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Underground storage

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ABSTRACT

The subsurface of the Netherlands has been a prolific source of raw materials and energy, key to the country's economic, technological and welfare development. However, due to the significant decline in domestic hydrocarbon production, especially natural gas, and despite the increase in geothermal projects, the subsurface is transitioning from being a provider of energy and resources to a provider of storage services, such as underground natural gas storage. This shift aligns with the current transition to renewable energy, increased energy imports, and global environmental and climate challenges.

Recent studies on the future energy system of the Netherlands point to the need for a (large) underground storage capacity, which can also facilitate the permanent storage of residues from energy production and conversion (e.g. wastewater and CO_2). This need arises from traditional variations in energy demand, such as seasonal heat demand, and the increased share of fluctuating energy production from renewable sources like wind and solar. Aboveground facilities can provide short-term storage, but the surface space required for mid-to-long-term storage would be extensive, making underground storage solutions essential.

In the Netherlands, there is a rich and broad knowledge of the subsurface derived from long-standing and large-scale exploration and production activities for natural resources. This knowledge allows for the potential use of large underground volumes in depleted oil and gas fields, aquifers, and engineered cavities. Coupled with ongoing research and development of various storage technologies and the growing need for flexibility services to balance the system and secure energy supply, this makes it feasible and attractive to store large amounts of energy (GWh to TWh) underground in the form of gas, liquid, heat, and mechanical power.

Current research focuses on identifying suitable geological formations on- and offshore and assessing the technical, economic, societal, and environmental feasibility for safe, efficient, and timely deployment of underground storage. Pilot and demonstration projects are crucial for scaling up and commercializing underground storage technologies (e.g. CO_2, hydrogen). It is important to realize that the successful integration of underground storage into the energy landscape requires informing and involving local communities and authorities at all stages of the project. Only in this way can underground storage contribute to a smooth transition towards a clean and climate-neutral future energy system.

<< The Porthos site in the Port of Rotterdam (Maasvlakte, west Netherlands) where CO_2 will be compressed and subsequently transported to an injection platform some 20 km off the coast. Photo: ©PorthosCO_2.

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Introduction

Several chapters in this book describe the role of the Dutch subsurface as a source of natural resources such as fossil fuels, geothermal energy, groundwater, salt, aggregates and clay. With the traditional oil and gas exploration and production activities (E&P) in decline, one may conclude that the future role of the subsurface is dwindling, giving way to renewable energy sources that, with the exception of geothermal energy, are largely harvested above ground. This chapter addresses the important role the Dutch subsurface can play in large-scale underground storage of fuel-based energy carriers, mechanical energy, heat and CO_2, for the successful realization of energy transition ambitions and greenhouse gas emission-reduction targets.

Since the discovery of the giant Groningen gas field in 1959, and subsequent discoveries of a large number of other gas fields onshore and offshore (the so-called small fields), the Netherlands has had access to a relatively low-cost and reliable source of energy (Fig. 20.1). It has also been one of the largest energy exporters in Europe (Correljé et al., 2003; Breunese et al., 2005; Doornenbal et al., 2019). It was almost sixty years later, in 2018, that the Netherlands became a net importer of natural gas for the first time (Fig. 20.1). This was due to restrictions imposed on the natural gas production from the Groningen field related to induced seismicity and to the continued natural decline in domestic production from the small fields both on- and offshore (Van Geuns et al., 2017). Until that time, the unique swing production capacity of the Groningen field had provided most of the flexibility required by securing the seasonal balance between natural gas supply and demand, not only for the Netherlands, but also for parts of Germany and Belgium (Van den Beukel & Van Geuns, 2019). From the start of production restrictions for the Groningen field in 2014 to 2022, the percentage

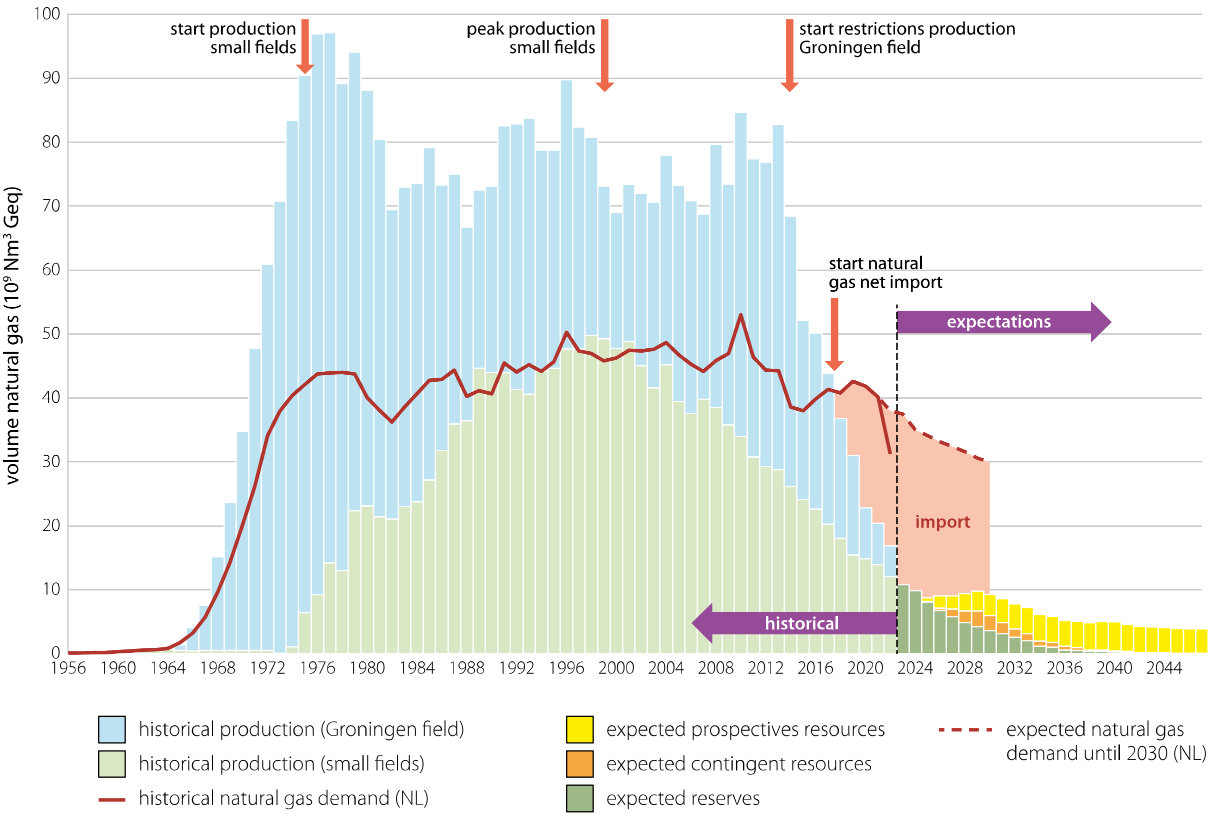


Figure 20.1. History of domestically produced natural gas from the Groningen field (blue bars) and the Small Fields (light green bars) in the Netherlands. The corresponding expected domestic natural gas production from the Small Fields is shown in three categories (green/orange/yellow bars; MEACP, 2023) and estimated according to the international Petroleum Resources Management System (PRMS, 2018). The historical and expected demand of natural gas in the Netherlands is represented by a red line (www.pbl.nl/kev). Due to high natural gas prices in 2022, significantly less natural gas was consumed than predicted. It is difficult to make new forecasts for natural gas demand due to the current high uncertainty (www.pbl.nl/kev). All types of natural gas are converted to the Groningen equivalent (Geq) based on their gross-heating-value (GHV). The Groningen gas has a GHV of 35.17 MJ/Nm³ (Megajoules per normal cubic metre; 'Normal' refers to the reference conditions: 0°C and 101.325 kPa).

