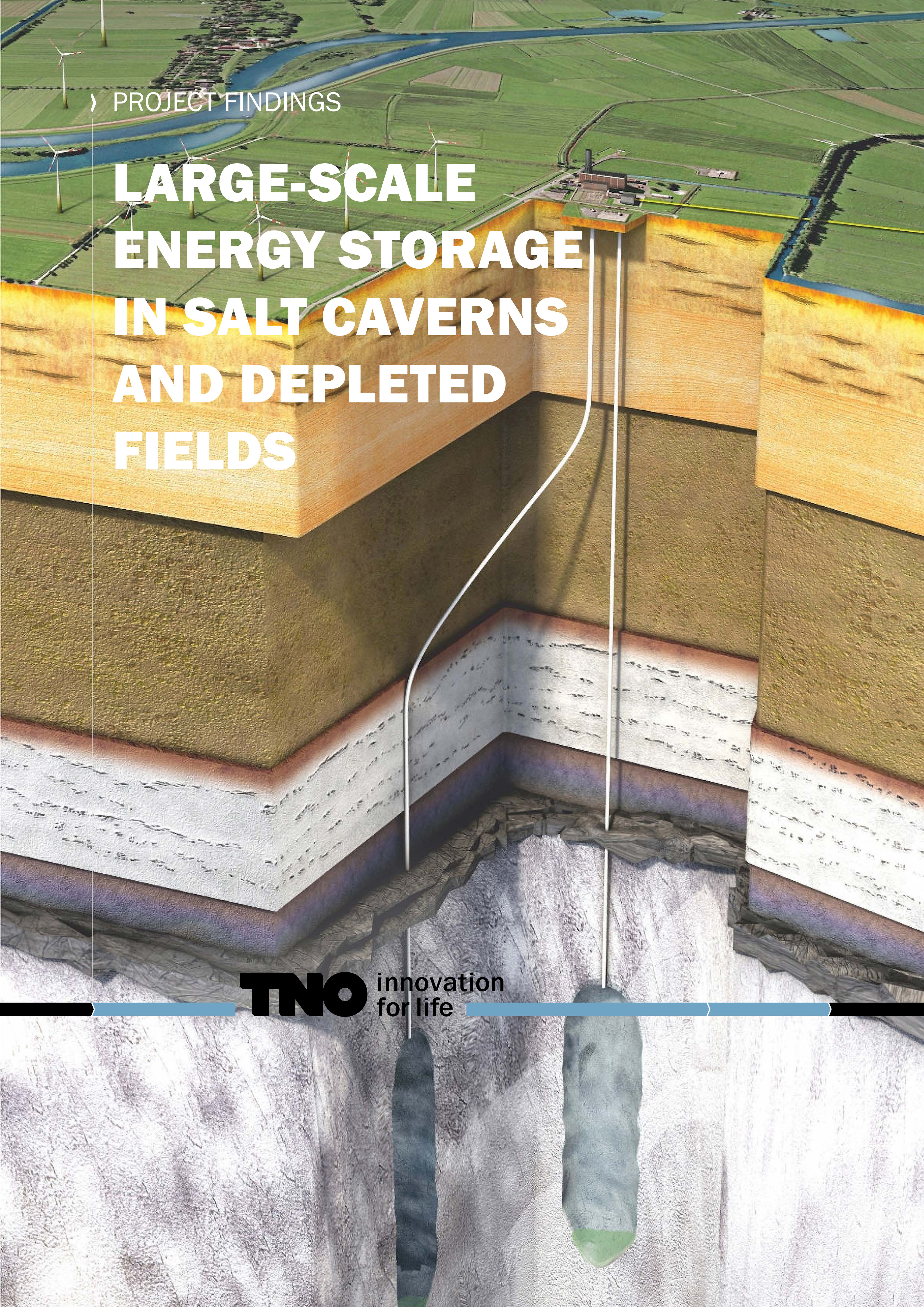
PROJECT FINDINGS

LARGE-SCALE ENERGY STORAGE IN SALT CAVERNS AND DEPLETED FIELDS



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TNO REPORT

TNO 2020 R12006

Large-Scale Energy Storage in Salt Caverns and Depleted Fields (LSES) – Project Findings

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PREFACE

This synthesis report details the results of the activities performed in the research project "Large-Scale Energy Storage in Salt Caverns and Depleted Gas Fields", abbreviated as LSES. The project, which was given subsidy by RVO, had two main goals:

1. Improve insights into the role that large-scale subsurface energy storage options can play in providing flexibility to the current and future transitioning energy system;
2. Address techno-economic challenges, identify societal and regulatory barriers to deployment, and assess risks associated with selected large-scale subsurface energy storage technologies, in particular Compressed Air Energy Storage (CAES) and Underground Hydrogen Storage (UHS).

The research was carried out by TNO in close collaboration with project partners EBN, Gasunie, Gasterra, NAM and Nouryon. Activities were divided over 4 work packages that ran in parallel:

1. Analysis of the role of large-scale storage in the future energy system: what will be the demand for large-scale storage, when in time will it arise, and where geographically in our energy system will it be needed?
2. Techno-economic modelling (performance, cost, economics) of large-scale energy storage systems, focusing on CAES and UHS in salt caverns, and UHS in depleted gasfields - analogous to UGS (Underground natural Gas Storage).
3. Assessment of the current policy and regulatory frameworks and how they limit or support the deployment of large-scale energy storage, and stakeholder perception regarding energy storage.
4. Risk identification and screening for the selected large-scale subsurface energy storage technologies.

In this synthesis paper, the main findings of the project are summarised. For a detailed description of methodologies and results we refer to the four individual work package reports:

1. Sijm, J., Janssen, G., Morales-Espana, G., van Stralen, J., Hernandez-Serna, R., and Smekens, K., 2020. *The role of large-scale energy storage in the energy system of the Netherlands, 2030-2050.* TNO report 2020 P11106.
2. Groenenberg, R., Juez-Larré, J., Goncalvez, C., Wasch, L., Dijkstra, H., Wassing, B., Orlic, B., Brunner, L., van der Valk, K., Hajonides van der Meulen, T., and Kranenburg-Bruinsma, K., 2020. T*echno-Economic Modelling of Large-Scale Energy Storage Systems.* TNO report 2020 R12004
3. Winters, E., Puts, H., Van Popering-Verkerk, J., and Duijn, M., 2020. *Legal and societal embeddedness of large-scale energy storage.* TNO report 2020 R11116.
4. Van der Valk, K., Van Unen, M., Brunner, L., and Groenenberg, R., 2020. *Inventory of risks associated with underground storage of compressed air (CAES) and hydrogen (UHS), and qualitative comparison of risks of UHS vs. underground storage of natural gas* (UGS). TNO report 2020 R12005

Project details
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Het project is uitgevoerd met subsidie van het Ministerie van Economische Zaken en Klimaat, Nationale regelingen EZ-subsidies, Topsector Energie uitgevoerd door Rijksdienst voor Ondernemend Nederland.

MANAGEMENT SUMMARY

THE NEED FOR FLEXIBILITY IN THE FUTURE ENERGY SYSTEM

Future outlooks agree that a portfolio of flexibility options needs to be deployed in the energy system to enable the integration of large-scale intermittent renewable energy sources. As part of the solution space, large-scale energy storage underground can provide flexible bulk power management services for electricity, gas and heat commodities, and offers essential services to society in the form of strategic energy reserves and balancing solutions for unavoidable seasonal variations.
In this project, we identified the opportunities and challenges (technical, economic, market, societal, and regulatory) for Compressed Air Energy Storage (CAES) in salt caverns and Underground Hydrogen Storage (UHS) in salt caverns and depleted gas fields.

TECHNOLOGY STATUS, POTENTIAL AND CHALLENGES

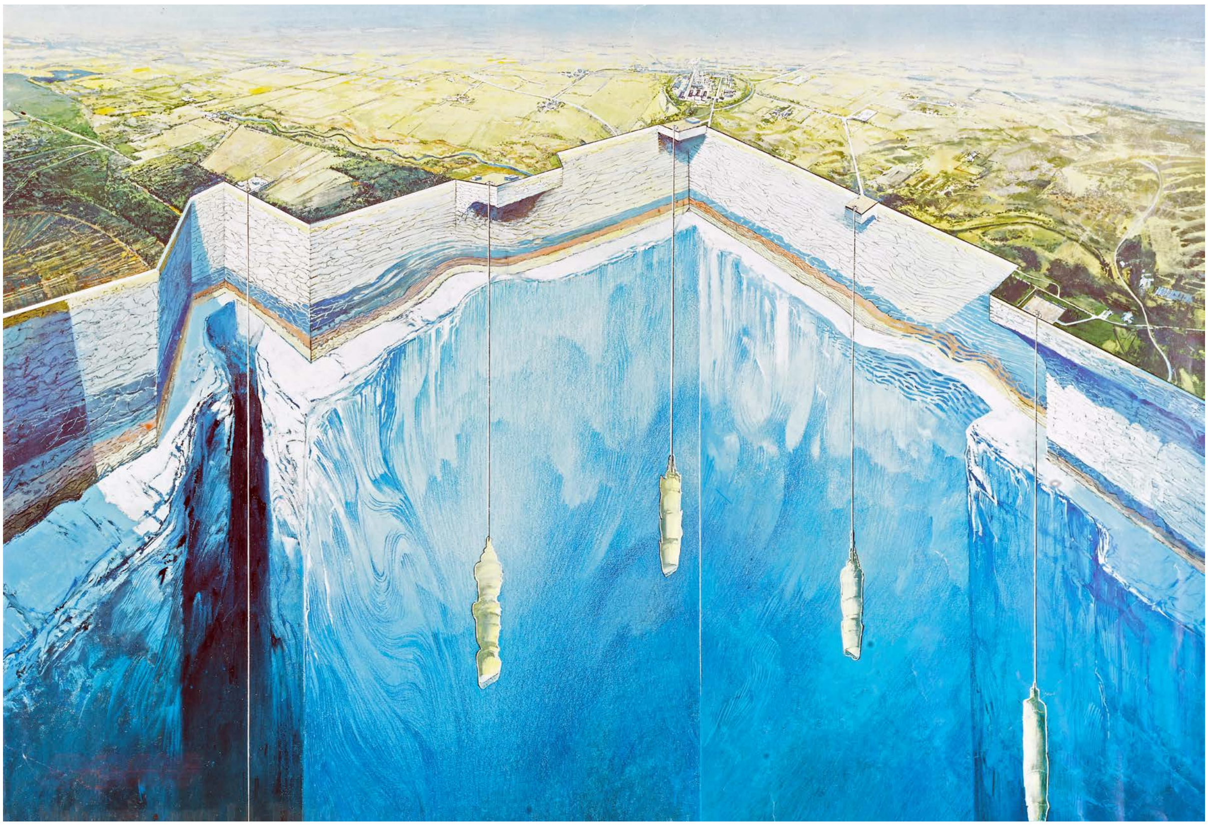
The technology concepts, deployment status, and technical performance of CAES and UHS were assessed, and several open questions regarding the techno-economic feasibility and risks of these technologies were addressed.

Compressed Air Energy Storage

CAES is an electricity storage technology. At charge, electrical energy is stored in mechanical form by compressing air, and stored in (commonly) salt caverns. At discharge, electricity is regenerated by using the compressed air to drive a turbo-expander/turbine.
There are two main technology concepts: diabatic CAES (D-CAES), without storage of compression heat, and advanced adiabatic CAES (AA-CAES), in which the heat generated during compression is stored for re-use during expansion. Round-trip efficiencies of up to 60% are deemed feasible for D-CAES with efficient utilization of waste heat and the technology is currently available at commercial scale. AA-CAES is not a mature technology, mainly because efficient thermal storage of heat at the very high temperatures involved (up to 580 °C) is challenging and costly. The technical potential for developing CAES in salt caverns in the Dutch subsurface is deemed high (about 0.58TWh).

Typically, the power range of CAES systems is between 100-500MW, and the duration over which this power can be delivered ranges from hours to a day, i.e., they operate on intra-daily to daily cycles. Geomechanical numerical simulations that were done in this project show that the pressure and temperature effects of this fast-cyclic injection and withdrawal of air do not jeopardize cavern stability and integrity.

Facility for underground storage of natural gas in salt caverns of Gas Storage Denmark A/S in Lille Torup, Denmark.
Illustration by Günther Radtke. © Zeitlupe, Ahrensburg, Germany



Underground Hydrogen Storage

Analogous to natural gas, hydrogen can be stored underground, in compressed gaseous form, in salt caverns and potentially also in depleted gas fields, in which tens of millions (cavern) to (potentially) billions of m^3 (depleted gas field) of hydrogen can be stored. In the Netherlands, the technical potential for UHS is large: 43.3 TWh_t in caverns, and 277 TWh_t in depleted gas fields.

Worldwide, four storage facilities for pure hydrogen in salt caverns are already operational, and practical experience with these sites has shown that hydrogen can be safely stored in this way for long periods of time. Important challenges remain to be addressed though, in particular in relation to the integrity and durability of wellbore materials and interfaces, because injection and withdrawal are expected to occur much more frequently and cyclically, and at higher volumetric rates than is currently the case.

Hydrogen can also potentially be stored in depleted gas fields. Recent demonstration projects in Argentina and Austria with injection of up to 10% of hydrogen in a mix with natural gas into a depleted gas field have shown that hydrogen can be safely stored without adverse effects to installations and the environment. However, not all hydrogen was recoverable due to diffusion, dissolution (into formation water), and conversion to methane.

No sites exist however where pure hydrogen is stored, and there are open questions and possible challenges regarding the influence of geo- and biochemical reactions of hydrogen with rocks, fluids and micro-organisms in depleted gas reservoirs and the potential (technical, environmental, economic) risks associated with these reactions; in particular the formation of hazardous and/or corrosive fluids, and the degradation of injection and/or withdrawal performance, that may negatively impact feasibility. Results of a literature review and geochemical modeling show that geochemical processes that could be of concern for hydrogen storage in the Netherlands include a) reduction of iron minerals forming H_2S; b) chemical reactions leading to sequestering H_2 and producing H_2O; and c) reactions and H_2S formation that may affect the performance, safety, materials selection, facility design and economics of storage. To accurately assess the risk of H_2S formation in hydrogen storage reservoirs it is of the utmost importance to improve the predictive power of the geochemical models with laboratory experiments.

Furthermore, biochemical modelling indicates that bacterial reactions may both pose a risk for underground hydrogen storage. To confirm and better understand these challenges further experimental and aligned numerical modelling research is required.

An analysis of a hypothetical conversion of existing gas storages to hydrogen storage reveals that the lower density (8-10 times) and viscosity of hydrogen results in 2.4 to 2.7 times higher withdrawal rates. These high rates partly compensate for the lower energy content (3-4 times lower) of hydrogen, resulting in an energy throughput of 0.7 to 0.8 times that of methane.

‘In the Netherlands, the technical potential for underground hydrogen storage is large: 43.3 TWh in caverns, and 277 TWh in depleted gas fields.’

Risks

The potential risks associated with UHS and CAES in salt caverns, and UHS in depleted gas fields were inventoried, and possible mitigation measures were explored through a literature review and expert knowledge. The purpose of the risk inventory is to serve as a starting point and checklist to identify and manage risks in development projects, and to provide guidance on potential mitigation measures to reduce the risks. The inventory follows the TEECOPS (technical, economic, environmental, commercial, organisational, political and societal) approach and includes 159 risks derived from 40 references.

A selection of six key risk themes associated with storage of hydrogen was made: material integrity/durability, leakage of hydrogen, blow-out, diffusion and dissolution, loss and/or contamination of hydrogen, and ground motion (subsidence, induced seismicity). A qualitative non site-specific comparison was made for these risk themes between UHS and underground storage of natural gas. Although in general, UGS and UHS have a similar risk profile, there are also differences and points of attention highlighted in this study, including: flammability range and ignition energy, hydrogen flame detection, explosion risk associated with leakage of hydrogen or methane in confined spaces, hydrogen flame characteristics and dimensions, and hydrogen geo- and biochemical reactions in the subsurface.

Although the risks associated with UHS are generally known, further research (laboratory experiments, numerical modelling, material testing, pilot-scale field tests) is required in particular on a) the long-term durability of rocks and (well) materials (steel alloys, cement, elastomers, etc.) when subjected to hydrogen under an alternating pressure regime that causes mechanical and thermal stresses, and b) interactions of hydrogen with rocks, fluids and microbes in reservoirs and their effects on reservoir performance, quality and retrievability of the stored hydrogen, and integrity and durability of materials subjected to products of such interactions (e.g. H_2S).

FUTURE ROLE AND MARKET POTENTIAL

The potential role of large-scale storage in the future energy system was explored with the use of two energy system optimization models and for two reference years: 2030 and 2050. COMPETES is an European electricity market model and OPERA is a national integrated energy system model of the Netherlands. Both models are optimization models with the aim to find the lowest social cost of the system under study.

For 2030 the results indicate that relatively limited electricity storage (1-2 TWh; up to 1.4% of total electricity demand) is foreseen. Furthermore, the annual volume of hydrogen stored in the models is in the range of 66 GWh to about 900 GWh.

For 2050 the results indicate that flexibility requirements for electricity are dominantly provided by cross-border trade and storage in electric vehicles. In both models electricity storage is dominated by batteries of electric vehicles (EVs), with total annual storage volumes between 30 and 33 TWh. Other technologies besides EV batteries, such as CAES, hardly play any role in electricity storage. Note, however, that the study only focused on the flexibility needs due to the variability of the residual power load – notably VRE supply – and did not consider other stability and flexibility needs of the power system. The results do show a significant role for UHS; notably in terms of annual volume of H_2 stored (17-22 TWh; ~20-30% of total H_2 demand). The required size (physical storage capacity) is much smaller (1.5-2.9 TWh, requiring 10-20 salt caverns). This indicates that the hydrogen storage is not just for seasonal storage, as the current storage of natural gas, but has many more annual cycles (6-14 annual full cycle equivalents).

From a system perspective energy storage contributes to achieving lowest cost system configurations. On the other hand the business case for both CAES and UHS for the short term, and just based on arbitrage, is not obvious and would require additional revenue streams to become profitable from a project developers perspective.

