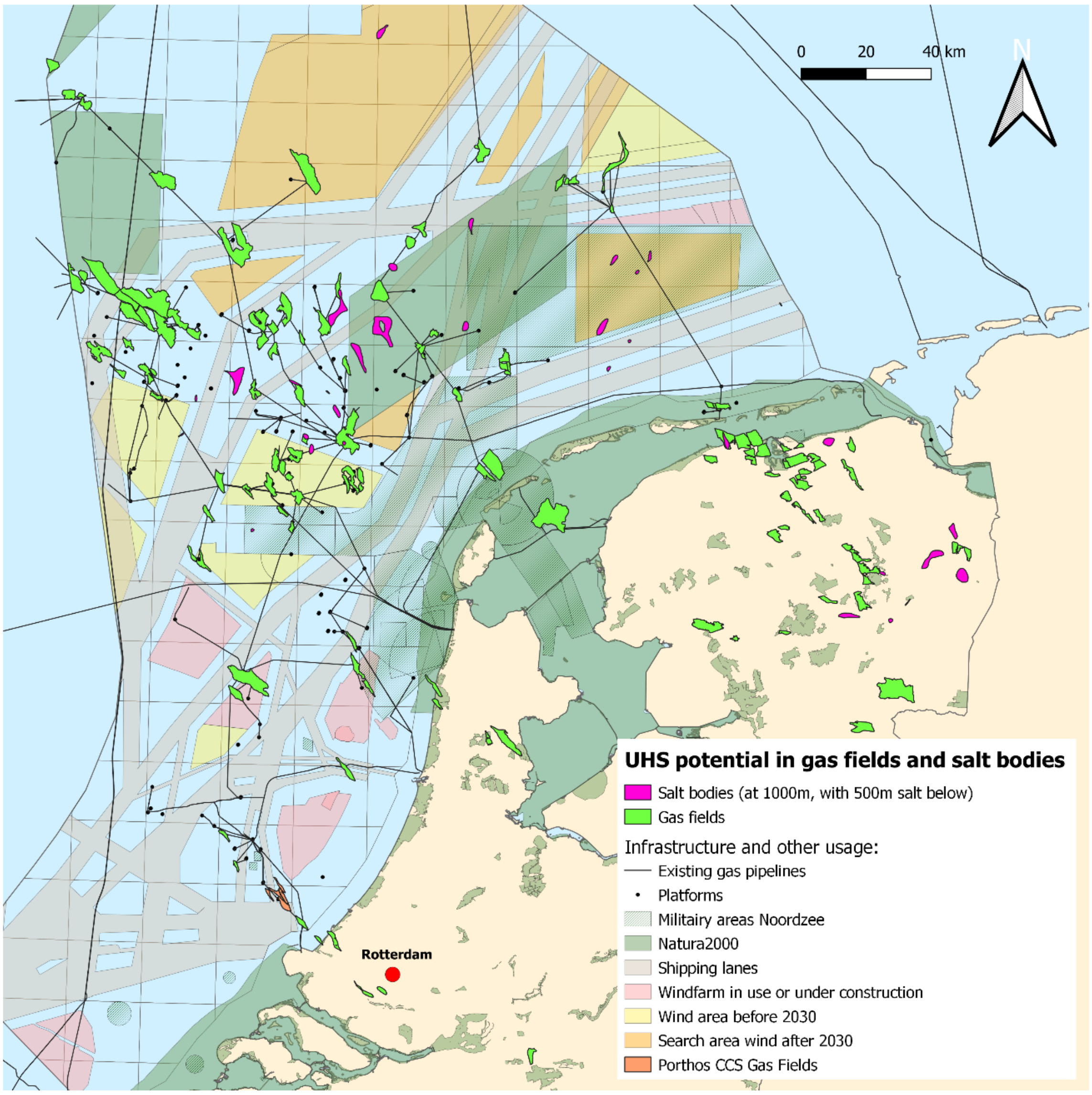

Figure 1 Map showing gas fields and salt bodies which may be feasible for UHS in the Netherlands. Salt body contours are based on TNO DGMv5. Gas fields based on selection in TNO-EBN (2022).

Simulating reservoir performance

The potential for UHS is partially determined by the reservoir performance of the fields, which in turn is determined by injection and production rates and (changes in) the purity of the back-produced hydrogen. EBN has performed dynamic box modelling of a UHS for a variety of representative reservoirs while varying the operational setup. The results can be input to feasibility studies and to the design of UHS (pilot) projects.