of natural gas stored in the Netherlands relative to annual gas demand increased from 5-10% to ~32% (CBS, 2022). Currently, natural gas is stored in five large underground storage sites, which together have a maximum storage capacity of ~14 x 10^9 m^3, corresponding to 140 TWh (agsi.gie.eu, gas.kyos.com).

The 2021 annual consumption in the Netherlands clearly shows the still high dependence on hydrocarbons, with an annual primary energy consumption of 840 TWh (3024 PJ), the majority of which comes from natural gas (44%) and oil (37%), and the rest from renewables (10%), coal (6%), nuclear energy (1%) and others (2%). Although total domestic consumption of natural gas has been relatively constant at around 40 x 10^9 m^3 (390 TWh) for the past 50 years, there is a large uncertainty about how fast consumption will decline in the future (Fig. 20.1; www.pbl.nl/kev). Following the decision to completely close the Groningen field (MEACP, 2020, 2022b, 2024), the need to continue matching natural gas supply and demand in the Netherlands will depend for some time on the use of the current underground storage capacity, remaining production from small gas fields, reduction in domestic consumption, imports from other countries and the use of other energy sources such as coal-fired and nuclear power plants. And all this will be needed before natural gas can be partly replaced by renewable energy sources (MEACP, 2019b; ENCO, 2020; Van den Beukel & Van Geuns, 2020; Patrahau & Van Geuns, 2021; MEACP, 2022a; Van den Berg et al., 2022). With the increase in electrification in many sectors of our society and the plans set out in the Dutch climate agreement, in which solar and wind power are expected to grow significantly producing up to 70% of electricity by 2030 (MEACP, 2019a), this transformation represents the most significant restructuring of the Dutch energy system since the introduction of natural gas in the 1960s. Today about 71% of the natural gas consumed is still used for the production of electricity and for heating purposes (CBS, 2022).

With underground storage of natural gas gaining more importance today due to the developments concerning security of gas supply in Europe (Patrahau et al., 2022), there are three main questions about the future need for any type of underground (energy) storage in the Netherlands. First, what will be the expected volume and type of storage needed (short cycle, seasonal and/or strategic) for commodities such as heat, electricity and any alternative energy carriers, in addition to natural gas? Second, to what extent will underground storage be integrated with other aboveground energy storage solutions and flexibility options at regional, national and international level? And how will this interfere with other subsurface activities? (e.g. Carbon Capture and Storage, oil and gas production, geothermal). Third, how will the life cycle of underground storage sites be assessed and monitored to ensure their timely, safe and responsible development, operation and decommissioning to guarantee societal acceptance?

These and other questions are currently being addressed by many (research) groups and studies (e.g. Afman & Rooijers, 2017; EBN & Gasunie, 2018; Van Gessel et al., 2018; Bos, 2019; Berenschot & Kalavasta, 2020; EP, 2020; Groenenberg et al., 2020a; Scheepers et al., 2020; Sijm et al., 2020; Winters et al., 2020; Eising, 2021; Guidehouse & Berenschot, 2021; Van Gessel et al., 2021; Mendrinos et al., 2022; NSE, 2022; Sprenkeling et al., 2022; Van Gessel et al., 2022; www.gasopslagnederland.nl). The results of some of these scenario studies show a wide range in the estimated future storage capacities that may be required, depending on how energy flexibility solutions are implemented and integrated into the energy system of the future. They also take into account uncertainties about the amount of renewable generation capacity, CO_2-free production capacity, demand management and interconnection capacities between the European and global energy markets.

The subsurface can be key in providing capacities for storage of electricity and heat at different time scales and volumes. Electricity from intermittent solar and wind production can be converted into mechanical energy, hydrogen or derivatives and be stored in large volumes underground. In addition, underground heat storage from power-to-heat, waste heat, geothermal and solar thermal energy can help reduce natural gas consumption and speed up the energy transition in the heating sector. Besides energy storage, the subsurface can also be used for the cyclic storage of feedstocks (e.g. nitrogen) and the permanent storage (disposal) of by-products such as waste water, radioactive waste and CO_2. Underground disposal of radioactive solid waste is not discussed here, as it is discussed in Neeft et al. (2025, this volume).

Like other countries with a long history of hydrocarbon exploration and production, the Netherlands has the advantage of having an extensive source of data and knowledge of the subsurface, much of which is publicly available (www.nlog.nl). Over the past century, a large amount of well data (e.g. well logs and cores, as well as pressure and temperature measurements) and 2D- and 3D-seismic data have been collected, enabling the mapping and characterization of a wide range of geological formations. This knowledge has opened the possibility to investigate the potential for deploying underground storage technologies. Despite significant advances have been made in the energy sector since the publication of the previous edition of this chapter (Bos, 2007), only the large potential of underground storage of natural gas is being fully exploited today (Juez-Larré et al., 2016). However, the storage potential of the Dutch subsurface is very large and further deployment will not be limited by the subsurface itself, but by other

Qué será, será… when two kings meet and the energy transition in the Netherlands

On June 14th 2023, His Majesty King Willem-Alexander of the Netherlands paid a two-day visit to His Majesty King Felipe VI of Spain. The King travelled to Andalusia together with Rob Jetten, Minister for Climate and Energy Policy and a group of representatives of Dutch companies and knowledge institutes. In essence, the reason for this trip was the same as that of many of the 3.7 million Dutch tourists that visit Spain every year: the Spanish sun. The King, however, did not enjoy the sun on the white sandy beaches of the Costa del Sol, but instead together with King Felipe visited one of the solar/wind parks that will become part of the largest green hydrogen factory in Europe. Green hydrogen is likely to be an important energy carrier in the future energy system. With this historic visit, the Netherlands confirmed the ambitions of the Spanish energy company Cepsa to export green hydrogen to the Port of Rotterdam. The production plant and the hydrogen export route are expected to be operational by 2026-2027. The transport of hydrogen will take place in the form of ammonia through an armada of large vessels.