For CAES, in recent years, several demonstration and (commercial) development projects have been conducted and/or are ongoing (in the Netherlands, Denmark, UK, and US). CAES systems are designed to be competitive in delivering a suite of flexibility services and generate revenue from two main groups of services: arbitrage and ancillary services (e.g. frequency regulation, reserve power, black start, load following, and synchronous inertia). An exploratory economic analysis that was done in this project indicates that a price arbitrage-only business case for D-CAES may not be viable and clearly would require additional revenue streams to become profitable from a project developers perspective.

For UHS, an exploratory analysis indicates no short term viable business case for a flexible hydrogen production asset with storage in a salt cavern vs. continuous hydrogen production. Especially an increase in the amount of hours with low electricity prices (due to a larger installed capacity of solar and offshore wind) and further developments in electrolyser technology provide perspective on a viable business case. Additional revenue streams (to selling hydrogen) can be generated by including alternative benefits of storage in the business model.

The study highlights the need for value stacking to create profitable business cases for large scale energy storage and indicates a discrepancy between long term value for the energy system and current absence of viable business models for energy storage as an important challenge towards implementation. Furthermore, some key limitations are identified regarding the applied energy system models that are used to estimate the long term market potential. The models do not capture and value all stability and flexibility needs of the power system and they optimise over a single year and not over a time horizon. Furthermore, key uncertainties and risks related to (extreme and yearly-varying) weather conditions are not factored in.

LEGAL AND SOCIETAL EMBEDDING

To successfully realize projects for large-scale storage of energy in the subsurface the legal and societal elements must be productively incorporated from the start. New storage initiatives should be sufficiently supported by clear laws and policies, permit procedures and contracts, and stakeholders (in particular the local community) should be involved well before, during and after the decision-making process. Several recommendations have been formulated:

- Develop policy ambitions related to large scale (subsurface) energy storage at all levels.
- Involve local residents and other relevant stakeholders at an early stage and let them participate in the development of regional plans.
- Connect participation at the (inter)national policy and business level to stakeholder engagement at the project level.
- Develop a participation strategy for large scale energy storage projects and start participation early in the process. Clearly communicate with the stakeholders on which topics they can participate.
- The operator and competent authority should deliberate at the start of the process on the division of roles.
- Ensure strong collaboration between the different policy levels in the development and decision-making process of large scale energy storage projects.

CONTENTS

'From a system perspective energy storage contributes to achieving lowest cost system configurations.'

The amount of energy that is produced from wind and sun varies because it depends on weather conditions. The wind does not always blow, and the sun does not shine at night.

1. INTRODUCTION

1.1 THE NEED FOR FLEXIBILITY IN THE FUTURE ENERGY SYSTEM

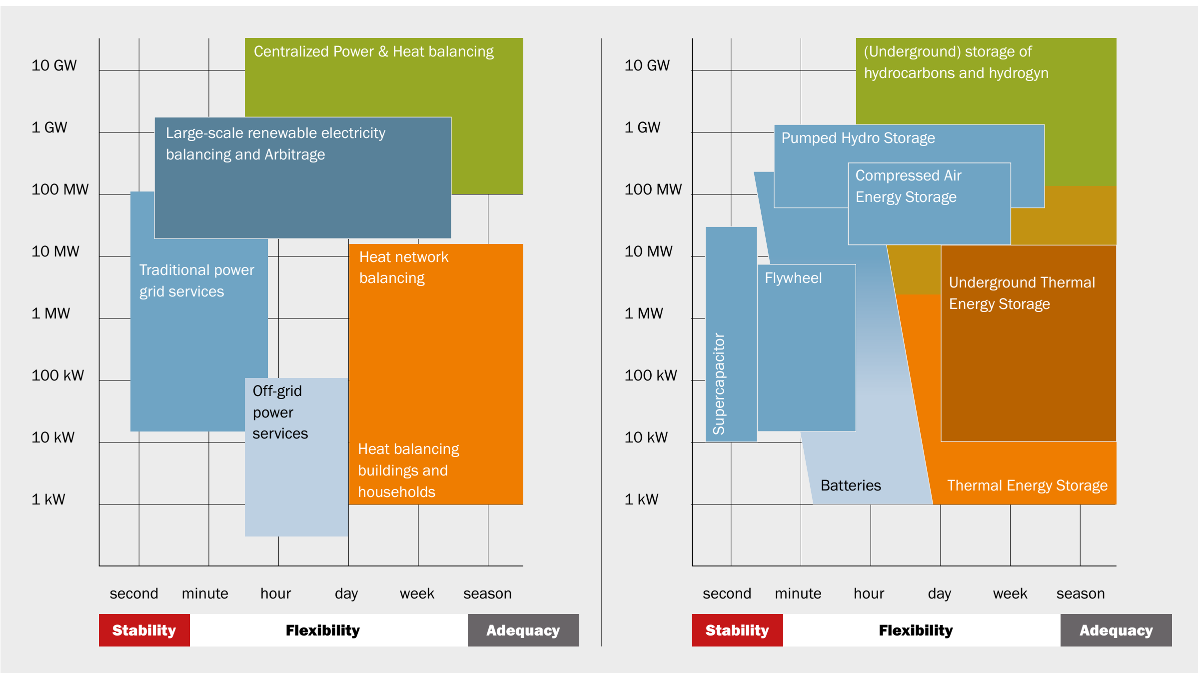
A low-carbon energy system requires adaptations to accommodate the changing and varying patterns of energy production and consumption. Integration of variable wind and solar energy requires flexibility of the rest of the system, and needs *“research and innovation to increase the flexibility of the system by means of more renewable dispatchable generation capacity (e.g. dispatchable renewables, hydrogen-based power), energy storage (e.g. storage capacities or power-to-gas solutions such as green hydrogen), demand-side management programmes, and by a faster reacting grid.”*[1] Future outlooks agree that a portfolio of flexibility options need to be deployed in the energy system to enable the integration of large-scale intermittent renewable energy sources in a reliable and cost effective energy system [2, 3, 4].

Energy storage will play a pivotal role in providing the needed system security, flexibility and adequacy in the future integrated energy system. Stability is here the response to very short and fast fluctuations (especially in the power system). Flexibility is the response to load and supply variations up to the seasonal timescale, while the ability to adapt to long-term trends and emergencies is dubbed ‘adequacy’.[5, 6] New supply and demand patterns affect the energy system on very different timescales, requiring different solutions. Greater deployment of energy storage is thus also foreseen at these different scales, i.e. from low power and fast response solutions (< 1kW; <1s) to longer-term balancing needs for the grid (>1GW; hours to days and beyond).

Clearly a portfolio of energy storage solutions is needed in the future energy system that exploits the benefits of each storage technology and together delivers the requested systems services, see Figure 1.1. As part of the solution space, large-scale and centralized energy storage can provide flexible bulk power management services for electricity, gas and heat commodities. In addition to flexibility, large-scale energy storage offers essential services to society in the form of strategic energy reserves (also termed ‘adequacy’, see above) and balancing solutions for unavoidable seasonal variations. It is also a key enabler for the Power-to-Gas value chain, i.e., the large-scale conversion of renewable electricity into versatile energy carriers (e.g. hydrogen) that can be efficiently transported and stored for longer periods of time.

1 https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf
2 A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. European Commission. 2018. COM(2018) 773. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0773&from=EN
3 ESTMAP, Energy Storage Mapping and Planning. EC Service Contract no.: ENER/C2/2014-640/S12.698827. www.estmap.eu.
4 https://www.sciencedirect.com/science/article/pii/S0306261919312619?via%3Dihub#s0065
5 DNV GL, 2020, The promise of seasonal storage, https://www.dnvgl.com/publications/the-promise-of-seasonal-storage-168761
6 “Security and adequacy are two facets of power system reliability.
Security is a power system’s ability to withstand the risk of massive contingencies in the short term. Adequacy is the power system’s ability to meet demand in the long term.”
Source: Identification of Appropriate Generation and System Adequacy Standards for the Internal Electricity Market, EC 2015, https://ec.europa.eu/energy/sites/ener/files/documents/Generation%20adequacy%20Final%20Report_for%20publication.pdf

Figure 1.1: Energy system services and storage options mapped according their power (Watt) and relevant timescales for charging and discharging. Colour coding indicates in which infrastructure system the storage technology is implemented: blue = electricity grids, green = gas infrastructure; orange is heat networks.



1.2 HOW TO REPLACE THE LARGE FLEXIBILITY CURRENTLY PROVIDED BY NATURAL GAS?

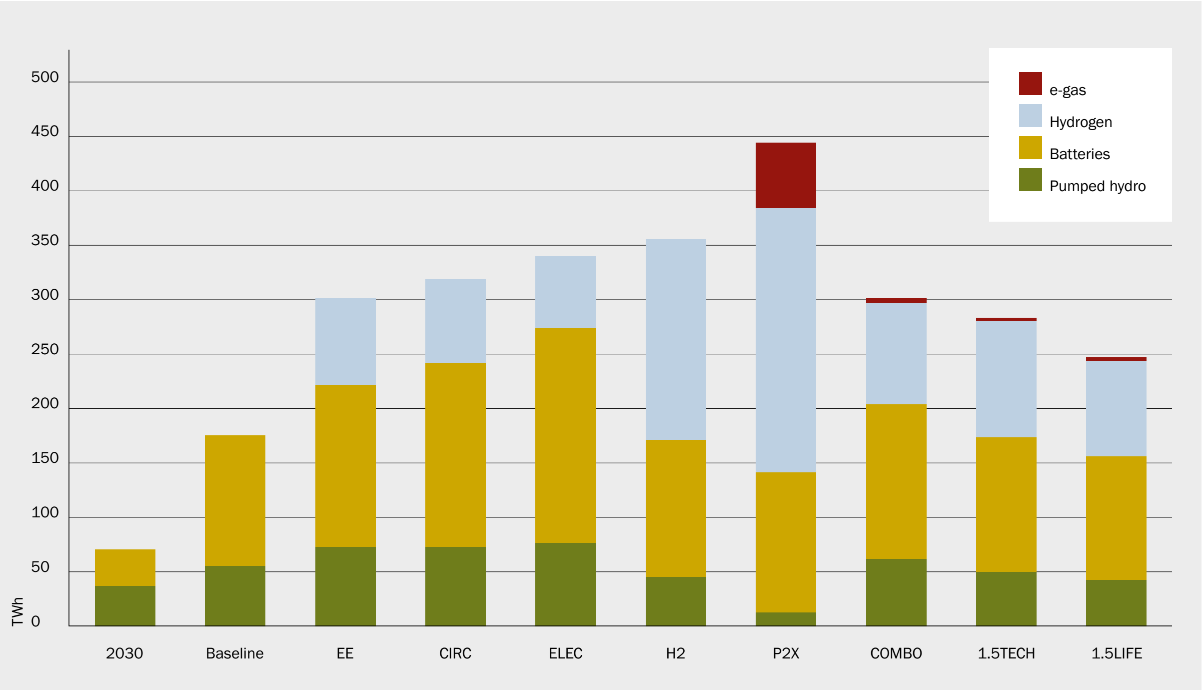
Currently, much of the energy system flexibility is being provided by the production, transport and storage of natural gas. In the Netherlands, the total consumption in 2017 was 40.8 billion m³, while the capacity for underground storage of natural gas (working gas volume, see below) is 12.9 billion m³ (31.6% of indigenous demand). Electricity production represents about 37.7% of natural gas demand, followed by households representing 22.3% of this demand (9.1 billion m³ demand).[7] In the same year the gas grid delivered a peak demand of 100 to 110 GW.

Natural gas is already safely stored in large quantities in salt caverns and porous reservoirs (depleted gasfields, aquifers[8]) in the Dutch subsurface and that of many other countries in Europe to balance supply and demand on a daily basis and secure supply during cold winters. In the European Union the total working gas volume in underground gas storages (UGS) exceeds 1100 TWh (in Europe it exceeds 1500 TWh) or ca. 9% of the total annual final energy consumption.[9, 10] These geological stores can supply a sustained baseload over periods of several days to months. In comparison: the most mature electricity storage concept in Europe today, pumped hydro storage (PHS), both in terms of installed capacity and storage volume, represents a total storage capacity of approximately 0.4 TWh.[11] As the role of natural gas will decrease in the Dutch and European energy system, the portfolio of options that contribute to system stability, flexibility and adequacy (security of supply) must be expanded.

The European Commission's proposal for a long-term decarbonisation strategy ("A Clean Planet for All") is intended to shape the EU's efforts to deliver on the Paris Agreement. This study states that in the future the share of variable renewable energy (VRE) in the total electricity generation increases significantly towards 81-85%. All scenarios foresee increased electrification; and energy storage is predicted to increase and become a key enabling technology to reach these ambitious targets (see Figure 1.2). The strategy also highlights the importance of technologies to convert electricity into new energy carriers and emphasizes the role of hydrogen and synthetic natural gas.

7 https://www.cbs.nl/nl-nl/nieuws/2019/22/aardgasbaten-uit-gaswinning-bijna-417-miljard-euro
8 Aquifers are porous, water bearing rock formations.
9 GIE Storage Map 2018 / data as of 1 July 2018. https://www.gie.eu/index.php/gie-publications/databases/storage-database.
10 Eurostat Energy, transport and environment statistics, 2019 edition.
11 Michael Child, Dmitrii Bogdanov, Christian Breyer, The role of storage technologies for the transition to a 100% renewable energy system in Europe, Energy Procedia, Volume 155, 2018, Pages 44-60.
12 A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. European Commission. 2018. COM(2018) 773. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0773&from=EN

Figure 1.2: Energy storage and the role of hydrogen in 8 pathways towards 2050 in the Commission's proposal for a long-term decarbonization strategy "A Clean Planet for All".[12]



1.3 THE SUBSURFACE AS SOLUTION SPACE

Underground storage is a widely used technology for storing a variety of gases (natural gas, hydrogen, helium, air, nitrogen) and liquids (oil, gasoline and derivatives of natural gas liquids such as ethane, ethylene, etc.). In particular, underground (natural) gas storage (UGS) is widespread, as it plays an important role in providing flexibility in matching demand and supply at daily to seasonal timescales. In total, about 417 bcm (billion cubic meters) of natural gas is stored underground worldwide (671 facilities), of which 104 bcm in Europe. About 80% of the storage capacity is in depleted gas fields, followed by aquifers (11%), and salt caverns (9%).[13]

Clearly, large-scale, centralized storage of energy underground is an attractive and potentially cost-effective solution. It can provide flexible bulk power management services for electricity, gas and heat commodities, and offers essential services to society in the form of strategic energy reserves, energy system adequacy and balancing solutions for unavoidable seasonal variations and other energy security challenges. The growth of these services to sufficient scale is key to ensuring a reliable and secure energy supply.

1.4 ACTION NEEDED AND GOALS OF STUDY

Action for these technologies is needed on multiple levels and barriers for deployment need to be removed. Challenges for large-scale subsurface energy storage are already identified in the technical, economic, market, societal & regulatory domain. Large-scale energy storage needs to be ready for deployment to enable a meaningful and substantial role in optimizing the productive use of renewable energy sources and substantially reducing curtailment as part of a cost-effective energy transition. This needs to be realized well before the share of renewable energy sources has grown towards targeted levels and the consistent supply from fossil resources has shrunk.

Goals of the research

1. Improve insights into the role that large-scale subsurface energy storage options can play in providing flexibility to the current and future transitioning energy system.
2. Address techno-economic challenges, identify societal and regulatory barriers to deployment, and assess risks associated with selected large-scale subsurface energy storage technologies, in particular Compressed Air Energy Storage (CAES) and Underground Hydrogen Storage (UHS).