A number of operational parameters were varied within bounds that are expected to be applicable in future projects, including the type of cushion gas (hydrogen, natural gas, CO_2), the UHS cycle period (weeks to seasonal), the minimum and maximum pressures and the production purity limits. The results of the simulations (example shown in figure 2) lead to the conclusion that the average and final production purity are better over a long time (up to ~80 to 100 cycles with a period of weeks) when H_2 is used as cushion gas instead of natural gas. After that, the purity of the back-produced hydrogen is the same, irrespective of whether the cushion gas is hydrogen or natural gas. The simulations also show that the behaviour of the methane – hydrogen interface is impacted by reservoir parameters such as permeability, heterogeneity, dip of the reservoir and the position and completion of the well(s).

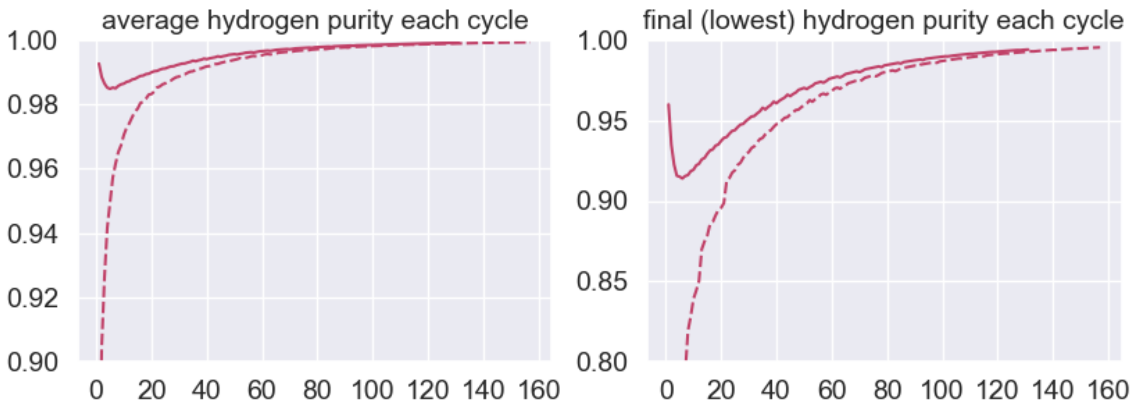

Figure 2 Average (left) and final (right) hydrogen purity for each cycle (period of weeks) for two cushion gas scenarios; methane (dotted line) and hydrogen (solid line) (from Reijnen-Mooij et al, 2024).

Cost estimates

A generic parametric cost model for the estimation of cost of commercial scale UHS systems was developed for the main cost drivers with the aim to facilitate techno-economic analyses, decision making on UHS (pilot) projects and to give insights on cost drivers and the impact of design choices. The model comprises the components of a UHS system, for both salt caverns and gas fields, onshore and offshore the Netherlands. By inputting UHS system design variables, technical design variables are deduced which are the input of the regression models resulting in cost estimations.