Cepsa has signed a collaboration agreement with Yara Clean Ammonia, a Norwegian multinational world leader in the field of green ammonia and with Gasunie, the Dutch national gas company and leader in gas transportation and infrastructure that connects the Port of Rotterdam with other European industrial clusters. This collaboration offers the Netherlands the possibility to create new import-export corridors for green energy to help secure energy supply in the current complex geopolitical situation around oil and natural gas import in Europe.

For the development of new sustainable energy markets such as that of hydrogen, the Netherlands must establish international collaboration to exchange knowledge, stimulate supply and demand, and build infrastructure for the production, import, transportation, storage and distribution of green energy. With the presence of King Willem-Alexander, the Netherlands shows a strong commitment to the green hydrogen revolution not only internationally but also nationally. This is why the King also attends important events on green hydrogen in the Netherlands. He presided over the inauguration of the first salt cavern storage test facility for green hydrogen in Zuidwending (HyStock project) in 2019, and spoke at the 'Wind meets gas' conference in 2021 on the importance of hydrogen for the Netherlands and the energy transition. He also visited students working with hydrogen at TU Delft (2021), the hydrogen cluster at the industrial park Kleefse Waard in Arnhem, the Port of Rotterdam and various green hydrogen projects in the North Sea (2022) including PosHYdon, a pilot project for offshore hydrogen production from wind power. Currently it is hard to say how fast the energy transition will take place in the Netherlands, as the current dependence on fossil fuels remains high (87%). We all hope for a swift and smooth passage, but just like in the famous song by Doris Day "Qué Será, Será, Whatever Will Be, Will Be, but is the (energy) future's not ours to see? Qué Será, Será...

Ammonia tanker Yara Nauma with, among others, their Majesties the King of Spain, Felipe VI, and the King of the Netherlands, Willem-Alexander, Mr. Maarten Wetselaar (CEO Cepsa), Ms. Monica Andres (EVP Yara Europe) and Mr. Michael Schlaug (Plant manager Yara Sluiskil). Copyright: Rijksvoorlichtingsdienst.

factors such as future energy needs, the availability of storage technology solutions with favourable economic and environmental performance and the level of societal acceptance. It is important to realize that the energy system in the Netherlands is becoming more complex and competitive than in the past. The increase in energy imports and the implementation of more renewable sources of energy and types of storage technologies may imply a major change in how the future role of the subsurface should be viewed, that is, as less of a molecule provider (with limited competition) and more of a service provider for storage (with extensive competition).

This chapter uses a top-down approach to look into the different types of underground storage technologies and their coupling to available/potential underground reservoirs in the Netherlands. The first part of the chapter presents the main state-of-the-art underground storage technologies available today, dividing them into two large groups: cyclic and long-term. For each, the main drivers and incentives for development and the services they can provide, are described in order to understand why underground storage is a crucial element in the energy transition and climate and environmental issues, and how it relates to aboveground storage and energy flexibility options. The second part of the chapter looks at the most relevant storage technologies for the Netherlands according to the type of underground reservoir and the commodities they can store. This includes a description of the general technical background and past, present and future implementations and developments in specific geological formations. Finally, the chapter concludes with a summary and outlook of the main factors to be considered for the future development of underground (energy) storage in the Netherlands.

Aboveground and underground storage technologies and rationale for application

Aboveground and underground storage technologies can be subdivided into two main categories, depending on the time frame involved: 'cyclic (temporary) storage' or 'long-term (permanent) storage'. Cyclic storage is mainly used for the temporary storage of energy and feedstocks with charge and discharge periods ranging from hours to months. Long-term storage is for the disposal of (by)products to minimize environmental impact or mitigate climate change. The storage technologies belonging to each category can support one or multiple services, each of which requires a total storage volume and a given injectivity or withdrawal capacity.

Cyclic storage

Cyclic storage of energy or feedstock can take place aboveground in tanks, pipelines, batteries, supercapacitors and underground in natural reservoirs and engineered cavities. However, underground energy storage has the main advantage that it generally has a larger volumetric capacity and lower unit technical cost than aboveground storage. Typical applications for underground storage are:

- Ensuring the supply of energy for peak and seasonal heat (and cold) demand.
- Balancing supply and demand with the increased share of variable energy sources in the energy mix.
- Serving international energy trade or large-scale energy flows between sectors in combination with arbitrage, i.e. the economic exploitation of price differences.
- Creating strategic reserves for possible prolonged periods of supply disruption that cannot be replaced by domestic and/or imported resources.
- More efficiently using the large-scale supply of constant (baseload) heat sources (e.g. geothermal, waste heat) and seasonal heat sources (e.g. solar) within local heat networks.

The future demand for cyclic energy storage will be influenced by many interrelated factors, such as:

- The configuration, predictability and intermittency of primary energy supply (base load production, variable renewable energy generation, imports).
- The characteristics of the final demand (type of energy carriers needed per sector, demand patterns, flexibility of demand, dependencies between sectors).
- The way in which supply and demand are linked (energy networks, conversions).
- The development of technology, energy markets, energy storage hubs and energy and climate policies (innovations, technology costs, energy prices, controls, subsidies).
- External influences such as weather, climate and geopolitical developments.
- Risks associated with the technologies and societal perception and acceptance.

Table 20.1 shows the most relevant types of flexibility solutions for the current gas, electricity and heat grids in the Netherlands. The table clearly shows that besides underground energy storage for natural gas and heat, there are aboveground storage solutions, which are used depending on their associated capacities, demand, prevailing legal and regulatory regimes, and cost-benefit ratio (Bos, 2019).

In general, above- and underground cyclic storage technologies can be typically categorized based on their send-out capacity (i.e. power in Watt) and discharge time

Table 20.1. Flexibility solutions and system levels per type of commodity (natural gas, electricity and heat) in the Netherlands. Transmission System (TS) and Distribution System (DS) are the infrastructures to deliver natural gas, electrical power or heat at a national and regional level, respectively.