13 Cedigaz Insights – Underground gas storage in the world – 2018 status.

A wellpad with two wellheads at the facility for storage of natural gas in salt caverns in Zuidwending, Netherlands. © EnergyStock

Aerial photograph of the facility for storage of natural gas in salt caverns of EnergyStock (a subsidiary of Gasunie) in Zuidwending, The Netherlands. © EnergyStock

2. TECHNOLOGY STATUS, POTENTIAL AND CHALLENGES

2.1 TECHNOLOGY CONCEPTS AND DEPLOYMENT STATUS

2.1.1 Compressed Air Energy Storage

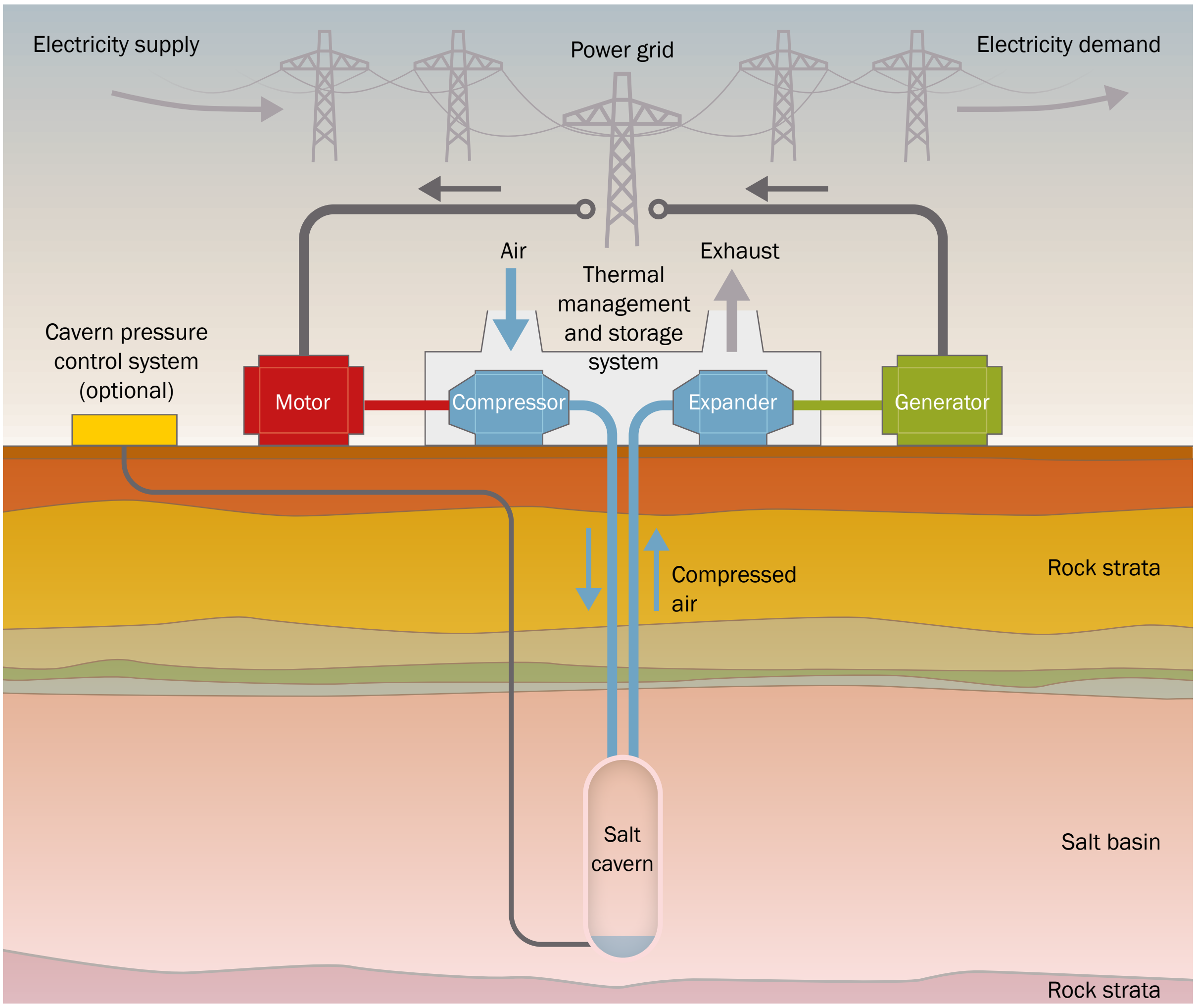
CAES is an electricity storage technology (see Figure 2.1). At charge, electrical energy is stored in mechanical form by compressing air. An electric motor drives a compressor that consumes electricity during off-peak hours when low-cost generating capacity is available (e.g. from nuclear or thermal power stations) or non-dispatchable electricity is produced from variable renewable energy (VRE; e.g. wind, solar). The compressed air is stored in underground reservoirs, commonly salt caverns, at high pressure. At discharge, electricity is regenerated by retrieving the compressed air from the reservoir(s) to drive a turbo-expander or a gas turbine that drives an electricity generator to deliver electricity back to the grid. Because compressed air has a relatively low energy density (2-6 kWh per m^3 of storage space at pressures of 50-200 bar[14]), large volumes of air (in the order of 50-100 million Sm^3) are required to conduct CAES at large scale (power outputs of hundreds of MW and discharge durations of 6-12 hours). Storage in salt proves to be the most economical option.[15]

Technology concepts

There are two main technology concepts, which mainly differ in how they deal with the temperature change of the air during compression and expansion: diabatic CAES (D-CAES) and advanced adiabatic CAES (AA-CAES). In a D-CAES system, the heat that is generated on compression of the air is not stored. Hence an external fuel must be combusted at time of generation to heat up the air prior to driving the turbine. Natural gas is conventionally used, but its combustion causes

14 Benedikt Lunz, Matthias Leuthold and Dirk Uwe Sauer Georg Fuchs, "Overview of Nonelectrochemical Storage Technologies," in Electrochemical Energy Storage for Renewable Sources and Grid Balancing. Durham, United States: Elsevier, 2014, vol. 1, pp. 89-102.
15 Eckroad, S., Gyuk, I., 2003. EPRI-DOE handbook of energy storage for transmission & distribution applications. Washington, DC, Department of Energy.

Figure 2.1: Illustration of a CAES system, reproduced from website (https://www.storelectric.com/technology)



CO_2 emissions. Hydrogen is emerging as an alternative, in particular because combustion of hydrogen does not emit CO_2, and it can be produced from renewable electricity (also without emitting CO_2). Worldwide, two CAES plants have been commercially operational for many years without any serious issues, one in Germany (Huntorf, 321MW/2.5GWh, since 1978) and one in the US (McIntosh, 110MW/2.6GWh, since 1991), both of which are based on the relatively mature D-CAES concept (TRL 7-8). Round-trip efficiencies of up to 60% are deemed feasible with efficient utilization of waste.

In an AA-CAES system, the heat of compression is stored in a TES (Thermal Energy Storage device) and re-used during the discharging process, which eliminates the need to combust a fuel. With this method higher round-trip (power-to-power) efficiencies of up to 70% can be reached. However, efficient thermal storage of heat at the very high temperatures involved (up to 580 °C) is challenging and costly, and the TRL of this technology (TRL 5) is currently not high enough to be commercially applied. RWE Power together with partners General Electric, Zublin and DLR launched the world's first large-scale AA-CAES demonstration project in Stassfurt - Germany in 2010 (Adele project). Although the concept and design have been established, this project is currently on hold.

Deployment status
Apart from the two operational CAES plants mentioned earlier (in Germany and the US), in recent years several demonstration and (commercial) development projects have been conducted and/or are ongoing (mainly based on the D-CAES concept). This indicates a strong renewed interest in CAES, probably sparked by the increasing need for flexibility services to integrate the growing share of variable renewables (wind, solar). Most recently, project developer Corre Energy Storage announced its intention to develop a 320-MW D-CAES plant in The Netherlands[16] with a storage capacity of 3-4GWh. The project obtained the status of European Project of Common Interest (PCI) in 2017 and receives financial support from the Connected Europe Facility fund, which can be considered a recognition of the potential value of this technology in providing flexibility to the increasingly renewables-based European energy system. A unique aspect of this project is that its two 160MW turbines will be designed to ultimately run on 100% (renewable) hydrogen.

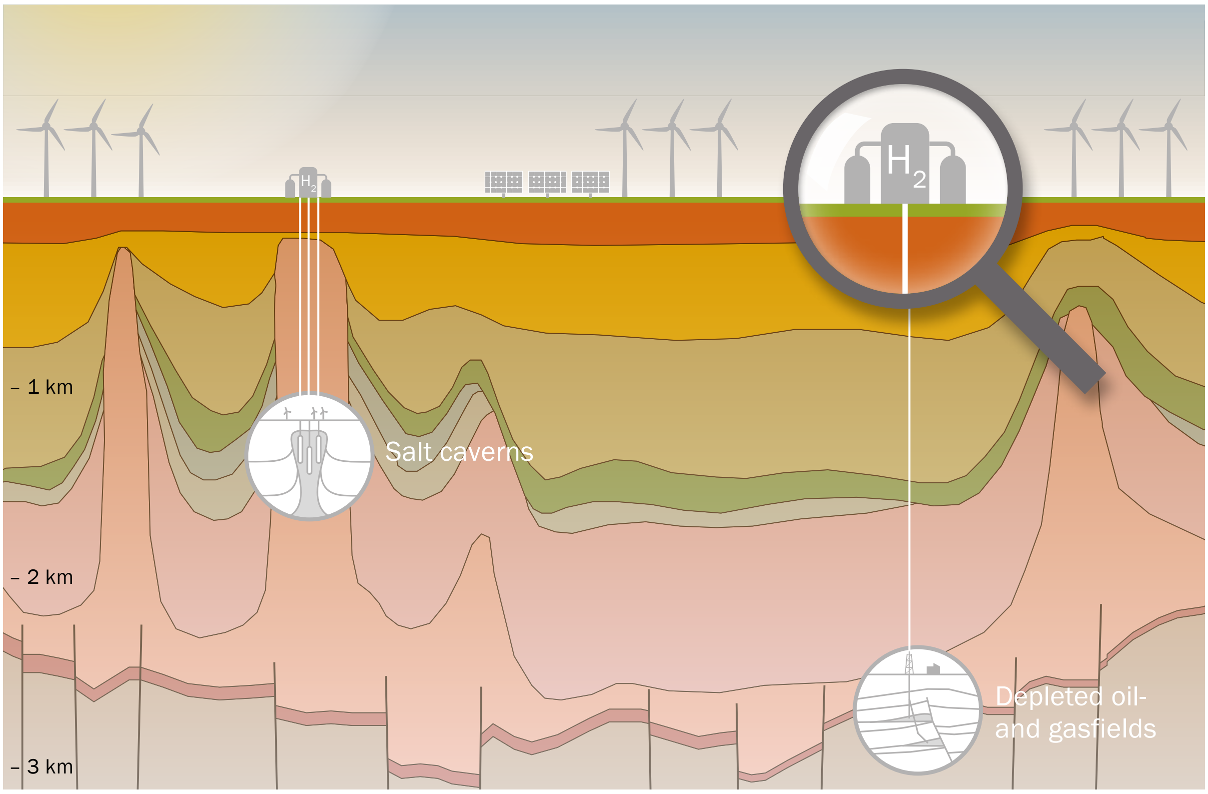
2.1.2 Underground Hydrogen Storage

Analogous to natural gas, hydrogen can be stored underground (see Figure 2.2), in compressed gaseous form, in salt caverns and potentially also in depleted gasfields (and aquifers[17]).

Technology concepts
Conceptually, an underground storage facility for hydrogen consists of a storage reservoir (one or more salt caverns, or a depleted gasfield), wells for injection into and withdrawal from the caverns/fields, pipelines connecting the wells to gas processing facilities above-ground and electrical equipment (see Figure 2.3). Gas processing includes compression, expansion, drying and cleaning. Drying is required because the hydrogen

16 https://correenergystorage.nl/caes-the-project/
17 Water-bearing porous rock formations that provide a natural trapping mechanism for gases

Figure 2.2: Schematic illustration of technology concepts for underground hydrogen storage



picks up moisture while stored in caverns or depleted gasfield, and for this glycol dryers are commonly used. Furthermore, cleaning of the hydrogen is an important step to ensure that the quality of the hydrogen meets the requirements. Quality requirements are very strict for use as chemical feedstock or in fuel cells (electricity generation, mobility), i.e., the hydrogen must be > 99% pure, but less so for use in gas turbines or burners. Storage in salt caverns is known to not meaningfully impact the quality of the stored hydrogen, i.e., the 99% purity level can be met without significantly cleaning it. In depleted gas fields though, the mixing with residual gases present in the reservoir (methane, nitrogen, carbon dioxide) will require cleaning to meet the quality requirements for injection into a transmission grid. Pressure swing adsorption is the most widely used technology to purify hydrogen.

At injection, hydrogen flows from the pipelines of the H_2 transportation network (backbone) to the storage facility. The backbone connects production facilities with facilities (chemical plants, power stations, refueling stations) where hydrogen is consumed (see Figure 2.3). While the pressure level in the backbone will probably be in the range of 30-50 bar[18], the storage pressures are higher, i.e., in the range of 80-200 bar for the current salt cavern storages. Additional compression and cooling of the hydrogen is therefore required (to temperatures between 15-40 °C), after which it is led via the local pipeline network of the facility to wells through which it is injected into the caverns. At withdrawal, the hydrogen flows through the wells back to the surface, where it is first dried and then cleaned before expanding it. Once it reaches the required specifications (e.g. purity level, pressure, temperature, dew point), the hydrogen can be fed into the backbone again.

Salt caverns are large cavities in rock salt created ("leached") by a process called "solution mining", whereby fresh water is injected through a well into a bedded salt formation or salt pillar with a thickness of more than 300m (in case of caverns for gas storage) in the subsurface. At depth, the water dissolves the salt, and (saturated) brine is pumped back up to be processed in a salt production facility, where it is purified, and the water is evaporated to obtain pure salt. Alternatively, the brine is purged into the sea, but this is not allowed under the Dutch Mining Law. As a result of the dissolution of salt (a process called "leaching"), a cavity (cavern) is formed in the salt. During solution mining, the cavity is at all times filled with brine. A unique property of rock salt is that it is so tight that it effectively does not allow any fluid or gas to pass through it, i.e., it is impervious. Because of this, a salt cavern is a perfect storage container for fluids and gasses. In general, geometric volumes of caverns that are created for the purpose of salt mining range from 100,000 m^3 to several millions of m^3. However, in practice, when caverns are solution-mined for the purpose of gas storage (compressed air, natural gas, hydrogen), they rarely exceed 1,000,000 m^3.

A depleted natural gas field is a field from which gas was previously produced. It typically consists of a porous reservoir rock in which the gas was accumulated, and an impermeable overburden (clay or salt) working as a "seal", and which prevents the gas from migrating

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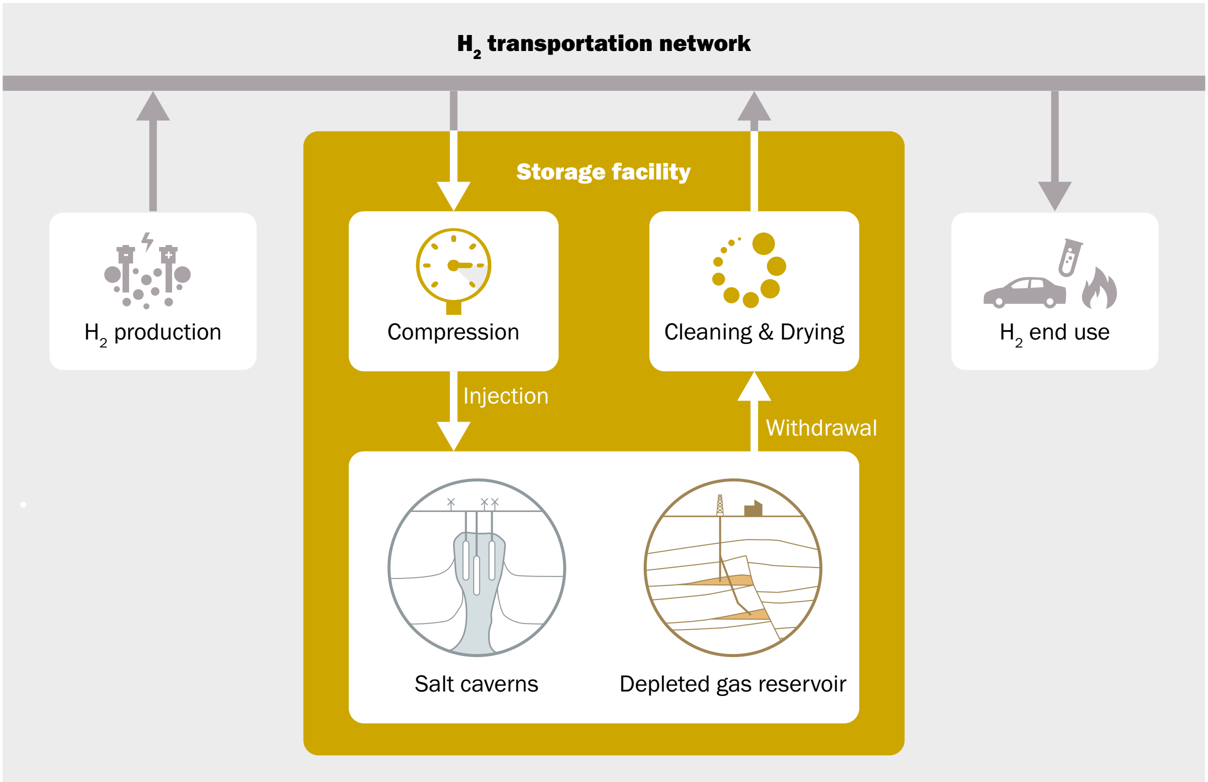
Figure 2.3: Schematic of the main components of an underground hydrogen storage facility.



further upward through the subsurface (see Figure 2.4). Because the natural gas has remained trapped in the pores of the reservoir rock for millions of years prior to being produced, the reservoir can be considered an effective storage medium. A third element is the aquifer underneath the reservoir, i.e., the part of the reservoir only filled with saline formation water, which in some cases can provide pressure support for the reservoir[19].

Deployment status

Hydrogen has long been stored in pure form and in large quantities (10-100 million m^3) in salt caverns in the US and in the UK (see Table 2.1). Practical experience with these storage sites shows that hydrogen can be safely stored in this way for long periods of time. So far, no issues such as biological and/or chemical degradation have been reported in literature. Despite the fact that only four storage facilities are currently operational in the world, hydrogen storage in salt caverns could be considered a mature technology.

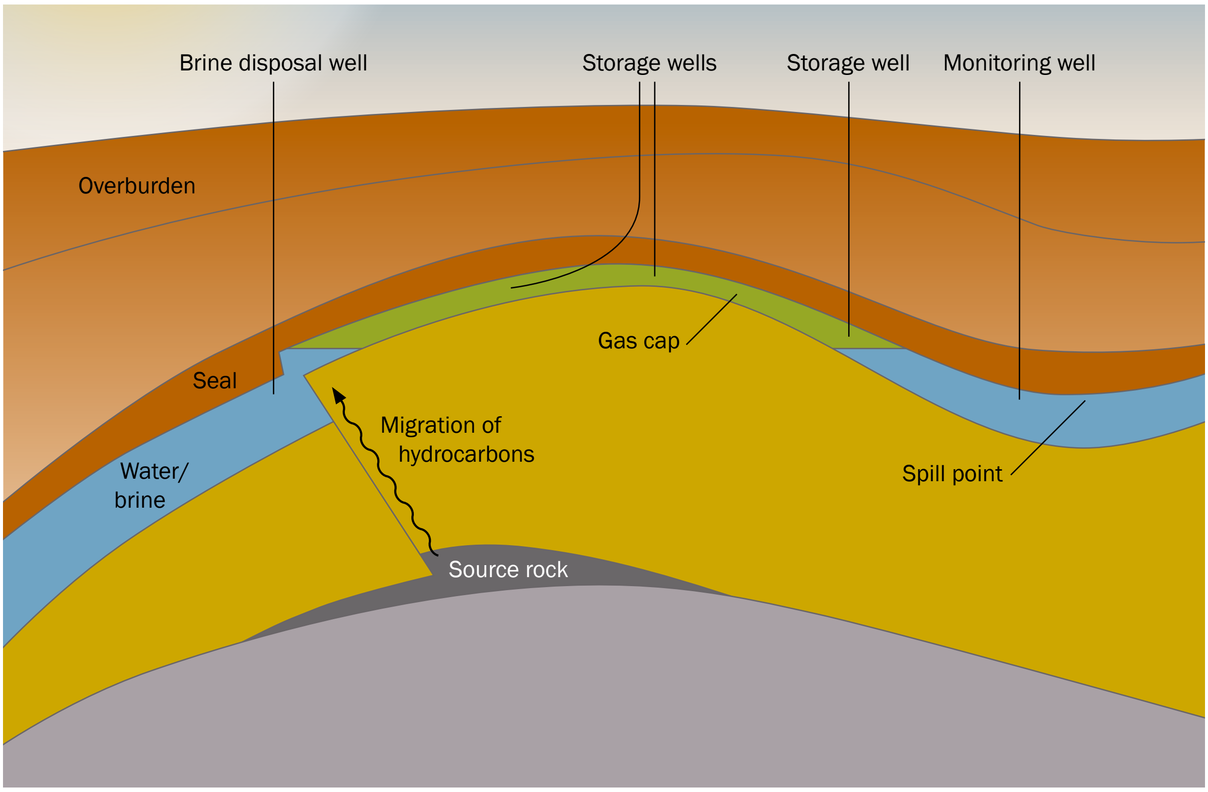
However, these storages are designed to provide security of supply of feedstock to the chemical industry, where annual demand profiles are typically constant, reflecting the continuous manufacturing process of the chemical industry. On the other hand, in order to balance supply and demand during periods with extreme weather conditions, higher injection/withdrawal rates and cyclicity are needed. This kind of fast-cycle operation brings with it specific challenges that must be addressed, in particular regarding the integrity of well the well materials, the salt cavern, and the interfaces. Hence the TRL must be considered to be lower. In Europe, several pilot- and demonstration projects are being prepared to raise the TRL to 7, one of which in the Netherlands by EnergyStock (a subsidiary of Gasunie).