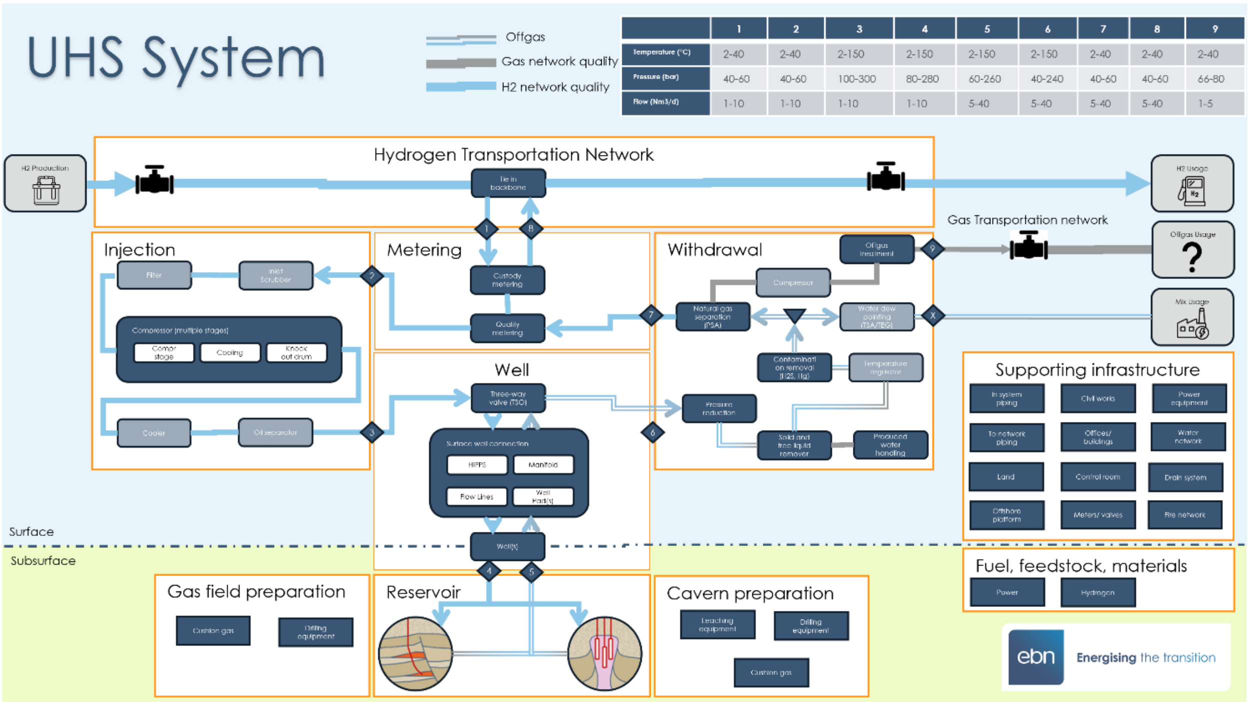

__Figure 3__ Generic system schematic illustrating the components within UHS systems. Each component comes with technical constraints, requirements, and solutions. Cost estimates associated with each component can be combined into overall cost estimates for UHS projects with variable set ups. (from Damoiseaux et al, 2024).

A good reference for input is IEA Hydrogen TCP-Task 42 (2023) which contains data from the handful of projects worldwide, showing the large bandwidth of cost estimates depending on project characteristics and modelling scope and approach. The resulting output includes regression models which come with uncertainties caused by the limited (access to) actual cost data. The results are utilized in project cost estimates.

Offshore caverns

One of the options under consideration for UHS is the development of offshore salt caverns. The Zechstein salt is present in large parts of the Dutch subsurface, onshore and offshore. The Zechstein salt in the Netherlands formed many diapirs as a result of halokinesis. Thickness, depth, shape and internal structure of the salt bodies are complex (Geluk, Paar and Fokker, 2007). The initial screening of offshore salt bodies (TNO/EBN, 2022) identified twelve structures that may be suitable for the development of at least 15 caverns for UHS per salt body. In 2024 public data and knowledge related to Zechstein salt caverns in the Netherlands was consolidated within the GEODE project (EBN-TNO, 2024). This project is a joint initiative of EBN and TNO to consolidate play based exploration data and knowledge into countrywide maps for hydrocarbon exploration, aquifer CCS and UHS. Maps and datasets are publicly available at an online platform with map viewer.

Regional datasets are available, such as depth of top and base salt, salt structure shapes, temperature, pressure and stress field data, faults and heterogeneity of the salt. A tailored seismic interpretation workflow was applied to improve the outline of the selected UHS salt bodies. Structure dip analysis was done to assess the risk of overhangs and necking geometries. An attempt to quantify heterogeneity in the salt bodies using well and seismic data proved difficult, due to large heterogeneity at small scale and poor seismic illumination and imaging quality within salt diapirs with steep flanks and steeper internal geometries. The seismic "chaos" attribute was used as a proxy for halite presence, increasing confidence on heterogeneity. Recommendations for seismic reprocessing / depth imaging were made.

Conclusions

The Dutch subsurface offers great potential for UHS in gas fields and salt caverns. Results from screening on technical and non-technical parameters support decision making on where and how much potential can be realized in the Netherlands. The results of reservoir simulations on representative fields are input to feasibility studies and to the design of pilot and commercial scale projects. A generic parametric UHS cost model facilitates techno-economic analyses and decision making on and the design of UHS (pilot) projects. Results are made available, amongst others via the GEODE Atlas.

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