Type commodity	General characteristics	Flexibility solutions (system level)	Description
(Natural) gas	The total domestic natural gas production from gas fields, (underground) gas storage sites, import, conversion, transportation/ distribution and biogas allow matching demand.	Line-pack (TS)	Using pressure differences in the existing transmission pipelines to store gas.
		Ramping (TS)	Adjusting the production from primary natural gas reservoirs (most reservoirs contain high-caloric* gas, but the Groningen reservoir and a few other reservoirs contain low-caloric* natural gas).
		UGS (TS)	Adjusting the withdrawal or injection rates of Underground Gas Storage sites (UGS, both high-caloric and low-caloric storage sites).
		Gas to power – G2P (TS)	Conversion of natural gas to electricity.
		Conversion of hi-cal natural gas to lo-cal gas (TS)	Conversion of hi-cal natural gas to lo-cal gas by adding nitrogen. In the Netherlands, nitrogen is captured from the air (Ommen, Wieringermeer, Pernis and Zuidbroek) and in one location stored in an underground salt cavern (Heiligerlee).
		Power to gas – P2G (TS)	Conversion of electricity to hydrogen gas or to syngas.
		International pipelines (TS)	- Import of natural gas through interconnection (pipelines) with foreign suppliers to ensure seasonal balancing (e.g. imported gas is supplied directly or used to fill the underground gas storage sites in summer, when demand is low). - Import of foreign LNG to LNG terminals using LNG carriers. LNG terminals in the Netherlands.
		Liquefied natural gas (LNG) (TS)	Gate Terminal, Rotterdam, capacity 8-12 billion m^3/yr (www.gateterminal.com). Eemshaven (floating storage regasification Unit), capacity 8 billion m^3/yr (www.eemsenergyterminal.nl).
		Biogas	Biogas is a mixture of gases (methane, carbon dioxide and hydrogen sulphide) produced from, among other things, sludge, waste from landfills, garden waste, vegetable and fruit residues, and animal residual products such as cow manure. The biogas is purified and dried to achieve the same quality as natural gas.
Electricity	Matching electricity supply and demand requires that the electricity grid is fully balanced, every second and in every sub-system of the grid (i.e. from low to high voltage systems).	Ramping (TS+DS)	Standby dispatchable power supply sources.
		Interconnectivity (TS)	Connection to other countries provided by TenneT (the national Transmission System Operator, TSO) and international trade to Balancing Responsible Parties (BRPs) for supply and demand matching.
		Storage at different scales	Batteries, capacitors, flywheel and potentially in the future e.g. Underground Hydrogen Storage (UHS), Pumped Hydro Storage (PHS), Compressed Air Energy Storage (CAES).
		Curtailment	Reducing or restricting energy delivery from an energy production capacity.
		Demand-response	Portion of the demand that can be reduced, increased or shifted in a specific period of time.
Heat	Heat grids are generally local (district heating) and often restricted to one or more heat sources (e.g. waste heat; geothermal)	Ramping up/down (DS)	Increasing/decreasing energy output in response to demand. Each heat production technology has different ramping rates and preferred operational modes (e.g. waste incinerator, Combined Heat and Power plant (CHP), geothermal installation).
		Gas to Power to Heat – G2P/P2H conversion (DS)	Supplying additional heat to the heat grid by burning gas or by using power to heat (i.e. electric boiler, heat pump) when heat demand is high.
		Aboveground thermal energy storage	Heat storage in tanks is very common in heating grids to balance heat supply and demand and to decouple heat demand from supply. Water is very often used as a storage medium.
		Underground shallow low-temperature thermal energy storage, borehole heat exchanger (heat and cold storage) (DS)	Mainly used on scales from individual houses to large buildings and complexes (e.g. offices, hospitals). And often in combination with a heat pump. This type of heat storage can be done in various geological formations, or even in buried steel vessels.
		Deeper high-temperature aquifer thermal energy storage – ATES (DS). Heat pump	- Heat grids use aquifers to store heat seasonally. In summer, when heat demand is low, hot water is injected into the aquifer. In winter, when heat demand is high, the hot water is produced from the aquifer. - Heat pump can be used in combination with heat networks.

* Natural gas with a low content of heavier hydrocarbons and higher contents of gases such a nitrogen are called low-caloric (lo-cal) gas. High-caloric (hi-cal) gases (with high content of methane and heavier hydrocarbons) are considered when the gross-heating-value (GHV) is above ~39 MJ/Nm^3.

(hours), which together determine the total storage capacity (amount of energy in Watt hour, Wh) that could be delivered in a full cycle. These technical characteristics determine the specific services that a particular technology can provide (Fig. 20.2).

Underground storage technologies score high in both capacity and discharge duration in comparison to aboveground storage technologies (Fig. 20.2). Underground storage of hydrocarbons and hydrogen can potentially provide the largest flexibilities for centralized power and heat balancing, with peak send-out capacities of hundreds of MW to tens of GW (thermal energy) for hours to months. In the case of hydrogen, which must first be produced from natural gas (steam reforming) or water and electricity (electrolysis), the energy stored underground can be used as fuel or for the generation of electricity through a Combined Cycle Gas Turbine (CCGT). Another large scale (underground) storage technology is the Pumped Hydro Energy Storage (PHES), which uses the gravitational potential energy of water to generate electricity. It can potentially deliver a capacity of hundreds of MW to a few GW for periods of up to a few weeks (i.e. up to 100 GWh) and is normally used for ancillary services (electricity grid balancing) and arbitrage, the latter being the energy stored during lower-priced hours and delivered during higher-priced hours. This is a typical aboveground technology often seen in water dams in mountainous areas. However, in regions with no topography, this can also be achieved by building an elevated water basin or by combining a large aboveground water basin (e.g. pit or river) and an underground reservoir (e.g. abandoned mineshafts or excavated lined rock caverns and tunnels). Large amounts of electricity needed during peak-off hours can also be stored in underground cavities in the form of mechanical energy using Compressed Air Energy Storage (CAES). CAES systems, with potential capacities of tens to hundreds of MW for more than a week (i.e. ~10 GWh), 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.

For the seasonal storage of heat, there are remarkable differences between the amount of energy that can be stored by above- and underground technologies. Since water is the preferred carrier for heat transport and storage, the amount of energy that an aboveground heat storage can deliver is generally on the order of a few kW to ~100