For pure hydrogen storage in depleted gasfields (or aquifers) the technology readiness level (TRL) is low, i.e. estimated at level 3. Recent demonstration projects in Austria (the Underground Sun Storage project)[20] and Argentina[21] show that injection and storage of natural gas with a mixture of up to 10% of hydrogen in a depleted gas field can be safely done without adverse effects to the reservoir, installations and the environment. However, not all hydrogen could be recovered due to processes such as diffusion, solution and bacterial conversion to methane.

Furthermore, experience from operation of sites for underground storage of town gas (a mixture of hydrogen, carbon monoxide, carbon dioxide, methane, nitrogen and volatile hydrocarbons) has long proved there are no safety issues regarding the tightness and integrity of caprock and well cements(e.g. Ketzin, Lobodice and Beynes). However, pure hydrogen has not been stored in any of these projects. Therefore, fundamental questions still remain on the influence of geochemical processes and biochemical interactions of hydrogen with different types of rock formations, fluids and micro-organisms in reservoirs and the potential technical/environmental/economic risks associated.

19 HyUnder D3.1, "Overview on all Known Underground Storage Technologies for Hydrogen", 2013
20 https://www.underground-sun-storage.at/en.html
21 http://www.hychico.com.ar/eng/underground-hydrogen-storage.html

Figure 2.4: Schematic diagram showing the key elements of depleted gas field[19]



2.2 TECHNICAL POTENTIAL FOR DEVELOPMENT

The Dutch subsurface has a large potential for storage of energy in the form of compressed air (CAES) and hydrogen (and green gases i.e., biogas, synthetic methane). In a recent study by TNO/EBN the technical storage potential for hydrogen and CAES has been estimated.[22] The geographical distribution of (potential) storage capacity is indicated in Figure 2.5.

2.2.1 Underground Hydrogen Storage

Compressor buildings (brown) and dryers of the Zuidwending natural gas storage facility of EnergyStock. © EnergyStock

In the TNO/EBN assessment of the technical potential for storage of hydrogen in salt caverns, only the largest salt structures were selected that would provide enough volume for the construction of caverns at depths between 1000 and 1500m. A standard cavern size of 600,000 m^3 was assumed (100 m diameter x 300 m height), similar to those found in the Zuidwending UGS facility. To calculate the maximum theoretical number of caverns that could be constructed in each salt pillar, design criteria as specified in the German salt mining regulations[23] were applied, i.e., a minimum required distance of 100 m and 150 m between the cavern wall and the flank and top of the salt structure respectively, and a distance of 160 to 210 m between neighbouring cavern walls[24]. Based on the above, up to 321 salt caverns can potentially be created in salt pillars onshore. If these were to be used for storage of hydrogen, the estimated working volume would be 14.5 billion m^3 (156 PJ; 43.3 TWh$_t$), distributed over the provinces Groningen, Friesland and Drenthe.

In the assessment of the technical potential for storage of hydrogen in (nearly) depleted natural gas fields the entire portfolio of onshore and offshore natural gas fields was also considered. Storage capacities for natural gas were first estimated, and only for those gas fields fulfilling certain selection criteria (accessible through wells, depth > 1000 m, no H_2S, permeability > 0.1 mD, not used for storage yet, transmissivity >100 mD.m, GIIP volume of less than 30 billion m^3, and an initial well productivity higher than 1 million m^3/day). GIIP (Gas Initially In Place) volume minus the working volume gave the resulting cushion gas.

Finally, volumes of working gas and cushion gas for hydrogen storage were derived from results on natural gas using an average expansion factor of 0.85, which is valid for the range of pressures (100-300 bar) and temperatures (80-140 °C) of all the gas fields investigated. Based on this, the estimated technical storage capacity for hydrogen in depleted fields is 93 billion m^3 (997 PJ; 277 TWh$_t$) onshore and 60 billion m^3 offshore (644 PJ; 179 TWh$_t$).

2.2.2 Compressed Air Energy Storage

McIntosh CAES plant, which stores compressed air in a salt cavern of 0,538 million m^3 volume. Courtesy Power South Energy Cooperative

In the TNO/EBN assessment of the technical potential for compressed air storage in salt caverns the evaluation methodology used was largely the same as for hydrogen storage in salt caverns (see above). Only the depth range for developing caverns for CAES was assumed to be lower, i.e., 700-1200m, due to lower operational

22 https://www.nlog.nl/sites/default/files/2019-08/juez_larre_et_al_2019_fb_st_july.pdf
23 "Allgemeine Bergverordnung" (ABVO) of Lower Saxony
24 Rock-mechanical appraisal on the positioning of caverns in a salt dome and safety distances between gas storage caverns. Appendix to the 2012 storage plan of the Zuidwending natural gas storage facility of EnergyStock. IfG Institut fur Gebirgsmechanik GmbH, 2008.
25 Final report for executing a study of the effects of hydrogen injection in natural gas networks for the Dutch underground storages. DBI-GUT, 2017

Table 2.1: Overview of operational hydrogen storage facilities in salt caverns[25]

Parameter	Clemens Dome (US)	Moss Bluff (US)	Spindletop (US)	Teesside (UK)
Geology	Salt diapir	Salt diapir	Salt diapir	Bedded salt
Operator	Conoco Phillips	Praxair	Air Liquide	Sabic Petrochemicals
Start	1983	2007	2016	1972
Geom. vol. [m^3]	580,000	566,000	906,000	3 * 70,000
Avg. depth [m]	1,000	1,200	1,340	365
Press. range [bar]	70-137	55-152	68-202	45
Working volume [10^6 m^3] (GWh$_{LHV}$)	27.3 (81.9)	41.5 (124.5)	92.6 (277.8)	9.12 (27.36)

pressure requirements (80-100 bar). A notional CAES facility was assumed with a discharge power of 300 MW for a period of six hours, which equals an approximate required energy storage capacity of 1800 MWh. Because compressed air has an energy density of about 3 kWh/ m^3 at the assumed operational pressures, this would require a single salt cavern with a size of 600,000 m^3. With these assumptions the total energy storage capacity for the ca. 321 salt caverns onshore is about 0.58 TWh.

2.3 PERFORMANCE CHARACTERISTICS OF CAES AND UHS

2.3.1 Compressed Air Energy Storage

CAES systems are designed to be competitive in delivering a suite of flexibility services that are valued by utility companies, owners of generation assets, and grid operators. Typically, a CAES facility is designed to generate revenue from two main groups of services:

1. Arbitrage, i.e., providing electricity traders a means to earn money by levering the hourly price differences on electricity markets; and
2. Ancillary services, such as frequency regulation, reserve power, black start, load following, and synchronous inertia, that are procured by grid operators and asset owners of generation assets to manage grid stability.

In designing a CAES facility, a key aspect is to maximize the revenue expected from delivering these services by stacking them. As an example, owners of a CAES facility can offer certain ancillary services to a transmission system operator (TSO), for which it gets remunerated. In doing this, it delivers generation capacity with a certain response time to allow the operator to stabilize the grid. However, the asset is also generating electricity that can be traded, and if this electricity was stored at lower prices this constitutes additional revenue from arbitrage.

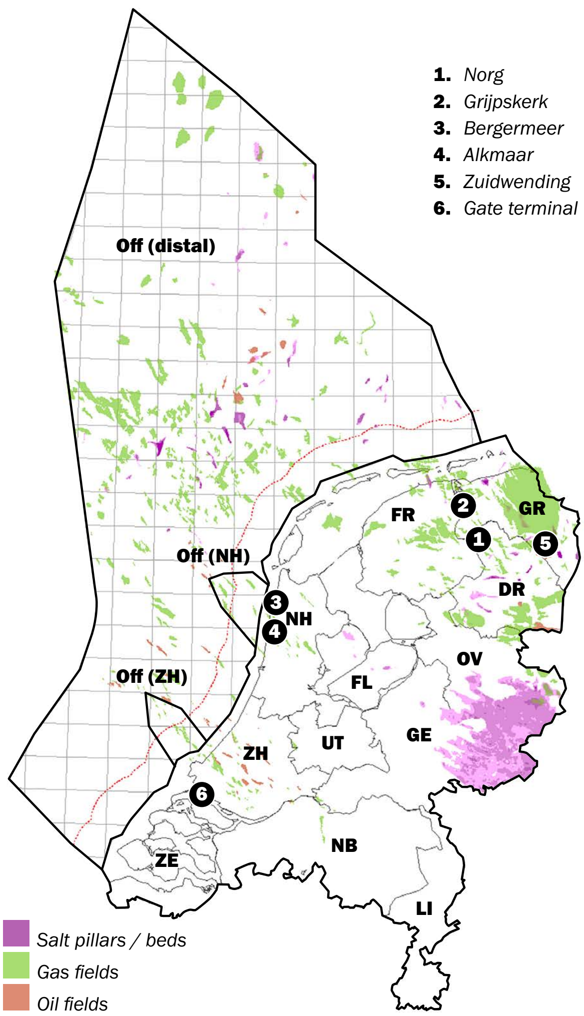
A CAES system typically consists of three groups of components (see Figure 2.1):

1. A multi-stage compressor train driven by a motor to charge the storage with compressed air;
2. A storage reservoir (typically salt caverns), wells and transport pipelines to store the compressed air and transport it to the plant;
3. An expander/generator train to discharge the storage and re-generate electricity, consisting of an expander or gas turbine and generator.

The technical performance parameters of each of these components are compared for the case of the Huntorf and McIntosh plants in Table 2.2.

CAES systems are commonly classified by two performance parameters: their generation capacity at full load (power output in MW), and the duration (in hours) over which this power can be delivered. By multiplying one with the other, the electricity production capacity (in MWh) is obtained. Typically, the power range of CAES systems is between 100-500MW, and the duration over which this power can be delivered ranges from hours to a day. Typical sizes of compressor trains (multiple compressor units) are in the order of tens to hundreds of MW, and typical sizes of turbo-expander/generator trains are in the order of 100-200MW. If larger capacities are required, and for reasons of redundancy, CAES plants often comprise of multiple compressor trains and multiple generation trains. While the compressor power determines the down-regulating capacity, i.e., the capacity to consume electricity (thus reducing grid load), the expander/generator train determines the up-regulating capacity, i.e., the capacity to produce electricity (and stabilize the grid). In CAES systems, compressor power is commonly lower than generation power, which to some extent reflects its principle of operation, i.e., charge at low prices and over a longer period of time (e.g. during the night), and generate at high prices at high capacity during a short period to maximize revenue.

Figure 2.5: Demarcation of the Dutch provinces and the three offshore areas for which the underground storage capacity was assessed. The contours of the gas/oil fields, rock salt formations — potentially suitable for cavern development — and the current gas storages are also shown (see numbered items; figure after [22])



Because CAES turbo-expander/generator trains are driven by the compressed air that comes out of the caverns, their size and design inlet pressure determine the pressure and rate at which the compressed air must be withdrawn. Inlet pressures of high-pressure CAES turbo-expanders in Huntorf and McIntosh are comparable (around 40 bar, see Table 2.2). However, mass flow rates during withdrawal in Huntorf (455kg/s) are 3 times higher than those in McIntosh (154kg/s). This large difference in mass flow determines the requirements for the diameters of the wells. While for natural gas storage well diameters of 9⅝ to 13⅜ inch (casing) are the standard, wells in CAES commonly have larger diameters in order to allow higher mass flow rates without a significant pressure drop and without damaging the well. In Huntorf for example, each cavern has a well with a 24.5 inch casing[26] to allow the mass flow rate stated in Table 2.2. Furthermore, multiple caverns are often developed, that typically range in geometric volume from a few hundreds of thousands m^3 to one million m^3, depending on the number and size of the generation train and the discharge duration.

Two other key performance parameters for a CAES are the "response time" and the "cycle efficiency". The response time is the start-up time needed to go from 0 power output to full capacity. A common start-up time for a standard CAES plant is of less than 15 minutes (see Table 2.2). This makes it possible to provide secondary (and tertiary) reserve power and black start services to grid operators. The cycle efficiency (often referred to as the round-trip efficiency), is calculated by dividing the amount of (primary) energy discharged by the amount of (primary) energy charged (consumed). However, because D-CAES is a hybrid electricity generation and storage technology, which requires firing of a secondary fuel at generation, round-trip efficiencies are commonly calculated by including the (thermal) energy value of the fuel in the charging step[27].

2.3.2 Underground Hydrogen Storage

At 5 UGS facilities in the Netherlands natural gas is already safely stored in large quantities in depleted gas fields (Grijpskerk, Norg, Alkmaar and Bergermeer) and salt caverns (Zuidwending). Table 2.3 displays their current technical performance parameters for natural gas, i.e., the (max. achieved) rates of injection (charge) and withdrawal (discharge), their storage capacities (working gas volume), and the volume of cushion gas required. It also displays the potential technical performance parameters of these facilities if they would

26 Crotogino F, Donadei S, Bunger U, Landinger H. Large-scale hydrogen underground storage for securing future energy supplies. Proceedings of 18th World Hydrogen Energy Conference (WHEC2010), Essen, Germany; May 16-21, 2010. p. 37-45
27 Budt, M., Wolf, D., Span, R., Yan, J., 2016. A review on compressed air energy storage: Basic principles, past milestones and recent developments. Applied Energy, 170, 250-268. http://dx.doi.org/10.1016/j.apenergy.2016.02.108
28 Pollak R. History of first U.S. Compressed Air Energy Storage (CAES) plant (110MW 26h): volume 2: Construction. Palo Alto; 1994.
29 Tuschy I, Althaus R, Gerdes R, Keller-Sornig P. Entwicklung der Gasturbinen in der Luftspeicher-Technologie. VGB PowerTech 2004;4:84–7.
30 Radgen P., 2008. 30 years compressed air energy storage plant Huntorf – experiences and outlook. In: 3rd international renewable energy storage conference. Berlin, p. 18.
31 Nakhamkin M, Andersson L, Swensen E, Howard J. AEC 110 MW CAES plant: status of project. ASME J Eng Gas Turbines Power 1992;114:695–700.
32 Pers. comm. Uniper

Table 2.2: Comparison of performance parameters of operational plants at Huntorf and McIntosh.[28, 29, 30, 31, 32]

Plant	Huntorf (Germany)	McIntosh (US)
Operating utility	Uniper	PowerSouth
Cycle efficiency	0.46	0.54
Energy input for kWh_{el} output	0.8 $kWh_{electricity}$/ 1.7 kWh_{gas}	0.69 $kWh_{electricity}$ / 1.17 kWh_{gas}
Energy produced	2568MWh	2640MWh
Start operation	1978 (refurbished 2007)	1991
Compression		
Max. electric input power	68MW	50MW
Max. air mass flow rate	108kg/s	90kg/s
Compressor units	2	4
Charging time (at full load)	18	38
Storage		
Cavern depth	640-790m	460-760m
Cavern pressure range	46-72 bar	46-75 bar
Cavern volume	310,000 m^3 (2 caverns)	538,000 m^3 (1 cavern)
Well diameter	24 inch casing / 20.5 inch tubing	unknown
Expansion		
Max. electric output power	321MW	110MW
Control range (output)	100-321MW	10-110MW
Discharging time (at full load)	8	24
Start-up time (normal/emergency)	14/8 minutes	12/7 minutes
Max. mass flow rate	455 kg/s	154kg/s
HP turbine inlet	41 bar	42 bar

be used for UHS, based on a reservoir and well performance analysis that was done as part of this project.

In general, for the performance of UHS in depleted gasfields the analysis showed that the lower density (8-10 times) and viscosity of hydrogen relative to methane results in 2.4 to 2.7 times higher withdrawal rates for hydrogen. These high rates partly compensate for the lower energy content of hydrogen (3-4 times lower than methane), resulting in an energy throughput of 0.7 to 0.8 times that of methane. Although maximum withdrawal rates for hydrogen of up to ~33 mln Sm^3/day (99GWh$_{LHV}$/day, or ~4.1GW energy throughput) for a well with a 7-inch tubing (internal diameter) are theoretically possible, there are several factors such as the erosional velocity limit, bottomhole drawdown, and expected duration of maximum plateau rate that can limit the theoretical withdrawal rate. For instance, for the Grijpskerk UGS, the withdrawal rate of hydrogen would drop to just below 20 mln Sm^3/day (57GWh$_{LHV}$/day, or ~2.3GW energy throughput) for a well with a 7-inch tubing. This is 62% of the energy throughput of the maximum ever reported withdrawal rate in Grijpskerk of ~92 GWh/day (8.5 mln Sm^3/day) (Table 2.3).

The use of a 9-inch tubing would allow increasing the maximum theoretical withdrawal rate of hydrogen by 57% for the Grijpskerk UGS (from 33 to 52 mln Sm^3/day), yet also the maximum bottom-hole drawdowns by up to 73% (from 82 to 143 bar), which would increase the risk of mechanical damage to the wellbore resulting in a reduction of the flow performances. Injection rates for hydrogen are generally higher than for methane at higher wellhead pressures. Despite the higher density (weight) of the methane, this gas has also a higher viscosity, which at high flow rate apparently hampers injection into the reservoir. Injection rates will also be limited by the erosional velocity and bottom-hole build-up as previously discussed for withdrawal. Further research is needed to understand how the injection rates are affected by the thermal effect of the cooler hydrogen front injected in the reservoir.

For UHS in a “standard” salt cavern, such as that in the Zuidwending UGS facility, withdrawal rates of hydrogen up to 35 mln Sm^3/day are theoretically feasible. This is 3-4 times faster than that of well in a salt cavern filled with natural gas, and 1.5 to 2.5 times faster than that of a well in a depleted gasfield with very good reservoir properties and filled with hydrogen (i.e. transmissivity of 11.000 mD.m). The very high theoretical withdrawal rates and the working volumes in salt caverns are primarily limited though by the maximum allowed daily pressure depletion of 10 bar/day. This is imposed in order to preserve the structural integrity of the cavern and reduce the loss of (geometric) volume due to salt creep. It significantly limits the withdrawal rate for hydrogen to 5.2 million Sm^3/day (15GWh$_{LHV}$/day), with the remark that this is the limit rate per day, i.e., higher withdrawal rates per hour are possible as long as the daily allowable pressure drop is not exceeded. If Zuidwending would be operated at the same pressure range of today, yet storing hydrogen instead of natural gas, the energy content of the hydrogen working volume (storage capacity) would be only 22% of the 3.6 TWh available today as natural gas.

2.4 TECHNOLOGY CHALLENGES

As with other subsurface technologies, the use of the subsurface for energy storage may introduce risks that can potentially negatively impact health, safety, and environment. While the risks associated with natural gas storage are well-known from decades of operational experience, the risks associated with UHS and CAES

Table 2.3: Summary results of the realized natural gas and estimated (hydrogen) withdrawal and injection rates and working/cushion volumes for the three UGS and one salt cavern. For Zuidwending the realized withdrawal and injection rates for natural gas are as reported in the Zuidwending storage plan. Volumes of working gas and cushion gas for natural gas were extracted from the storage licenses www.nlog.nl. (*) Realized daily rates are based on values reported by the operator NAM. (**) Estimated range of maximum theoretical withdrawal rates for hydrogen based on bottom-hole and erosional velocity restrictions. Working gas and cushion gas volumes for hydrogen calculated using working pressure range as currently used for natural gas. Here (n.a.) indicates not available (realized) or further analysis are required to generate a good estimate (estimated).

CH_4-realized*/ H_2-est.**		Grijpskerk		Norg		Alkmaar		Zuidwending	
		CH_4*	H_2**	CH_4*	H_2**	CH_4*	H_2**	CH_4*	H_2**
Max. withdrawal rate	million Sm^3/day	~8.5	<20.0-21.9	~12.5	<26.0-28.6	~4.0	<11	7.6 (avg.)	n.a.
Max. injection rate	million Sm^3/day	~5.5	n.a.	~9	n.a.	n.a.	n.a.	4.6 (avg.)	n.a.
Volume at max. working pressure (GIIP)	billion Sm^3	10.8	9.9	29.4	24.7	3.8	3.2	0.76	0.61
Working Gas Volume (WGV)	billion Sm^3	2.5	3.5	6.3	7.9	0.56	0.76	0.38	0.29
Cushion Gas Volume (CGV)	billion Sm^3	8.3	6.4	23.0	16.8	3.3	2.4	0.37	0.32
WGV : CGV ratio	-	0.3	0.54	0.27	0.47	0.18	0.33	1.02	0.90

are relatively underexplored. Therefore, in this project the potential risks associated with these technologies were inventoried, and possible mitigation measures were explored. Risks were inventoried by conducting a literature review, and supplemented with expert knowledge. All risks were included in a risk inventory that categorizes the risks into their relevant project phase, system component, reservoir storage type (cavern or porous reservoir) and TEECOPS[33] category. In total, 159 risks were derived from 40 references, of which about half (75) pertain to operating the storage facility. The purpose of this inventory is to serve as a starting point and checklist to identify and manage risks in development projects, and to provide guidance on potential mitigation measures to reduce the risks, and is available upon request.

The term risk is defined as the effect (consequence) of a potentially hazardous event times its probability of occurrence. In general, in relation to the risks associated with the two subsurface components of a storage system, the storage reservoir (salt cavern or porous reservoir) and the well, three potentially hazardous events can been identified:

1. Leakage of stored product out of the storage system, either below-ground, or above-ground at the wellhead;
2. Subsidence, either a gradual sinking of the ground surface to a lower level or a sudden collapse of the ground;
3. Seismicity, i.e., sudden shaking of the surface, either induced by the storage operation itself, or by an external cause.

In the next 2 sections, we provide a brief summary of two studies conducted that provide better insight into specific risks associated with CAES and UHS. The first one focuses on the effects of cyclic storage of air and hydrogen on the mechanical integrity and stability of salt caverns, and the second one on the effects of geo-and biochemical interactions of hydrogen with rocks, fluids and micro-organisms in porous reservoirs.

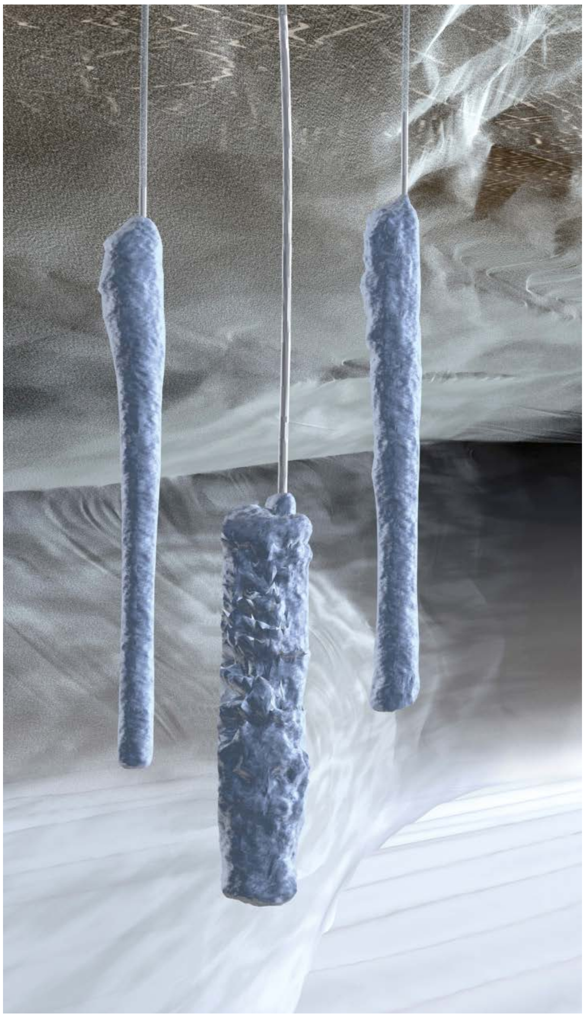
Finally we present the conclusions of a qualitative non site-specific comparison of the risks associated with UHS vs. those of UGS.

2.4.1 Effects of cyclic storage of air and H_2 on cavern stability and integrity

After the leaching stage, during which the salt cavern is created (see Section 2.1.1), the brine in the cavern must be displaced to make room to store the gas (air, hydrogen). During this process, which is called "debrining", gas is injected into the cavern through the production string that ends at the top of the cavern. While gas accumulates in the top part of the cavern, the pressure increases, and when it exceeds the halmostatic pressure (the pressure due to the weight of the column of saturated brine), the saturated brine is pushed down and out of the cavern through the debrining string that ends at the base of the cavern. Eventually, the bulk of the cavern volume will be filled with compressed gas, with only a few meters of brine column remaining at its base, and the cavern is then ready for fast-cyclic storage operations.

The fast-cyclic injection and withdrawal of gas (air or hydrogen) causes variations in the internal cavern pressure and temperature, which in turn could have adverse effects on the integrity and stability of the salt cavern. A geomechanical modelling study that was conducted as part of this project shows that effects of cyclic injection and withdrawal of air during CAES operations do not jeopardize cavern stability and integrity. Although temperature fluctuations are observed that may lead to the creation of fractures in a thin skin at the cavern wall (<1m thick damage zone), they do not pose a real threat to cavern integrity due the limited depth of penetration in the cavern wall. Even during maintenance periods, or in extreme cases, when the cavern would experience atmospheric conditions for a prolonged period (months), although the width of the damage zone would be larger, the results suggest that it would not jeopardize cavern stability and integrity.

Visual representation of three salt caverns surrounded by salt, based on sonar measurements. Each cavern is connected to the surface by a well. *© DEEP.KBB GmbH*



33 TEECOPS: technical, economic, environmental, commercial, organisational, political and societal

A similar geomechanical modelling study for UHS shows that effects of cyclic injection and withdrawal of hydrogen also do not jeopardize cavern stability and integrity. Temperature fluctuations of up to 40 °C are simulated within a distance of 1 m into the cavern wall, in particular when injection cycles are short (weekly) or wellhead injection temperatures are high. Although such temperature fluctuations may lead to the creation of fractures in a thin skin at the cavern wall (<1m thick damage zone), they do not pose a real threat to cavern integrity due the limited depth of penetration in the cavern wall. In a scenario with monthly cycling of 23 days injection (3 weeks) and 7 days production (1 week) the simulation shows a cavern wall displacement of 35 cm. However, the geological tightness of the cavern and cavern integrity are not jeopardized during normal UHS cycling operations.

2.4.2 Effects of geo-and biochemical reactions with H_2 in porous reservoirs

Underground storage of hydrogen in porous reservoirs (depleted gasfields or aquifers) is non-proven technology. To advance this technology towards commercial-scale implementation, several research questions must be addressed to clarify if hydrogen can be safely and economically stored, and with no adverse effects to the environment. One of the main uncertainties is the possibility of hydrogen-fluid-rock interactions in the storage reservoir. These reactions may:

- Produce toxic and/or corrosive fluids (e.g. H_2S) that pose a threat to environment, health, safety, injection and production facility integrity, project economics and overall feasibility;
- Reduce the porosity and/or permeability of the reservoir and more specific the near-wellbore area by precipitation of minerals and microbial growth, affecting the reservoir performance and loss of H_2 injectivity;
- Lead to loss of H_2 by microbial activity and consequential contamination of the stored H_2 with other gases (CH_4, H_2S, etc.) in the reservoir that are co-produced upon withdrawal from storage.

> ‘To accurately assess the risk of H_2S formation in hydrogen storage reservoirs it is of the utmost importance to improve the predictive power of the geo- and biochemical models with laboratory experiments.’

Geochemical processes that could be of concern for hydrogen storage in the Netherlands include:

- Reduction of iron sulfide minerals (pyrite) forming H_2S;
- Reduction of hematite to magnetite, sequestering H_2 and producing H_2O; and
- Reduction reactions, H_2S formation, and the presence of additional (residual) gases such as CO_2, leading to changes in the fluid composition and pH, possibly resulting in precipitation and dissolution of secondary minerals, and degrading reservoir performance.

Geochemical simulations with PHREEQC that were conducted as part of this project show that pyrite reduction as a result of H_2 storage may occur, leading to H_2S formation in the gas phase, which may affect safety, materials selection, facility design and economics. H_2S release increases with depth (as the partial pressure increases), and with the amount of initial pyrite in the reservoir. However, because kinetic effects were not taken into account, these results reflect a worst case scenario. Also, the presence of H_2S scavenging minerals such as siderite may again “absorb” the H_2S, a reaction that was not extensively studied in this project. To accurately assess the risk of H_2S formation in hydrogen storage reservoirs it is of the utmost importance to improve the predictive power of the geochemical models, which will require incorporation of kinetic rates at high temperatures and high H_2 partial pressures (obtained with laboratory experiments), as well as H_2S scavenging reactions and transport in the reservoir.

In addition to the risks of chemical reactions between H_2 and reservoir rock, the risks associated with conversion of H_2 to CH_4 and H_2S due to microbial activity also were investigated in this project. Biochemical simulations with PHREEQC indicate that bacterial sulphate reduction and methanogenesis may both pose a risk for underground hydrogen storage, which is also reported in literature.[34, 35] In the simulations, the extent of sulphate reduction modelled leads to significant levels of H_2S. How likely these amounts of H_2S are to develop will require further experimental and numerical modelling research. Furthermore, in the simulations maximum microbial growth rates were assumed that occur at temperatures of 37 °C for methanogenesis and 30 °C for bacterial sulphate reduction. Because the temperature in potential reservoirs for hydrogen storage in the Dutch subsurface is considerably higher, the results must be considered a worst-case scenario.

When storing hydrogen in a depleted field, large volumes of cushion gas will have to be injected to keep the working pressure in the reservoir above a threshold

34 Hagemann, B., Rasoulzadeh, M., Panfilov, M., Ganzer, L., & Reitenbach, V. (2016). Hydrogenization of underground storage of natural gas - Impact of hydrogen on the hydrodynamic and bio-chemical behavior. Comput. Geosci. (2016) 20:595–606. doi: 10.1007/s10596-015-9515-

35 Greksák, M., Šmigáň, P., Kozánková, J., Buzek, F., Onderka, V., & Wolf, I. (1990). Methanogenic bacteria and their activity in a subsurface reservoir of town gas. Microbiology and Biochemistry of Strict Anaerobes Involved in Interspecies Hydrogen Transfer, 381-383. doi:10.1007/978-1-4613-0613-9_39

minimum value. In reservoirs used for underground storage of natural gas the residual gas in the reservoir upon cessation of production can serve as cushion gas, and further pressure support is provided by injecting natural gas, which constitutes an additional investment. However, in the case of underground hydrogen storage in reservoirs, this additional investment would potentially be much higher, because of the significantly higher production costs for H_2 compared to natural gas. Investment costs could be significantly reduced if other gases with lower unit cost could be used as cushion gas. An interesting candidate for this is nitrogen. Geochemical modelling indicates that nitrogen has negligible impact on rock-gas-water reactions. A modelled effect is the change in hydrogen partial pressure when nitrogen is present as cushion gas, which causes lower reactivity of hydrogen in the reservoir. Therefore, from a geochemical perspective nitrogen would potentially be suitable to use as a cushion gas for hydrogen storage.

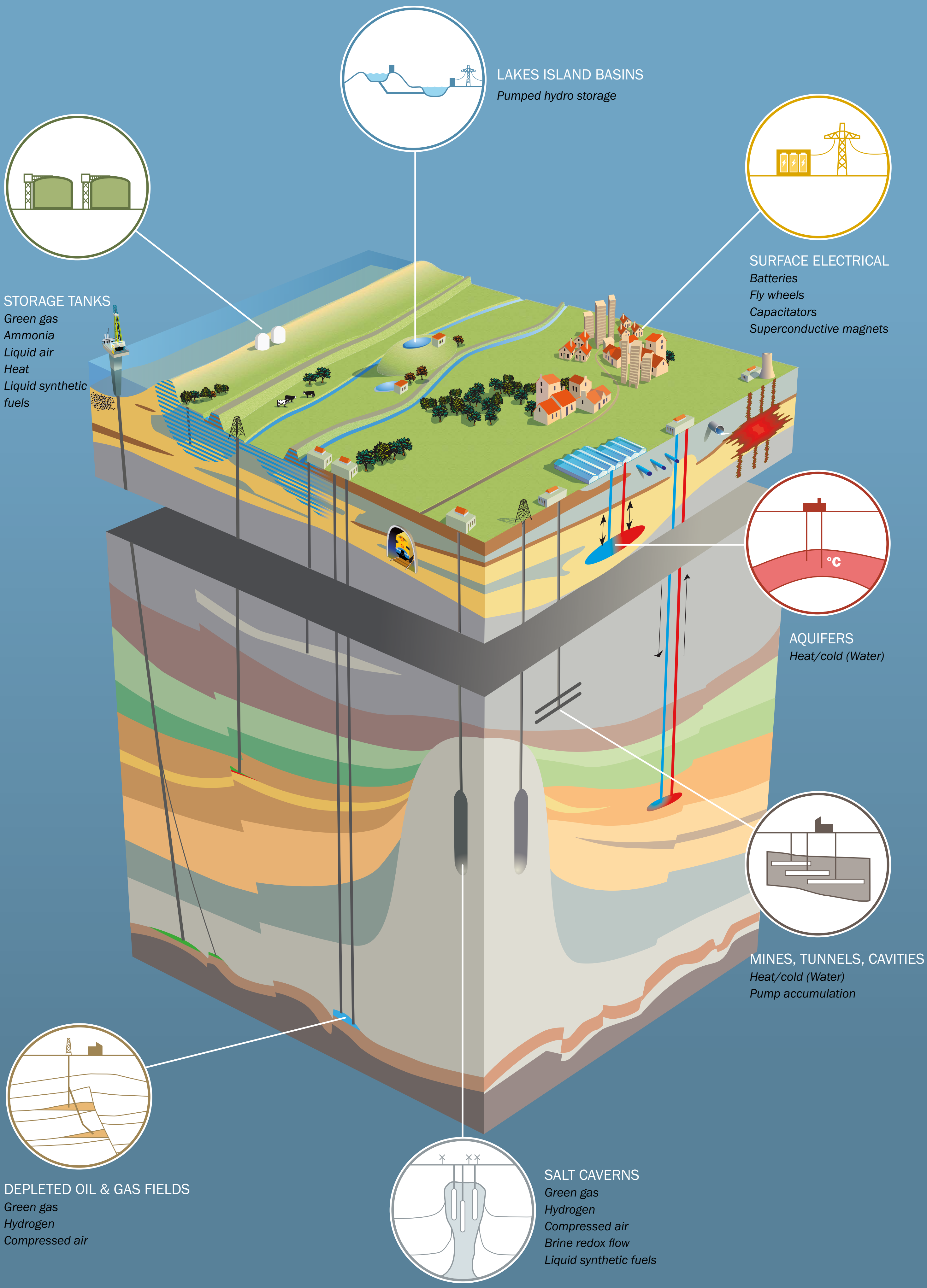
2.4.3 Qualitative comparison of risks of UHS vs. UGS