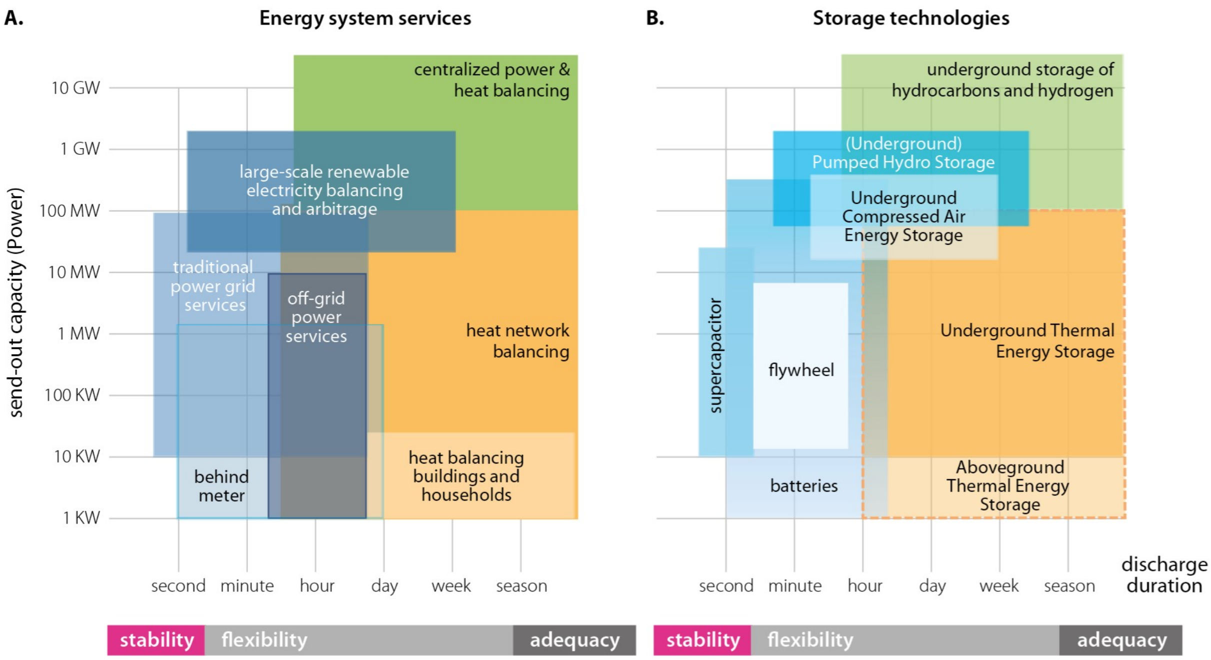


Figure 20.2. a) Energy system (balancing) services mapped according to their power (Watt) and relevant timescale for discharge. The types of services can be classified as stability, flexibility and adequacy based on their duration: stability is defined as the response to very short and fast fluctuations (especially in the power system); flexibility represents response to load and supply variations up to the seasonal timescale; adequacy (security of supply) determines the ability to adapt to long-term trends and emergencies. These three types of services are referred to in the text with the general term 'flexibility'. b) Above- and underground storage technologies that can provide the energy system services. The colour code indicates to which grid the energy system service and storage technology belongs: electricity (blue), gas (green) and heat (orange). Modified from IEA and Groenenberg et al., (2020b).

MW for several hours or days (i.e. up to several GWh). This is suitable as a daily or weekly buffer for buildings and local heat networks, but underground heat storage can supply up to 100 MW of capacity and, depending on the volume stored, can supply heat up to several months.

Besides pumped hydro and thermal storage at surface, there are other important aboveground storage technologies such as batteries, flywheels and supercapacitors. Although they can offer a considerable power range (between 1 kW and >100 MW) to provide grid stability and/or flexibility for traditional power grids, off-grids and behind meter services, their deliverability period is mostly limited to less than one day. Recent development of very large battery stacks may result in an extension of this period to a few days, albeit against very high costs and surface area requirements.

Permanent (long-term) storage

Permanent storage generally applies to substances that need to be disposed or safely stored in large quantities for long periods (thousands of years) as they can be harmful to the environment or climate (e.g. waste water, filtrated residues and CO_2). For this, the underground is the preferred storage medium. For the screening of potential underground reservoirs, a large volumetric capacity is often a critical factor, as well as the long-term integrity of the reservoir and seal, among others (EBN & Gasunie, 2018; Verhoef et al., 2020).

Waste waters produced during the extraction of petroleum and natural gas (so-called production waters) are often reinjected into the same (or similar) underground reservoir, or into nearby deep aquifers to minimize the environmental impact, and occasionally used for enhanced oil recovery (EOR; Liang et al., 2018). This is because these waters are brines that are more saline than seawater and may still contain small amounts of hydrocarbons and radioactive elements, as well as traces of chemicals used during the production process. Other types of water waste are the filtrate residues derived from water treatment facilities, which can be readily and safely disposed of in shallow aquifers a few hundred metres deep.

In the case of CO_2 storage, or so-called carbon sequestration, the goal is to isolate CO_2 from the atmosphere long enough for it to become part of the geological carbon cycle (Ringrose, 2020). Carbon Capture and Storage (CCS) is considered an essential technology for a timely achievement of Greenhouse Gas (GHG) emission reduction targets. It can be applied to centralized fossil-based energy production facilities and CO_2-intensive industries (such as steel, ammonium (fertilizer), cement plants, refineries and hydrogen production) whose emissions cannot be easily reduced in the short-term in any other way. Direct air capture of CO_2 is also an option under development for the longer term, which could result in net negative emissions when sequestered (Ringrose, 2020). CO_2 can be (re)injected for enhanced oil recovery (EOR). Rather than sequestering CO_2 for climate considerations, this is a commercial application where the costs of CO_2 capture and injection are offset by revenue from the extra oil produced.

Geological potential for underground storage in the Netherlands

The development of underground storage in the Netherlands, as elsewhere, will be determined by the need for specific storage services and by the availability of suitable underground formations. Underground storage can be accomplished in either 'natural reservoirs' or 'engineered cavities' (Muhammed et al., 2022). The term 'natural reservoirs' refers to porous reservoirs, such as depleted gas fields and aquifers. Engineered cavities represent constructed underground voids, which are either created by solution mining in salt formations, excavation and tunnelling in rock formations, or by drilled wells. For these two main underground storage options, there is a wide range of technologies for the storage of different types of commodities and their current degree of technical development or implementation in the Netherlands and abroad (Fig. 20.3). In this chapter we show that the Netherlands holds a strong position in the significant amount of research being carried out on many types of underground storage technologies and, as a result, is experiencing a notable increase in the number of storage projects in natural reservoirs and salt caverns. Only the use of engineered cavities in hard rock (i.e. crystalline and metamorphic rock) is limited, but this is due to the generally great depth of the basement in the Netherlands, and the large abundance of overlying geological formations with good reservoir properties (Rotliegend to Upper North Sea Group; Fig. 20.4).

Today, depleted gas fields in Rotliegend sandstones and Zechstein carbonates are the most commonly used reservoir types for the cyclic storage of natural gas and permanent storage of production water in the Netherlands (Figs. 20.3 and 20.4). Along with sandstones of the Lower Triassic, they are also emerging as potential candidates for large scale permanent storage of CO_2 (Fig. 20.4). Deep aquifers in the Rotliegend and Triassic are also being considered as candidates for CO_2 storage, while shallow aquifers (up to 200 m depth) in the Quaternary are already widely used for low-temperature (<25°C) aquifer thermal energy storage (LT-ATES; Fig. 20.4). Shallow aquifers have also been used for the storage of filtrate residues left after the purification of water for drinking purposes. Slightly deeper aquifers in the North Sea Supergroup are being considered as thermal storages of water at higher temperatures