Risks associated with UGS are well understood from decades of (industrial) experience with storage (and production) of natural gas. In this project, this knowledge and expertise served as a point of reference for assessing the risks associated with UHS. A qualitative non site-specific comparison was made between storage of hydrogen and methane (as a proxy for natural gas, which consists of 70-90% of methane). Although in general UGS and UHS are expected to have a similar risk profile, there are also differences:

- Hydrogen has a much wider flammability range and a much lower ignition energy compared to methane, and is therefore more prone to ignite when released. Hydrogen is therefore classified as a high reactive[36] gas, while methane is classified as a low reactive gas. On ignition methane radiates heat and creates a flame that is clearly visibly. Ignited hydrogen on the other hand radiates little (infrared) heat (IR), but emits substantial UV (ultraviolet) radiation. The lack of IR gives little sensation of heat, but the exposure to a hydrogen flame will still cause severe burns because of the UV radiation. Because a burning hydrogen flame is also not easily detectable (contrary to methane), it increases the risks associated with hydrogen when it ignites to form a flame. Detection sensors validated for hydrogen should be used to detect possible hydrogen releases.
- In case of leakage of hydrogen or methane in confined spaces, where leakages can remain undetected, or in case of large volume releases (e.g. a blow-out, see below) there is an elevated risk of explosion for both hydrogen and methane. However, the effects of a hydrogen explosion are different compared to methane. When a mixture of hydrogen and air explodes, the higher flame propagation speed potentially generates high pressures that could result in an explosion (a pressure shock wave) with massive burst damage, i.e., damage to buildings or even collapse. In contrast, when a mixture of methane and air explodes, the potential for burst damage is lower, but the longer duration of the flame, in combination with the heat that it radiates, can potentially lead to lasting harm. In the absence of confinement and congestion though, no overpressures are generated, and the consequence of an explosion is limited to a flash fire.
- A catastrophic event on the wellpad (e.g. an accident with a heavy truck, or a dropped object) could lead to complete or partial removal the wellhead and/or Xmas tree with all valves, which could lead to uncontrolled outflow of gas (also referred to as a blow-out). When ignited, both hydrogen and methane will form a jet flame (flare), but the hydrogen flame is expected to be narrower and reach higher. This together with the lower energy content likely reduces the effect of heat radiation. A properly installed and operationally tested subsurface safety valve (SSSV), which is mandatory for gas (production and) storage wells, must prevent significant outflow in case of such catastrophic event. Although SSSVs are extensively used in oil and gas industry, their effectiveness in shutting in a flowing hydrogen storage well is yet to be confirmed.
- Hydrogen is in contrast to methane a reactive[37] gas that has the ability to react with rocks and reservoir fluids and may interact with microbes in the reservoir (see also Section 2.4.2).This might affect reservoir performance (e.g. by pore clogging due to precipitation of minerals or rapid bacterial growth in the near-wellbore region) and/or could result in loss of hydrogen and/or contamination of the production stream due to the formation of H_2S, a toxic, corrosive gas that degrades wellbore materials and poses a threat to human health when released to the atmosphere.

Although the risks associated with UHS are generally known, further research (laboratory experiments, numerical modelling, material testing, pilot-scale field tests) is required in particular on a) the long-term durability of rocks and (well) materials (steel alloys, cement, elastomers, etc.) when subjected to hydrogen under an alternating pressure regime that causes mechanical and thermal stresses, and b) interactions of hydrogen with rocks, fluids and microbes in reservoirs and their effects on reservoir performance, quality and retrievability of the stored hydrogen, and integrity and durability of materials subjected to products of such interactions (e.g. H_2S).

36 "Reactive" here refers to the ability to ignite
37 "Reactive" here refers to the ability to react with other chemicals (in the reservoir and/or casing)



Schematic illustration of energy storage technologies above-ground and below-ground. © TNO

3. FUTURE ROLE AND MARKET POTENTIAL

3.1 FUTURE ROLE OF ENERGY STORAGE IN THE TRANSITIONING ENERGY SYSTEM

The technical storage potential for both UHS and CAES has been estimated to be large, see section 2.2. A next step is to better understand their future role in the energy system and estimate the market potential of (large-scale) energy storage in the Netherlands. This basically represents the storage potential that is suitable from a techno-economic perspective. It is paramount to not only include in this assessment the techno-economic performance of the storage options under study but also the competition between storage technologies and other options that provide flexibility to the energy system (i.e. demand-response, grid expansion, flex supply and conversion).

For the Netherlands recent studies have addressed this need and value for large-scale energy storage in the Dutch energy system.[22, 38] The results show that technical potential and market potential for both CAES and hydrogen storage can be large in scenarios with high shares of variable renewable energy technologies. The Flexnet study developed several scenario cases up to 2050 which show the increase in flexibility needed in the electricity system[38]. The study shows that energy storage plays a role in the future supply of flexibility in the Netherlands, but the applications and market size depend strongly on the services the storage facility can offer to the energy system and the value of these services. The role of hydrogen storage was not studied in detail in that study. This was followed-up by a TNO/EBN study that takes scenarios for the future demand for flexibility when taking into account natural gas phase out scenarios, bringing a role for green gas and hydrogen production and storage.[22]

These studies have assessed the required storage volume to range between 0.36 TWh and 16.75 TWh per annum until 2050. For reference, a typical CAES stores up to several GWh, existing hydrogen caverns 27-274 GWh and a depleted gas reservoir could store 0.3 - 30 TWh.[39] With a potential need for 6 TWh of hydrogen storage volume this would entail about 45 typical salt caverns (600 000 m^3) or 2 depleted gas fields with 1 bcm of H_2 working volume each.[40]

In one of EU's future pathways hydrogen storage in the EU grows towards ~175 TWh (see Figure 1.2 – earlier in document).[12] This represents possibly a volume of hundreds (even more than 1000) of salt caverns or the equivalent of tens to hundreds of hydrogen storage operations in porous reservoirs.[41]

In the ESTMAP study with a broader geographical scope the energy storage potential (surface and subsurface) was estimated for 33 European countries including the Netherlands.[3] The potential assessment has been used to perform location specific energy system modelling for the region comprising of Germany, The Netherlands and Belgium. This has yielded insights in both the potential for storage as the market needs for large-scale storage towards 2050. One of the key insights is that for CAES the north-east area of the Netherlands and the north of Germany is a high potential area with up to 10-20 GW of installed capacity and 100 GWh of storage volume in 2050. The study further highlights the fact that the outcomes of energy system analysis strongly depend on key storage technology parameters.

In a study by Berenschot and Kalavasta four scenarios were developed that show possible futures for the Dutch energy system. The role for electricity storage (no distinction between technologies) is estimated to range between 1.5 and 17 GW of installed capacity in 2050. For underground hydrogen storage a range between 16 and 193 TWh is estimated.[42, 43]

The studies agree that there remain important market barriers that hinder actual investments and deployment in large-scale subsurface energy storage technologies. This includes the lack of policy incentives, regulatory barriers, non-valued energy system services, public perception and general market uncertainty for the long term to allow for large-scale investments needed. And further it needs to be recognized that the business case for the selection of specific storage technologies will strongly depend on the geography, subsurface, market structure and (existing and future) energy infrastructure.

In this project the potential for market deployment is assessed from different perspectives. The first is the energy system perspective. This perspective provides insights in whether energy storage has a value in the future energy system as a whole. And provides answer to questions whether energy storage deployment helps minimizing the (social) cost of the future energy system and the transition towards it. The second perspective is that of the project developer. This stakeholder is

38 https://www.ecn.nl/nl/flexnet/
39 Assuming work volume between 0.1 and 10 bcm H_2
40 Based on insights from TNO/EBN[22]
41 Note that this depends very strongly on the amount of annual full cycle equivalents being assumed for the hydrogen storage options.
42 For an extreme weather year up to 240 TWh of hydrogen storage is estimated to be required.
43 Klimaatneutrale energiescenario's 2050, Scenariostudie ten behoeve van de integrale infrastructuurverkenning 2030-2050. Berenschot en Kalavasta, 2020.

obviously interested in understanding how to build a positive business case when developing energy storage projects. And is concerned with the above mentioned market barriers and drivers that affect the business case.

3.2 THE MARKET POTENTIAL FROM SYSTEM PERSPECTIVE

The role of energy storage in the future, low-carbon energy system of the Netherlands is explored with the use of two energy system models: the European electricity market model (COMPETES) and a national integrated energy system model of the Netherlands (OPERA), see textbox below for details on the approach.

3.2.1 Energy Storage in 2030

Following the ambitions of the Climate Agreement of June 2019, a modest additional 2 GW of electrolysis capacity has been assumed for both models. COMPETES assumes a correspondingly (policy-supported) high demand for H_2 from domestic electrolysis of 24 PJ (6.7 TWh) whereas OPERA determines endogenously that the (market-based) demand for H_2 in CA2030 is much lower (6.7 PJ) and is predominantly met by hydrogen produced from natural gas by means of Steam Methane Reforming (SMR, without CCS).[44]

Two energy system models: OPERA and COMPETES
Both models minimise the social cost of the power (COMPETES) or energy (OPERA) system while satisfying demand and emission requirements. Both models can use a one-hour temporal resolution. A key difference is that COMPETES focuses on flexibility of the electrical power system in the Netherlands in connection to other countries, while OPERA includes the integrated energy system of the Netherlands. This includes for example the demand, supply and storage of electricity and hydrogen in competition with other energy sources and energy carriers. Besides analysing the potential role of CAES and UHS, the study considers also other storage technologies – such as batteries or hydrogen storage in cars, filling stations or vessels – as well as other flexibility options such as demand response or cross-border energy trade.

Two reference scenarios: for 2030 and 2050
For 2030, the reference scenario is based on the targets and policy measures of the Climate Agreement (CA) of June 2019 and designated briefly as CA2030. For 2050, the reference scenario is based on the National Management (NM) scenario, developed recently by Berenschot and Kalavasta, and designated briefly as NM2050.[43] This scenario is characterised by a strong governance by the Dutch national administration as well as by a high level of national energy self-sufficiency (i.e. with minimal energy imports). Moreover, it shows a strong further electrification of all energy-use sectors, enabled by a very large installed capacity of solar PV and offshore wind. In addition, both industry and freight transport rely on a substantial deployment of domestically produced green hydrogen. Imbalances of the energy system are met by national storage – among others of hydrogen – in combination with flexible power plants fuelled by green (bio)gas and green hydrogen that can (re)generate electricity on-demand, thus providing back-up capacity for periods of low production from variable renewable energy (VRE) sources such as sun or wind. COMPETES and OPERA use the NM2050 scenario and corresponding data obtained from the ETM model[45] as input for the expected energy demand in 2050, although energy supply capacity and production are to some extent endogenously determined. This leads to differences in modelling outcomes, notably of the production of hydrogen and electricity by wind and solar PV.

The difference between the models in hydrogen demand and production has an effect on both electricity and hydrogen storage requirements, which are shown in Table 3.1. The required size of UHS in 2030 is estimated at 10 GWh by OPERA and 66 GWh by COMPETES, while the total volume of H_2 to be stored underground on an annual basis is estimated at 21 GWh by OPERA and 900 GWh by COMPETES.

The total storage size of all electric vehicle (EV) batteries, is about 50% higher in OPERA than in COMPETES, i.e. 45 GWh vs 31 GWh, respectively. As the (assumed) average battery size per EV is similar in both models (75 kWh), this difference in total EV storage size is solely due to the total number of EVs operating in these models. The stored electricity is primarily used for propulsion of vehicles, although COMPETES also includes some EV battery storage for Vehicle-to-Grid (V2G) transactions. In OPERA, additional stationary battery storage capacity provides flexibility to match variability in VRE supply, whereas in COMPETES this variability is mainly matched by hydrogen production and underground hydrogen storage.

The H_2 storage foreseen in the OPERA model outcomes is combined with much less variably produced H_2 from

44 Note, that this is new H_2 demand for mobility (high-duty vehicles) and for heating in the built environment, which is on top of 162 PJ of H_2 demand being part of conventional industrial processes such as oil-refining and ammonia production.
45 https://energytransitionmodel.com

natural gas reforming. The storage need originates from serving different end-use functions, such as the H_2 demand by high-duty vehicles in the transport sector and H_2 boilers for (seasonal) heating in the built environment, as endogenously determined by OPERA. COMPETES does not differentiate total H_2 demand into specific use functions or categories and assumes that the hourly profile of total hydrogen demand is constant.

This indicates clearly that the need for H_2 storage depends strongly on the source(s) of hydrogen (production variability) as well as on the end-use sectors in which H_2 is consumed (demand variability).

In conclusion, relatively limited electricity storage is foreseen for the year 2030 and the amount of required hydrogen storage depends strongly on reaching the Climate Accord ambitions to install up 3-4 GW electrolysis capacity and the demand sectors (and their demand profiles) for this additional hydrogen.

3.2.2 Energy Storage in 2050

OPERA results indicate a domestic electricity supply (400 TWh) and hydrogen production (92 TWh) that is similar to the Berenschot and Kalavasta scenario.[43] Results indicate however less solar PV capacity and production, compensated by mostly offshore wind capacity and production. COMPETES uses the VRE capacities from the Berenschot and Kalavasta scenario as input, but foresees a lower domestic electricity demand and lower H_2 production.

Table 3.1: Summary of storage results calculated by OPERA and COMPETES for CA2030

Electric vehicle storage	Size	Annual Volume	FCE[a]	Charge power	Discharge power
	GWh	GWh	#	GW	GW
OPERA	45	1500	24	10.1	0.5[b]
COMPETES	31	1450[c]	48	1.5	1.5
Total electricity storage	**Size**	**Annual Volume**	**FCE**	**Size/Demand**	**Volume/Demand**
	GWh	GWh	#	%	%
OPERA	64	1946	30	0.05%	1.4%
COMPETES	31	1461	48	0.02%	1.1%
H_2 Underground storage	**Size**	**Annual Volume**	**FCE**	**Charge power**	**Discharge power**
	GWh	GWh	#	GW	GW
OPERA	10	21	2	0.01	1.3
COMPETES	66	900	14	0.16	0.77
Total H_2 storage	**Size**	**Annual Volume**	**FCE**	**Size/Demand**	**Volume/Demand**
	GWh	GWh		%	%
OPERA	42	1157	28	2.3%	62.2%
COMPETES	66	900	14	1.0%	13.4%

a) FCE is Full Cycle Equivalent i.e. the ratio between the annual volume stored and the size of the storage medium;
b) Discharge is to vehicles only and not back to the grid (V2G);
c) Including 197 GWh fed back into the grid (V2G).

Table 3.2: Summary of energy storage results calculated by OPERA and COMPETES for the NM2050 reference scenario

Electric vehicle storage	Size	Annual Volume	FCE	Max. charge power	Max. discharge power
	GWh	TWh	#	GW	GW
OPERA	975	30	31	24.3	57.5
COMPETES	1037	33	32	38.4	38.4
Range (min-max)[a]	969-1037	20-50	20-48	24.3-38.4	38.4-57.5
Total electricity storage	**Size**	**Annual Volume**	**FCE**	**Size/Demand**	**Volume/Demand**
	GWh	TWh	#	%	%
OPERA	975	30	31	0.25%	7.6%
COMPETES	1037	33	32	0.30%	9.6%
Range (min-max)[a]	975-2074	31-66	29-48	0.25-0.60%	8.0-19.0%
H_2 Underground storage	**Size**	**Annual Volume**	**FCE**	**Charge power**	**Discharge power**
	GWh	TWh	#	GW	GW
OPERA	2893	17	6	13.2	21.2
COMPETES	1536	22	14	4.5	8.6
Range (min-max)[a]	1268-4280	14-34	4-16	3.8-6.7	8.6-23.4
Total H_2 storage	**Size**	**Annual Volume**	**FCE**	**Size/Demand**	**Volume/Demand**
	GWh	TWh		%	%
OPERA	2944	26	9	3.2%	28.6%
COMPETES	1536	22	14	2.0%	28.7%
Range (min-max)[a]	1268-4280	19-41	8-16	1.6-5.6%	24.0-44.4%

a) These are the minimum and maximum values found in the sensitivity runs of COMPETES and OPERA combined.

Table 3.2 shows a summary of the storage results calculated by OPERA and COMPETES for the NM2050 reference scenario. The main conclusions from the analyses of the reference scenario as well as of some sensitivity cases for NM2050 are outlined below.[46]

Electricity storage by electric vehicle batteries

In both models electricity storage is dominated by batteries of electric vehicles (EVs). Table 3.2 shows a total annual storage volume of all EV batteries in NM2050 that is fairly similar in both models (30-33 TWh). In the model outcomes, other technologies besides EV batteries hardly play any role in electricity storage. It is foreseen that by 2050 about 10 million EVs will have about 1000 GWh storage capacity. This capacity is first of all used to store electricity to be used by EVs for mobility services, while the share used for vehicle-to grid (V2G) storage services is often lower.

An important difference between the models (and outcomes) is that of the 33 TWh EV battery storage volume in COMPETES, almost 31.8 TWh refers to gross battery charges for driving (including storage losses), while 1.2 TWh is fed back to the grid (V2G). In OPERA, on the other hand, out of 30 TWh EV battery storage volume, approximately 16.7 refers to net battery charges for EV driving (including storage losses), while the amount of V2G transactions is estimated at 13.3 TWh.[47]

The electricity storage in EVs is characterised by about 30-40 effective charge/discharge cycles per year. A sensitivity case where we excluded V2G in OPERA resulted in more use for stationary batteries, but also for a higher and more continuous H_2 production, with effectively less demand for H_2 storage.

Due to data limitations OPERA and COMPETES do not sufficiently take into account all costs and possible limitations of EV battery storage transactions, such as the costs of the EV (dis)charging infrastructure or the preferences of EV owners regarding minimum/maximum levels of EV battery charges and V2G discharges.