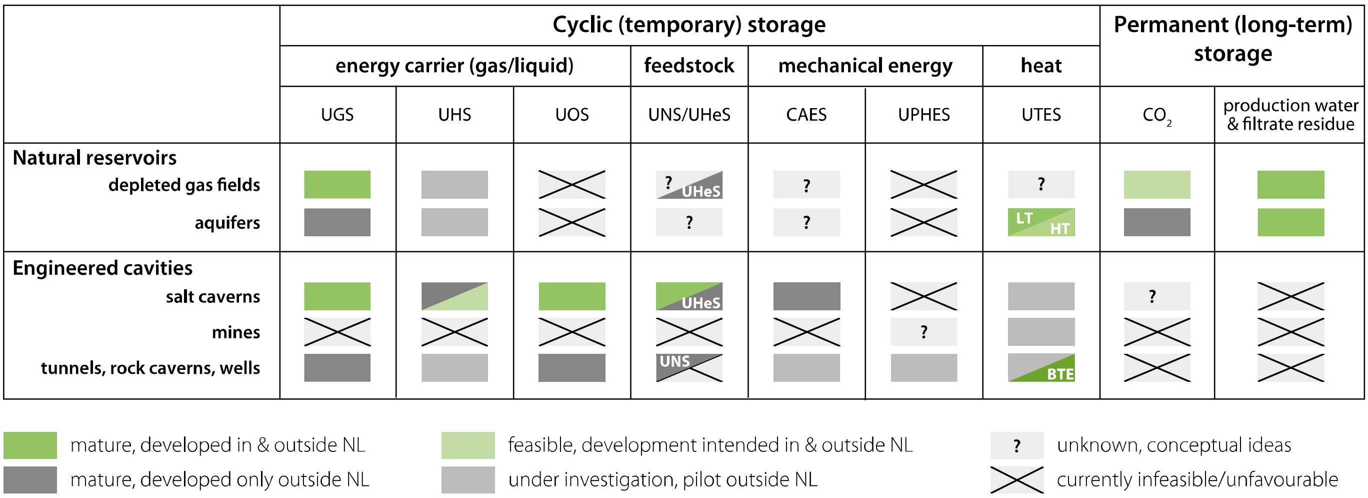


Figure 20.3. *Overview of various underground reservoirs and storage technologies that are used or considered for application in the Netherlands and/or elsewhere. Abbreviations: UGS = Underground (natural) Gas Storage, UHS = Underground Hydrogen Storage; UOS = Underground Oil Storage; UNS = Underground Nitrogen Storage; UHeS = Underground Helium Storage; CAES = Compressed Air Energy Storage; UPHES = Underground Pumped Hydro Energy Storage; UTES = Underground Thermal Energy Storage; BTE = Borehole Thermal Storage; HT/LT = High/Low Temperature (LT <25°C; HT >25°C).*

(HT-ATES). The stable nature and large abundance of salt formations of the Zechstein and Triassic groups have long been used for the storage of a wide variety of fuel-based energy carriers, such as natural gas and oil, and nitrogen for feedstocks (Figs 20.3, 20.4). Salt caverns may also see the development of Compressed Air Energy Storage (CAES) and Underground Hydrogen storage (UHS) in the near future. Regarding the lower Carboniferous (Dinantian) carbonates, since the 1980s many research efforts have been made to support the construction of an Underground Pumped Hydro Energy Storage (UPHES) facility in the southeast of the Netherlands (Limburg) (Fig. 20.4). In the following sections of this chapter, both cyclic and permanent underground storage technologies along with their corresponding most suitable geological groups are described in more detail for the Netherlands.

Cyclic underground storage of energy carriers, feedstocks and mechanical energy

Underground storage facilities for cyclic (temporary) storage of energy carriers (in gaseous or liquid form), mechanical power or feedstock share several common features. They all require an underground porous reservoir (depleted oil or gas field, aquifer) or cavity (one or several salt or lined rock caverns), and one or more wells connecting the underground reservoir to the aboveground processing facilities. Gas processing includes compression, expansion, drying and cleaning. The storage facilities are typically interconnected with a supplier (production facilities, import terminals) and the consumers (households, industry, power plants) via a transmission and distribution (pipeline) network. During periods of excess supply and/or low demand, a fuel-based energy carrier, compressed air or feedstock is injected (charged) into the underground storage, which then becomes a pressurized gas container. It is withdrawn (discharged) from the storage during peak demand or as needed, depending on its use and purpose. In the case of underground gas storage, the total volume of gas/liquid contained in the reservoir is divided into two volumes: the cushion volume (cv) and the working volume (wv). The cushion volume is the volume of gas/liquid that must remain in the reservoir to maintain sufficient pressure to allow delivery of the working volume at a pre-defined minimum rate throughout a withdrawal period (Muhammed et al., 2022). In salt caverns, this pressure is especially important to maintain the structural and mechanical integrity of the cavern and to minimize the inwards closure of the cavern walls by salt creep (e.g. Kumar et al., 2021; Kumar & Hajibeygi, 2021; De Bresser et al., 2022). Therefore, the working gas volume is the actual storage volume for repeated injection and withdrawal. It is important to note that the capacity of a storage facility generally refers to the working volume, and not to the cushion and working volume together.

Caverns are often considered a better option for underground storage than depleted oil or gas fields and aquifers. The advantages of underground storage in a salt cavern are:

- Lower cushion gas volume requirements, therefore higher percentage working volume. Relative to the total volume, the average percentage of working volume for a salt cavern is 70-80%, although it can vary due to

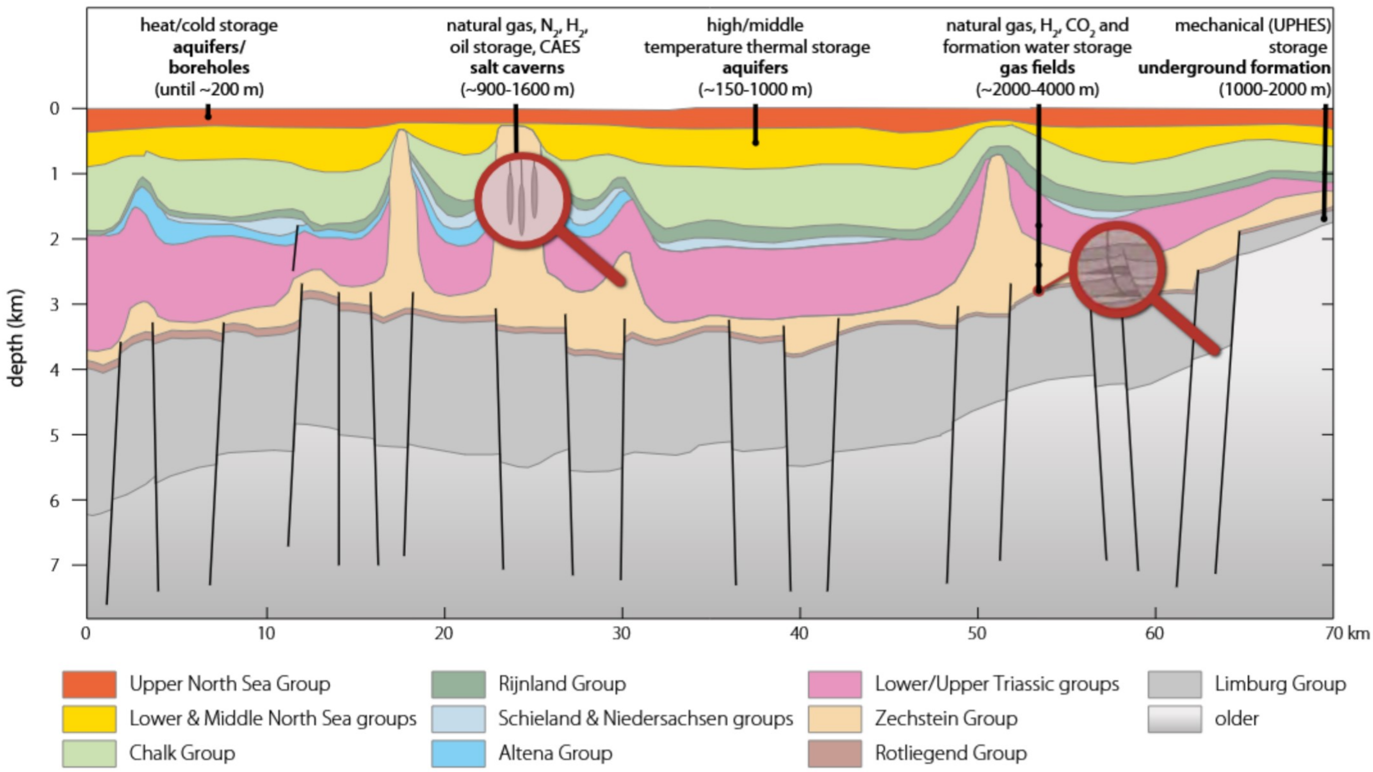


Figure 20.4. A representative cross-section through the Dutch subsurface with the different storage technologies that are (or can be) applied to particular geological groups.

site-specific factors such as depth and required storage capacity. In depleted gas fields the percentage is usually ~50-60%, whereas in aquifers it is ~20% (Matos et al., 2019).

- High sealing capacity, mechanical stability and chemically inert nature of the rock salt (in the absence of non-salt rock intercalations).
- A high level of technical maturity for the storage of many types of gasses.
- Injection and withdrawal through the (single) well used to make the salt cavern (by solution mining) is less expensive than the multi-well drilling required in depleted gas fields and aquifers.
- Eventually higher injection and withdrawal rates for short- and medium-term storage.

There are also disadvantages of underground storage in salt caverns:

- Limited availability of large underground salt formations.
- Limited storage volume capacity of hundreds of millions of cubic metres per cavern (relative to billions in a typical gas field/aquifer), although storage in salt caverns, depleted fields or aquifers can be complementary.
- Restrictions on the number of salt caverns that can be developed in a salt structure in view of surface subsidence and cavern stability issues.
- Limitations to the daily volumes that can be injected or withdrawn to preserve the structural integrity of the cavern.
- The shallower depth of some caverns (to minimize cavern volume loss due to salt creep) may increase surface effects (e.g. subsidence).
- Environmental issues related to the water necessary for cavern leaching and the disposal of the produced brine.
- Salt cavern long-term abandonment issues.

Depleted oil and gas fields are the second preferred subsurface storage medium due to their proven ability to contain large volumes of natural gas for millions of years, unlike storage in aquifers which may still require testing to identify potential issues regarding containment (e.g. Tarkowski, 2019; Heinemann et al., 2021; Zivar et al., 2021). Besides the choice of the type of underground reservoir, its location (onshore or offshore) can also be a decisive factor based on the distance to production and supply sites, surface limitations, legal aspects and societal acceptance.

Underground Natural Gas Storage (UGS)

Underground natural gas storage (UGS) is currently one of the most prominent technologies being used to flexibly match energy supply and demand on daily to seasonal timescales around the world. In Europe there is ~100 x 10^9 m^3 (1096 TWh) of working gas capacity in natural gas storage sites, which corresponds to 24% of the annual demand (Cihlar et al., 2021). Most of these storage sites are in porous reservoirs and salt caverns (ESTMAP, 2014; Cihlar et al., 2021). In the Netherlands, the current capacity for underground natural gas storage (working gas volume) is ~14 x 10^9 Nm^3 (~139 TWh), accounting for 34% of the annual domestic demand (CBS, 2022). Natural gas is stored in four natural gas fields and one cluster of salt caverns (Fig. 20.5). The four UGS sites in porous reservoirs are Norg, Grijpskerk, Alkmaar (since 1997) and Bergermeer (since 2014). While the Bergermeer and Alkmaar natural gas fields were significantly depleted prior to their conversion to UGS sites, the Norg and Grijpskerk conversion came after a relatively short period of conventional gas production, and thus their yet-to-be-produced natural gas has been used as cushion gas. The sandstone reservoirs of Norg, Grijpskerk and Bergermeer belong to the Upper Rotliegend Group, and the carbonate reservoir of Alkmaar to the Zechstein Group (Bouroullec & Geel, 2025, this volume). The Upper Rotliegend Group is the most widely used for UGS because of its excellent reservoir properties with clean, well-sorted eolian and/or fluvial sandstones with thicknesses up to a few hundred metres (Juez-Larré et al., 2016). Uplifted horst blocks provide good structural traps and the thick Zechstein salt layers form an excellent top seal. The Zechstein carbonate reservoir at the Alkmaar UGS site is thinner (50 m thick on average) and presents a more complex reservoir as it is part of a marine carbonate platform where the best reservoir properties (permeability) are often found in areas affected by karstification, fracturing and/or faulting. The reservoir is sealed by anhydrites and salts of the same rock unit and is bounded laterally by a combination of fault- and dip-closure.

The only UGS site in a cluster of salt caverns is at Zuidwending, which has been in service since 2011. It consists of a group of six vertical cylindrical salt caverns created by solution mining in a large salt pillar of the Zechstein Z2 Formation (Zechstein Group). The pillar extends from a depth of 2700 up to ~200 m below surface. Four of the caverns have a geometrical volume of 600,000 m^3 (radius ~25 m x height 300 m) and two of them of ~10^6 m^3 (radius ~25 m x height 500 m). They are located at depths between 1550 and 1050 m and are operated at pressures between 50 and 190 bar (Table 20.2). The reported annual loss of cavern volume due to salt creep is very small (~0.4%/yr) and the predicted subsidence at the surface is estimated to be around 1 mm per year (Energystock, 2017).