H_2 underground storage

The results show a clear, significant role for large-scale H_2 underground storage, notably in annual volume terms

(17-22 TWh). This type of energy storage, however, is not typical seasonal storage – such as the current storage of natural gas. An indicator for this are the annual full cycle equivalents (FCEs) of H_2 underground storage ranging from 6 to 14.[48]

This requires some explanation of the causes and effects in the model. Although solar and wind VRE have a seasonal pattern, the net residual power load does not show a clear seasonal pattern. Instead it shows large, short-term variability of the residual power load. As noted, this leads to heavy short-term fluctuations of electricity prices and, subsequently to short-term fluctuations in mainly H_2 supply from electrolysis (P2H$_2$) and, therefore, to a need for absorbing this produced H_2 in storage facilities.

As stated earlier, the H_2 storage need is also highly determined by the patterns in H_2 demand. Whereas in COMPETES the H_2 demand profile in NM2050 is assumed to be flat, the storage need is thus determined by the supply profiles. For OPERA, the demand for hydrogen has a lower and flatter seasonal pattern. This is largely due to a lower heat demand in 2050 due to insulation and also due to the contribution of other heat sources besides hydrogen, such as electricity, geothermal and ambient heat. This appearance of short-term energy storage needs – and the disappearance of a clear seasonal pattern – is also observed in the recent report by DNV GL on seasonal storage[49].

A general result is that the required size of this storage medium is therefore much smaller (1.5-2.9 TWh; 2-3% of total H_2 demand) than the total annual volume stored at 17-22 TWh (20-30% of total H_2 demand).

In summary, the marked differences in the model outcomes of OPERA and COMPETES is due to the differences in the factors mentioned above: seasonality of demand, and difference in sources and variability of H_2 supply. This affects the annual full cycle equivalents of H_2 storage being higher in COMPETES (14) than in OPERA (6).

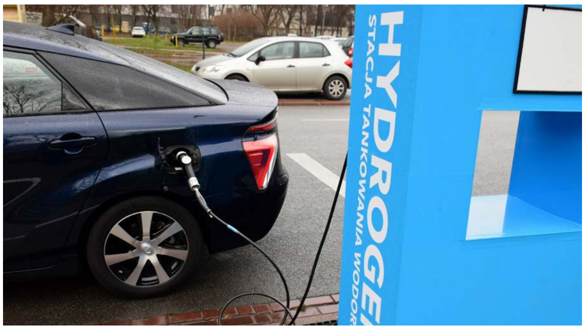
46 A detailed account of sensitivity cases can be found in the full report: Sijm et al 2020, The role of large-scale energy storage in the energy system of the Netherlands, 2030-2050, TNO 2020 P11106.

47 The gross battery charges for EV driving (including storage losses) in OPERA, however, are largely similar to these charges in COMPETES, i.e. approximately 34 TWh and 32 TWh in NM2050, respectively.

48 For pragmatic reasons we have used the techno-economic parameters of H_2 storage in salt caverns as the proxy (or default option) for H_2 underground storage, while we did not include the alternative option of H_2 storage in depleted gasfields. Despite some techno-economic differences between these two H_2 underground storage options, from a modelling perspective, the parameters of H_2 storage in salt caverns are largely similar to H_2 storage in depleted gasfields. Therefore, our reported modelling results regarding H_2 underground storage apply largely to H_2 storage in both salt caverns and depleted gasfields.

49 DNV GL (2020). The promise of seasonal storage. Position Paper, DNV GL Netherlands, Group Technology & Research, Arnhem.

Hydrogen storage in the transport sector



In OPERA hydrogen storage in the transport sector – by means of H_2 vehicles and H_2 filling stations – plays a major role in NM2050, notably in volume terms. Hydrogen storage in the transport sector, however, refers primarily to hydrogen charged and used for mobility services rather than flexibility services to stabilise the hydrogen balance.

Hydrogen-to-power

In comparison with Berenschot and Kalavasta, both OPERA and COMPETES foresee a minimal role for Hydrogen-to-Power as the low net efficiency of this cycle renders this option more costly than alternative flexibility options such as demand response or electricity trade. This relates to the fact that in OPERA and COMPETES uncertainties in supply are not taken into account. The models assume perfect foresight. No provisions for system adequacy (i.e. back-up) are then included, which in turn on efficiency grounds avoid deploying the power > hydrogen > power cycle.

Underground compressed air energy storage

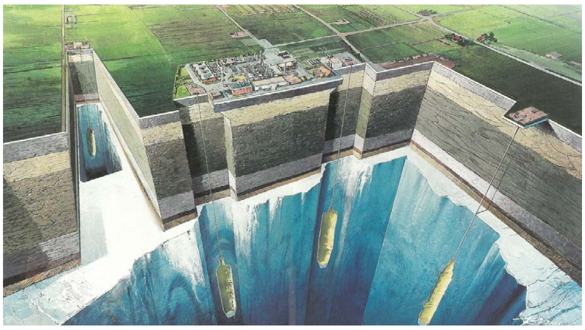


Illustration by Günther Radtke, © DEEP.KBB GmbH

In neither model does there seem to be a role for large-scale electricity storage such as compressed air energy storage (CAES/AA-CAES). Apart from specific modelling characteristics and limitations, the major reason for this finding is that alternative flexibility options in the model have a better techno-economic performance to meet the flexibility needs of the Dutch power system. Note, however, that the current study focusses on the flexibility needs due to the variability of the residual power load – notably VRE supply – and did not consider other stability and flexibility needs of the power system.

Cross-border electricity trade

An important difference relates to import and export of electricity in the original NM2050 scenario by Berenschot and Kalavasta and the model results from COMPETES and OPERA[43]. COMPETES optimises the import/export profiles of electricity based on cross-border trade, and these profiles are also adopted within OPERA modelling.

According to COMPETES, cross-border electricity trade is a major flexibility option to meet the variability of VRE, with annual electricity exports of 83 TWh and imports of 40 TWh, resulting in a net export position of about 43 TWh. This requires a substantial cross-border interconnection capacity of approximately 33 GW, larger than the 15 GW envisaged by Berenschot and Kalavasta.[43] A sensitivity case where all cross-border electricity trade was excluded resulted in storage requirements for electricity and hydrogen that are up to 60% larger in volume.

Demand response

COMPETES shows that there is a large, cost-efficient potential to meet short-term fluctuations in the residual electricity load by means of demand response, in particular of electricity demand for power-to-mobility (EVs), power-to-hydrogen and power-to-heat in both households and industry. The main challenge or uncertainty, however, is to which extent this flexibility potential can be actually realised. Sensitivity cases by COMPETES show that excluding all demand response options (including power-to-hydrogen) results in a significantly higher need for electricity storage volumes, notably by vanadium redox batteries (11-13 TWh). This in turn reduces the need for hydrogen storage to zero.

Variable renewable energy capacities, curtailment, electricity trade and storage

In COMPETES, domestic electricity demand in NM2050 turns out to be relatively low (compared to installed VRE capacities), resulting in a large amount of hours with a large domestic VRE surplus – before curtailment – and low electricity prices. This in turn leads to large net electricity exports by the Netherlands and large amounts of VRE curtailment (as major flexibility options besides demand response).

While VRE curtailment is still negligibly small in CA2030, it is rather substantial in NM2050. About 73 TWh of VRE output generation is curtailed, i.e. 16% of total VRE supply before curtailment. As the operational (marginal) costs of offshore wind are slightly higher in COMPETES than of onshore wind or solar PV, COMPETES prefers to curtail offshore wind as the first option. Consequently, in COMPETES almost all VRE curtailment in NM2050 is assigned to offshore wind.
In one of the sensitivity cases a substantial reduction of the (assumed) installed VRE power generation capacities in COMPETES (about 40%) resulted in less VRE curtailment (33% reduction) and a significant shift from large net electricity exports to large net imports, but hardly or not to significant changes in storage of electricity or hydrogen.

In summary

In 2050 the flexibility requirements for electricity are dominantly provided by cross border trade and storage in electric vehicles. Underground storage of hydrogen will be a significant contribution to the energy system in 2050. Hydrogen storage will be mostly underground. Although comparable in size to electricity storage, the number of discharge cycles is much lower. The size required by this storage is assessed at 1.5-3TWh, requiring approximately 10 to 20 caverns (depending on cavern size).

3.2.3 Reflections on models, outcomes and next steps

A limitation of both models is that they optimise over a single year only and not over a time horizon. Moreover, as the models aim for minimal cost, they do not allow for any redundancy in the system to cover for events that jeopardize the security of supply (e.g. exceptional weather conditions, supply disruption, etc.) and to meet other policy-strategic considerations (e.g. strategic reserves, energy independence, etc.).

The optimisation models OPERA and COMPETES are based, among others, on the assumption of perfect foresight and, hence, they do not consider uncertainties or risks regarding, for instance, capacity investments or security of energy supply. In addition, these models do hardly or not address other social or behavioural issues such as the social acceptance of energy technology innovations, the long lead times for implementing investments in (cross-border) transmission and distribution networks, or the practical limitations to achieve the estimated potentials of demand response.

In the current study, the analyses by OPERA and COMPETES are primarily focused on the supply of flexibility options – including energy storage – due to the variability of the residual power load (defined as total electricity demand minus electricity supply from VRE sources). This implies that the study does not consider the need for flexibility options (such as electricity storage) due to either the uncertainty (‘forecast error’) of the residual load – resulting in the need for flexibility on intraday/reserve markets – or the local congestion (overloading) of the electricity distribution network (resulting in local congestion and flexibility markets to deal with these grid overloads). In addition, it does not include the need for electricity storage (or alternative options) to address other power system issues such as inertia, black starts or frequency control. Although the day-ahead or spot market is by far the most important market (in terms of power and trade volumes), the other markets (intraday, reserve) or system functions may offer interesting revenue streams for some types of electricity storage such as (AA)-CAES.

> ‘Results do show a significant role for underground hydrogen storage, notably in terms of annual volume of hydrogen stored (17-22 TWh; ~20-30% of total hydrogen demand).

Moreover, the model analyses in the current study are focussed solely on the flexibility (storage) needs during a typical (‘normal’) weather year and do not consider these needs during more extreme weather years, e.g. with a Dunkelflaute.[50] In addition, the present study does not analyse energy storage needs due to political-strategic considerations, for instance to reduce uncertainties and risks of relying on energy imports to ensure security of energy supply. Finally, the model analyses in the present study are focused on the role of electricity and hydrogen storage, but do not consider other means of energy storage such as heat storage in industries, households and district heating systems.

By specifically including flexibility options such as demand response and electricity trade, this study includes elements that were not explicitly part of the study by Berenschot and Kalavasta.[43] This, and the larger emphasis on minimising social costs, leads to some differences in the envisaged energy system in 2050, including the role of energy storage. Together with the limitations indicated above, these differences offer interesting topics for further studies aiming to develop a sustainable energy system that combines security of supply with cost-effectiveness and practical/realistic timelines for infrastructural transitions.

3.3 THE MARKET POTENTIAL FROM PROJECT DEVELOPMENT PERSPECTIVE

3.3.1 Compressed Air Energy Storage

CAES systems are designed to be competitive in delivering a suite of flexibility services that are valued by utility companies, owners of generation assets, and grid operators. They can generate revenue from two main groups of services: arbitrage, i.e., providing electricity traders a means to earn money by levering the hourly price differences on electricity markets; and ancillary services, such as frequency regulation, reserve power, black start, load following, and synchronous inertia, that are procured by grid operators and asset owners of generation assets to manage grid stability.

50 Energy storage needs due to extreme weather conditions or policy-strategic considerations have been analysed recently by Berenschot and Kalavasta by means of the Energy Transition Model (ETM).[43]

An exploratory economic analysis indicates that a price arbitrage-only business case for diabatic CAES may not be viable. Due to a significant price spread requirement to break-even operationally, diabatic CAES only charges at a very low electricity price in the analysis, which results in a very limited number of operational hours, and thus limited revenues. Although the business case for adiabatic CAES shows more operational hours than for diabatic CAES, due to a less severe price spread requirement, revenues are not sufficient to realise a positive business case.

An important limitation in the analysis is the assumption of full-load only operation mode, which leads to economically suboptimal simulated asset operation. CAES is however well-suited to operate at lower power, and can do so with minimal efficiency loss at power outputs down to 15% of rated power. Furthermore, the exploratory analysis does not include additional (complementary) revenue streams (e.g. from ancillary services such as grid balancing, redispatch, black start, etc.), and excludes a multi-year stochastic analysis of the variability of renewables feed-in and its influence on electricity prices. Hence the total revenue is probably underestimated significantly. Several recent studies show the basis of a positive business case and the importance of co-optimising energy revenues with ancillary services.[51, 52, 53] Hence, to be able to conclude on the economic viability and business case of the diabatic and adiabatic CAES technology, additional key business models should be assessed in addition to the day-ahead wholesale market business model of this study.

3.3.2 Underground Hydrogen Storage

An exploratory analysis of the economics of a flexible hydrogen production asset with storage in a salt cavern vs. continuous hydrogen production indicates that the lower electricity costs in the business case for the flexible production asset, due to reaped benefits from being able to "overproduce" (and store) hydrogen at low electricity prices, appears insufficient to compensate for the extra investments in a larger electrolyser, the storage and the related equipment, and the higher operational costs. Especially an increase in the amount of hours with low electricity prices (due to a larger installed capacity of solar and offshore wind) and further developments in electrolyser technology favour the business case of flexible hydrogen production and storage, and provide perspective on a viable business case. Additional revenue streams (to selling hydrogen) can be generated by including alternative benefits of storage in the business model that were outside the scope of this study. Examples are earnings from offering flexibility services to the electricity system with the up- and down- regulating capacities of the electrolysers, and remunerations for offering security of supply of hydrogen to market players and society.

3.4 MARKET POTENTIAL OF UHS AND CAES

In summary, the studies agree there is a large technical potential for energy storage in the subsurface in caverns and depleted gas fields. A part of this technical potential can be implemented in the energy system as commercial projects. The potential explored in this study indicates electricity storage of approximately 1 TWh of installed battery capacity in 2050, clearly dominated by storage in electric vehicles. For underground hydrogen storage this is approximately 1.5-3 TWh of storage volume capacity. With respect to earlier studies this estimate is relatively conservative.

The need for storage technologies in the future energy system is clearly strongly depending on the market modelling assumptions and future scenarios, especially related to the amount of variable renewable energy supply options in the energy mix (i.e. wind and solar) and assumptions on competing flexibility options.
What also stands out is that from a system perspective energy storage contributes to achieving lowest cost system configurations. On the other hand the business case for both CAES and underground hydrogen storage for the short term, and just based on arbitrage, is not obvious and would require additional revenue streams to become profitable from a project developers perspective.

This discrepancy between long term value for the energy system and current absence of viable business models for energy storage is an important challenge towards implementation. And brings the questions whether the current market structure and incentives are well enough suited to capture the value of energy storage.

From a modelling perspective this also shows limitations of the energy system models to capture the possibility of energy storage technologies operating on different markets to stack value and create a viable business model.

51 Clara F. Heuberger, Iain Staffell, Nilay Shah, Niall Mac Dowell (2017). A systems approach to quantifying the value of power generation and energy storage technologies in future electricity networks, Computers & Chemical Engineering, Volume 107, 2017, Pages 247-256.
52 Guerra, O.J., Zhang, J., Eichman, J., Denholm, P., Kurtz, J., & Hodge, B. (2020). The Value of Seasonal Energy Storage Technologies for the Integration of Wind and Solar Power. Energy and Environmental Science.
53 Van Hout, M., Koutstaal, P., Ozdemir, O., and Seebregts, A. (2014). Quantifying flexibility markets, ECN, ECN-E--14-039.

4. LEGAL AND SOCIETAL EMBEDDING

Successful realization of projects for large-scale storage of energy in the subsurface requires that legal and societal elements are productively incorporated into the design of such projects from the start. New storage initiatives should be sufficiently supported by clear laws and policies, permit procedures and contracts. Furthermore, previous experience with subsurface initiatives has shown that the response of the local community towards a large-scale subsurface energy storage initiative has a decisive impact on the success of the project.

In this project the legal and societal challenges were explored by answering three questions:

- How does the current legal framework, and more specifically the permit procedures, support the development of large-scale subsurface energy storage projects, in particular CAES and UHS?
- What is needed to meet the societal requirements (at the generic level and the project level) of large-scale energy storage in the subsurface?
- How does the legal framework interact with the societal requirements for the development of large-scale subsurface energy storage projects?

To answer the questions above, the permit procedure, and legal developments corresponding to the permit procedure for large-scale subsurface energy storage were studied. In addition, a literature study was carried out into the societal embedding of large-scale subsurface energy storage projects. These studies were complemented with 8 interviews with professionals involved in the development of large-scale subsurface energy storage. In the interviews we focused on their experience with permit procedures and stakeholder management. In the next three sections we summarize the conclusions related to the legal and societal challenges regarding large-scale subsurface energy storage. A more in-depth description of the analysis can be found in the report of work package 3 of the LSES project and the two background reports that are included as appendices of that report.[54]

> ‘Involve the local community well before, during and after the decision-making process.’

4.1 LEGAL REQUIREMENTS FOR SOCIETAL EMBEDDEDNESS AND PARTICIPATION STRATEGY

The New Environmental Act sets minimum requirements that the participation process must meet. The Environmental Act demands that citizens, businesses, interest groups and administrative bodies are involved in the exploration phase and prescribes when the local community is given the opportunity to present their views. The competent authority has the responsibility to ensure that all relevant parties are reached as effectively as possible. Although the current rules structure the process and provide guidance, the interviewees indicate that following the legal requirements does not guarantee societal embeddedness of large-scale subsurface energy (storage) projects. The legal framework leaves room for the range of minimum compliance to cocreation.[55]

One of the key results from both the literature study and from the interviews with the various operators is the importance of involving the local community well before, during and after the decision-making process. At the start of a project, the societal playing field (stakeholder analysis, cultural and historical background, community dynamics) must be taken into account. From this knowledge, a level of participation and the participation strategy could be determined. The law facilitates the participatory process, but with minimal requirements. The Environmental Act will include, for storage projects, new requirements for participation at an early stage (the exploration phase) in addition to the decision-making phase. The new rules, too, have little substance and leave a great deal of room for further interpretation. Consequently, the level of participation must not be determined from legal frameworks, but from the societal playing field and in relation to the overall project strategy. For each phase, and even during the phases, the strategy needs to be revisited. Involving stakeholder is important in all the phases, from the early preparations till the realization.

4.2 IMPORTANCE OF POLICY AMBITIONS

The literature study shows the importance of discussing the importance, usefulness and necessity of LSES at various levels: national, regional and local. In the current situation, national government focus on their facilitative role. To further support LSES governments at all levels should formulate policy ambitions and support initiatives

54 Winters, E., Puts, H., Van Popering-Verkerk, J., and Duijn, M., 2020. *Legal and societal embeddedness of large-scale energy storage.* TNO report 2020 R11116

55 Grift et al. (2020) discovered from a Q-sort three perspectives of professionals related to community engagement: cocreation, control by project management, and legal compliance.

which fit with these ambitions. Because of the missing link between national regulation and local projects, policy-related discussions take place around a specific project at the local level.

In this study, we found a need for supporting energy policy at the national as well as the regional and local level. An important policy instrument for large-scale subsurface energy storage is the Vision on Subsurface Planning (In Dutch: *Nationale Structuurvisie Ondergrond - STRONG*), in which subsurface energy storage in depleted gas fields and salt caverns is anchored.[56] Subsequently, it is important that energy storage is also sufficiently embedded in provincial/regional and municipal/local policy related to the ambitions on sustainability and the energy transition. If types of energy storage such as CAES and UHS are given a role in local energy policies and environmental plans, it will give the local community and stakeholders the opportunity to submit their views and discuss the role of this type of storage in their immediate environment.

Formulating policy ambitions is also a participative process, in which societal engagement must be guaranteed and by doing so, local projects are less burdened with questions around the importance of these types of storage in general, but can focus on the discussion that is relevant for the specific project; e.g. alternative routing for above-ground pipelines, limiting noise pollution etc.[57] During the exploration phase of a concrete subsurface energy storage project, the discussion about the usefulness and necessity of storage has then already been conducted with the relevant stakeholders at both national and local level. The focus can then be on the usefulness and necessity of the specific project.

4.3 PERMIT PROCEDURES

The (pre-) development phase of large-scale subsurface energy storage projects is long due to the complexity of these projects, the long duration of the permit process to get all required permits, and the interaction with the local community. Given the limited amount of LSES projects there is, according to the interviewees, a lack of experience among developers and the competent authority and their advisors with the development and decision-making process for large-scale subsurface energy storage. More experience would help to set up a more effective decision-making process. Building on a solid knowledge base, getting routines in the permit procedures as well as providing clarity on the different roles of all bodies that are involved in evaluating and granting the permits are essential elements in speeding up the decision-making process.

The Minister of Economic Affairs and Climate has a decisive role in the duration and the quality of both the licensing procedure and the participation process. At the same time, the fact that the Minister has to combine different roles and responsibilities (policy maker, coordinating body and competent authority) in different stages of project development is very challenging and previous research shows that it could cause distrust in the fairness of the decision making process[58]. The new coordination regulation that applies to LSES projects[59] is intended to strengthen the governing role of the Minister of Economic Affairs and Climate and provides tools to do so.

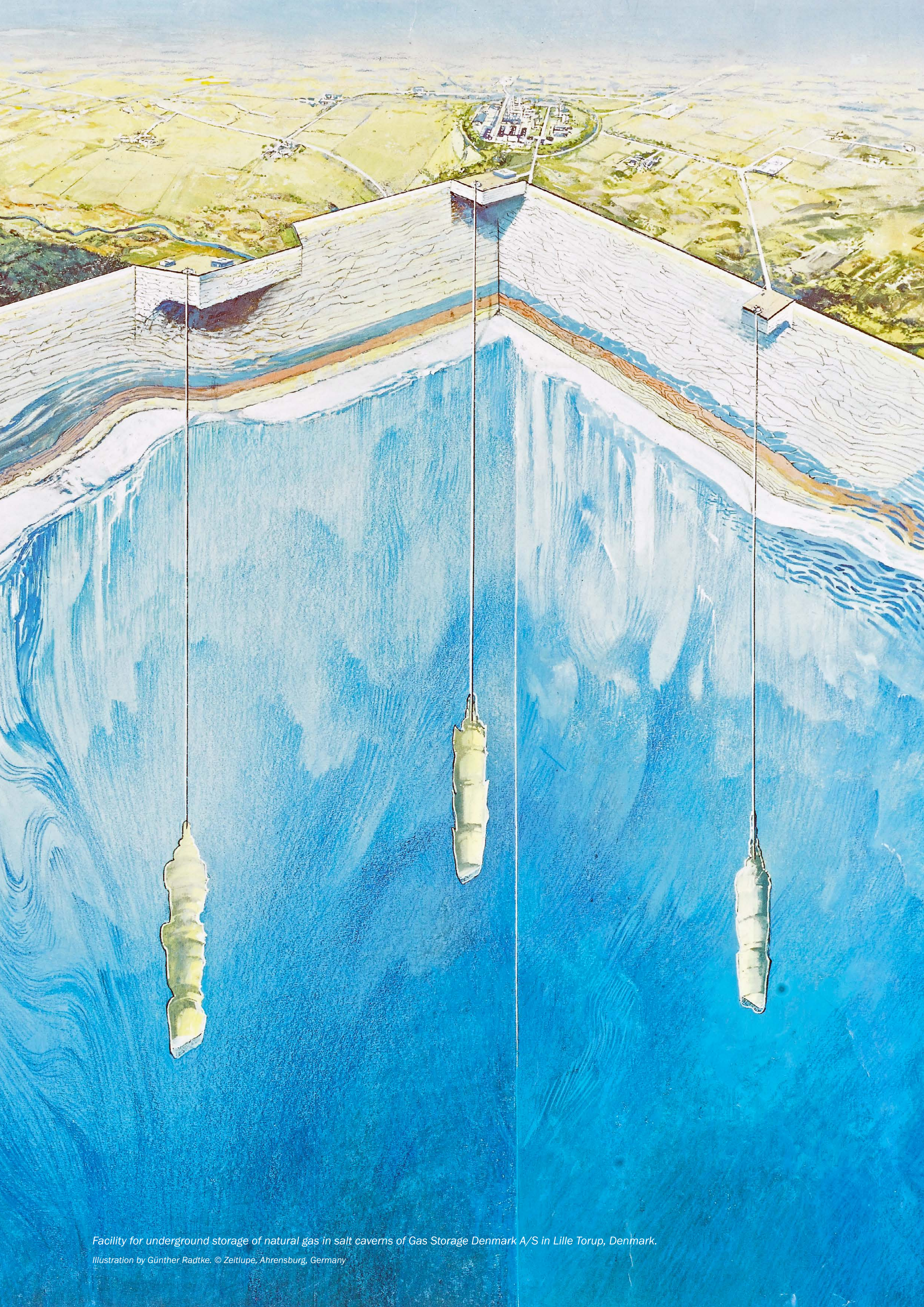
> ‘Formulating policy ambitions is also a participative process, in which societal engagement must be guaranteed.’

56 Structuurvisie Ondergrond (2018), p. 69

57 Barend van Engelenburg and Hanneke Puts, Lessons learned from CCS development in the North of the Netherlands, 2015 at globalccsinstitute.com

58 Puts, Hanneke and Celine Brus (TNO), March 2020. *CO_2 Storage Best Practice Indications from Rotterdam Area. Lessons Learned from a long-term collaborative research process with a group of Dutch citizens: towards societally embedded CO_2 geological storage projects.* Deliverable D5.4 from the EU-project ENOS. www.enos-project.eu

59 Article 16.7 Environmental Act in conjunction with Article 3.5 of the new General Administrative Act



Facility for underground storage of natural gas in salt caverns of Gas Storage Denmark A/S in Lille Torup, Denmark.

5. FUTURE PERSPECTIVES

Based on the research conducted we see several important building blocks that could bring the technologies under study towards fast track implementation.

TECHNOLOGY

MARKET

LEGAL & SOCIETAL

5.1 TECHNOLOGICAL DEVELOPMENT PATH AND KEY CHALLENGES TO BE ADDRESSED

The following key challenges must be addressed to bring CAES and UHS towards commercial-scale realization.

Compressed air energy storage
Although diabatic CAES (D-CAES) is mature technology, additional cost reduction can be achieved by optimally recuperating waste heat at generation. For D-CAES there is innovation potential in transitioning from co-firing natural gas to hydrogen to fully decarbonize electricity (re)generation, and in the optimization of design to deliver services to different markets simultaneously while maximizing revenue.

Adiabatic CAES (AA-CAES) holds the promise of higher round-trip (power-to-power) efficiencies of up to 70%. Further research and development is required though, in particular on efficient thermal storage of heat at the very high temperatures involved (up to 580 °C), which is challenging and costly.

Fast-cycle storage of air and hydrogen in caverns
To gain a better understanding of the risks of fast-cycle storage of air and hydrogen, a logical follow-up to the assessment on the geomechanical effects of cyclic injection and withdrawal on salt cavern stability and integrity in this project would be to extend the assessment to the well system through which the gas (compressed air, hydrogen) is injected and withdrawn from the cavern. For this purpose, a geomechanical model of the wellbore and near well area could be developed to simulate the effects of cyclic gas injection and withdrawal on durability and integrity of wells. In particular, the formation of micro-annuli (i.e. circumferential fractures) at interfaces between the salt and well (at the last cemented casing shoe and along the wellbore) could then be examined, as well as the potential for leakage of air along those micro-annuli and through annular cement.

> ‘There are many depleted gasfields in the Netherlands that could potentially be good candidates for underground hydrogen storage’

Practical potential and technical performance of specific fields for H_2 storage
Although the current underground storages for natural gas are good quality reservoirs they require a large cushion volume to deliver high performances, mainly because of their large size and great depth. There are many other potential gasfields in the Netherlands that could also be good candidates for UHS. A more detailed investigation of their practical potential and technical performance on a field-by-field basis requires better analytical and numerical models to be developed that are capable of simulating:

- Multi-phase (fluids and gases) and multi-component (e.g. hydrogen and natural gas) flow in the reservoir, near-wellbore region and well;
- Thermal effects that may occur during injection cycles due to the difference in pressure and temperature between the injected gas as it expands on entering the reservoir and that of the reservoir itself, and cushion gas in it; and
- Geochemical and biochemical reactions of hydrogen with rocks, fluids and microbes in the reservoir

On the geochemical reactions with hydrogen in reservoirs, experimental research (literature) and numerical modeling studies indicate that pyrite reduction as a result of H_2 storage may occur, leading to H_2S formation in the gas phase, which may affect safety, materials selection, facility design and economics. To accurately assess the risk of H_2S formation, and the influence of H_2S scavenging minerals such as siderite the predictive power of geochemical models must be improved. This can be achieved by incorporating kinetic rates at high temperatures and high H_2 partial pressures. Targeted experimental research is required to obtain such kinetic rates, and to assess the effects of exposure of rocks, wellbore materials and interfaces and its impact on their integrity and durability under pressure and temperature conditions typical for H_2 storage.

Furthermore, recent work on microbiological reactions with hydrogen in reservoirs indicates that sulphate reduction and methanogenesis may both take place, leading to loss of hydrogen and production of H_2S and methane. Under which conditions these processes occur in reservoirs, and the rate at which they consume hydrogen to produce H_2S or methane, will require further (experimental) research.

5.2 MARKET DEVELOPMENT PATH

From technical potential to market potential...
In recent studies the technical potential for the large scale energy storage options compressed air energy storage and underground hydrogen storage has been estimated. With this study a new perspective has been added towards the possible future market potential and which factors have an important role to play in the magnitude of this potential.
The next step is to define the potential market application for storage in certain locations/regions that are matched in time and space with energy infrastructure with viable market prospects. In this step market critical factors are assessed that determine whether a certain storage site has potential market application in the current or future energy infrastructure. This approach should be spatially explicit on the proximity of suitable underground stores with existing and future renewable energy production, electricity grid, hydrogen production locations, hydrogen demand and conversion centres, and transport infrastructure.

... and towards commercialization
Then most likely commercial and repeatable market introduction of the technologies under study is after 2030, with CAES and H_2 storage in caverns being more likely to be introduced earlier than hydrogen storage in depleted reservoirs. The strategy is to bring the technologies into the pilot/demonstration phase within the next years. Lessons learned with these pilots can be integrated in projects that see commercial application from 2030 onwards; possibly even sooner. The focus of this project is to reduce the technology and market risks for both hydrogen and compressed air energy storage technologies. This will reduce the costs and timelines needed for market penetration of these technologies.

The estimate is that the market readiness of hydrogen storage and CAES (conventional and advanced) is currently too low. The business case for large-scale subsurface energy storage will be strongly supported by the further roll-out of variable renewable energy technologies, such as wind and solar in the Netherlands and surrounding countries. But even then the development of innovative business cases and market structure evolutions is probably required to build a viable business case.

Future business case analysis and business models for CAES
An important limitation in the analysis is the assumption of full-load only operation mode. Together with the hourly decision-logic and minimal risk acceptance level, the fill level of both the diabatic CAES and adiabatic CAES therefore shows economically suboptimal asset operation. Power discharge occurs as soon as the required marginal price spread is met. Subsequently, the stored energy is sold for the electricity price that generates minimum revenue. Furthermore, our analysis excludes a multi-year stochastic analysis of the variability of renewables feed-in and its influence on electricity prices is not included.

> ‘The strategy is to bring the technologies into the pilot- and demonstration phase in the next ten years’

Several recent studies show the basis of a positive business case and the importance of co-optimising energy revenues with ancillary services.[51, 52, 53]
To be able to conclude on the economic viability and business case of the diabatic and adiabatic CAES technology, additional key business models should therefore be assessed in addition to the day-ahead wholesale market business model of this study, based on multi-year stochastic analysis of the variability of renewables feed-in.

Future business case analysis and business models for UHS
Complementary revenue streams are needed to make investments in flexible hydrogen production with underground hydrogen storage (UHS) in a salt cavern pay back. Results of this research and earlier work shows that large-scale energy storage could offer essential services to society in the form of strategic energy reserves and security of supply. The system value of contributing to system adequacy is currently not clearly translated into a market value. And as we learned that value stacking is critical for achieving a viable business case for energy storage projects it would be of high interest for project developers to provide adequacy as a service and capture market value from this offering.

Further research could focus on the potential value of (and business models for) additional revenue streams, such as:

- Offering stability and flexibility to the electricity system with the up- and down- regulating capacities of the electrolysers (TSO and DSO), e.g. by services like aFRR and FCR from TenneT, the Dutch TSO;
- Avoid or reduce investments in grid capacity expansion by TSO and DSO;
- The value of services to society in the form of strategic energy reserves and energy system adequacy (security of supply).

Integrated energy system model improvements
Some key limitations are identified regarding the applied energy system models that are used to estimate the long term market potential. Important improvements would work towards a sustainable energy system that combines security of supply with cost-effectiveness and practical/realistic timelines for infrastructural transitions. This entails that uncertainties and risks related to (extreme) weather conditions are factored in and preferences for policy-strategic considerations are included (e.g. strategic reserves, energy independence, etc.). An improvement for hydrogen would include sector specific and realistic demand profiles. Finally, spatial explicit energy system modelling with high(er) resolution would also capture the challenge of the energy system transition better. Especially in relation to energy storage as (subsurface) energy storage potential is bound by geographic and geological conditions. Moreover, the market opportunities for energy storage are also geographically defined, i.e. due to the location specific local/regional grid congestion, VRE production potential and demand centres.

5.3 LEGAL AND SOCIETAL EMBEDDING

To successfully realize projects for large-scale storage of energy in the subsurface the legal and societal elements must be productively incorporated from the start. New storage initiatives should be sufficiently supported by clear laws and policies, permit procedures and contracts, and stakeholders (in particular the local community) should be involved well before, during and after the decision-making process. Our recommendations towards achieving this are as follows:

- Connect participation at the (inter)national policy and business level (national government and energy companies) to stakeholder engagement at the project level (local and regional government and local communities and stakeholders).
- Develop a participation strategy for large scale energy storage projects as part of the overall process management approach. This participation strategy could differ per development stage, depending on the type of technical and societal challenges at stake.
- Start participation early in the process, i.e., in the exploration phase as required by the new Environmental Act, but preferably even earlier. Be aware of the current societal embeddedness of the project, i.e. by assessing the societal requirements at different stages of the development and decision making process.[60] Use this information to design and revisit the participation strategy.
- Communicate with the stakeholders on which topics they can participate. The new law offers residents the opportunity to come up with alternative solutions. If policy choices have already been made regarding these possibilities, this should be clearly communicated. This prevents the stakeholders from coming up with solutions that are not considered and helps them to contribute to the aspects of the project that are still open for discussion.
- The operator and competent authority should deliberate at the start of the process on the division of roles. Deliberate questions like: who facilitates and organizes the participation? What is the role of the project initiator(s) and of the competent authorities in the participation process? And are independent third parties needed in this process? This division of roles must be clearly communicated, so that third parties know which questions and requests they can address to which party.
- Develop policy ambitions related to large scale energy storage at all levels, i.e. as part of the ambitions on sustainability and the energy transition, and communicate to the wider public on the usefulness and necessity of this type of storage and storage in general.
- Develop policy ambitions with regard to subsurface energy storage at the *regional level,* policy ambitions are needed with regard to subsurface energy storage. Incorporate these regional ambitions in, for instance, a regional spatial development plan, a regional vision on subsurface planning or regional socio-economic plans.
- Involve local residents and other relevant stakeholders at an early stage and let them participate in the development of regional plans.
- Ensure strong collaboration between the different policy levels in the development and decision-making process of LSES projects, because it is crucial for an inclusive decision making process in which all interests and perspectives are weighted.

60 As part of the European research project ACT Digimon, TNO is currently coordinating the development of the so-called Societal Embeddedness Level (SEL) Methodology, which indicates what the societal requirements are towards small-scale implementation of an innovation. The SEL is strongly connected to the TRL system and supports researchers and initiators insight in the societal factors that play a role in the development of a technology towards small scale implementation, upon which a strategy can be developed to improve the societal embeddedness of an innovation. The publication of a Guideline for applying the SEL Methodology to CCS was planned for July 2020.

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