Table 20.2 shows the storage capacity and operating ranges for each of the five UGS sites. Norg, Grijpskerk and Alkmaar store low-caloric gas from the Groningen field or pseudo-Groningen gas produced from the mixture of high-caloric gas and nitrogen. The low-caloric gas from these three UGS sites is used primarily to provide flexibility to the residential sector for heating purposes (www.pbl.nl/kev). This replaces the former swing production capacity of the Groningen field (Fig. 20.5). Zuidwending also stores Groningen-type gas, but this gas is only traded on the spot market, while the high-caloric gas stored in Bergermeer is mainly used for international trade. There is a salt cavern storage facility in Gronau-Epe (Germany) near Enschede that is connected to the Dutch high-pres-

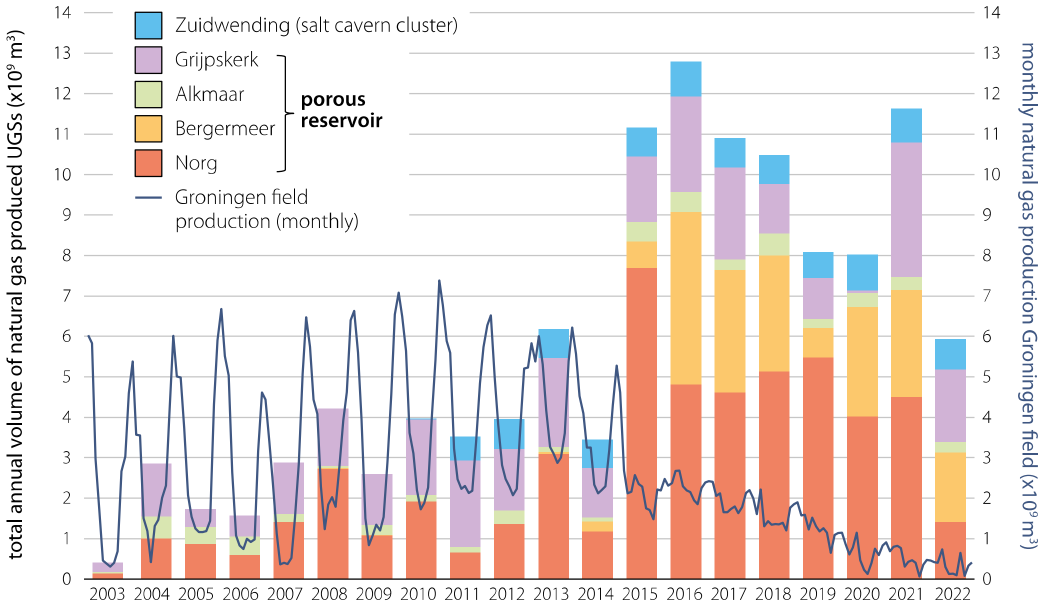


Figure 20.5. Volumes of natural gas withdrawn (discharged) from the various UGSs in the Netherlands. The corresponding monthly production from the Groningen field is plotted as a continuous blue line (MEACP, 2023).

Table 20.2 *Rates of withdrawal and injection (single well/facility) and storage capacities of the current underground natural gas storage facilities in the Netherlands. Volumes of working gas and cushion gas for natural gas were extracted from the storage licenses (www.nlog.nl).*

Storage natural gas (realized)	Units	Grijpskerk	Norg (Langelo)	Alkmaar	Bergermeer	Zuidwending
Reservoir type	-	Partly depleted gas field	Partly depleted gas field	Depleted gas field	Depleted gas field	Salt caverns (6 caverns)
Geological reservoir	-	Slochteren Fm (Upper Rotliegend Group)	Slochteren Fm And Lower Ten Boer Member-Silverpit Fm (Upper Rotliegend Group)	Zechstein Z3 Member (Zechstein Group)	Slochteren Fm (Upper Rotliegend Group)	Zechstein Z2 (Stassfurt) Fm (Zechstein Group)
Lithology	-	sandstone	sandstone/ conglomerate	dolomite/ limestone	sandstone	salt
Top reservoir depth	m (TVD)	3200	3000	2000	2200	1050
Reservoir thickness (avg.)	m	180	150	50	200	n.a.
Seal	-	Zechstein (salt, claystone)	Zechstein (salt, claystone)	Zechstein (salt, claystone)	Zechstein (salt, claystone)	Zechstein (salt)
Max. withdrawal rate (facility)	-	~60 x 10^6 m^3/d	96 x 10^6 m^3/d	~1.5 x 10^6 m^3/hr	57 x 10^6 m^3/d	1.8 x 10^6 m^3/hr
Max. injection rate (facility)	-	-	51 x 10^6 m^3/d (498 GWh/d*)	0.15 x 10^6 m^3/hr (1 GWh/hr*)	42 x 10^6 m^3/d (455 GWh/d*)	27.12 x 10^6 m^3/hr (11 GWh/h)
Volume at max. working pressure	x10^9 Sm^3	10.8	29.4	3.8	16	0.76
Working Gas Volume	x10^9 Sm^3	2.5 (24.4 TWh*)	6.3 (61.5 TWh*)	0.56 (5.5 TWh*)	4–6 (43–65 TWh**)	0.38 (3.7 TWh*)
Cushion Gas Volume	x10^9 Sm^3	8.3 (89.9 TWh**)	23.0 (249 TWh**)	3.3 (32.2 TWh*)	10–12 (108–130 TWh**)	0.37 (3.6 TWh*)
wv: cv ratio	-	0.3	0.27	0.18	0.3-0.6	1.02

* Low caloric natural gas (35.17 MJ/Nm^3); ** High-caloric natural gas (39 MJ/Nm^3).

sure gas transmission system. This facility provides some additional storage capacity for natural gas to meet the demand in the Netherlands (www.uniper.energy/energy-storage-uniper, 2022).

A study on the maximum theoretical natural gas storage performance of onshore depleted gas fields in the Netherlands, including the five UGS sites, shows that the largest storage capacities and highest withdrawal rates mainly belong to the reservoirs from the Upper Rotliegend and Lower Germanic Trias groups (Fig. 20.6; Juez-Larré et al., 2016; Van Gessel et al., 2018). These results clearly reveal two main things. One is that the four UGS sites in porous reservoirs rank high in their storage performance relative to other depleted gas fields, and the other is that their individual performances are far greater than those of the six salt caverns at Zuidwending (Fig. 20.6). However, in most cases their estimated cushion volumes are very large, as it is the case for Norg, Bergermeer and Grijpskerk (Fig. 20.6, Table 20.2). Initially, this was not a problem for the storage sites of Norg and Grijpskerk, as the original gas-initially-in-place was used as cushion gas. In order to reduce the cushion gas volume, these storage sites could be operated at lower working pressures, however this would reduce their performance. Alternatively, other onshore or offshore depleted gas fields, with better wv:cv ratios, could be developed for underground gas storage in combination with some clusters of salt caverns.

Based on the projected natural gas annual consumption in the Netherlands up to 2030, natural gas imports are expected to increase up to ~20 x 10^9 m^3 (www.pbl.nl/kev; Fig. 20.1). Developments since 2022 regarding security of gas supply are driving Europe to move away from importing Russian natural gas (Patrahau et al., 2022). With climate goals in mind, it is important to note that much of the imported natural gas has a significantly higher Greenhouse Gas (GHG) footprint compared to the natural

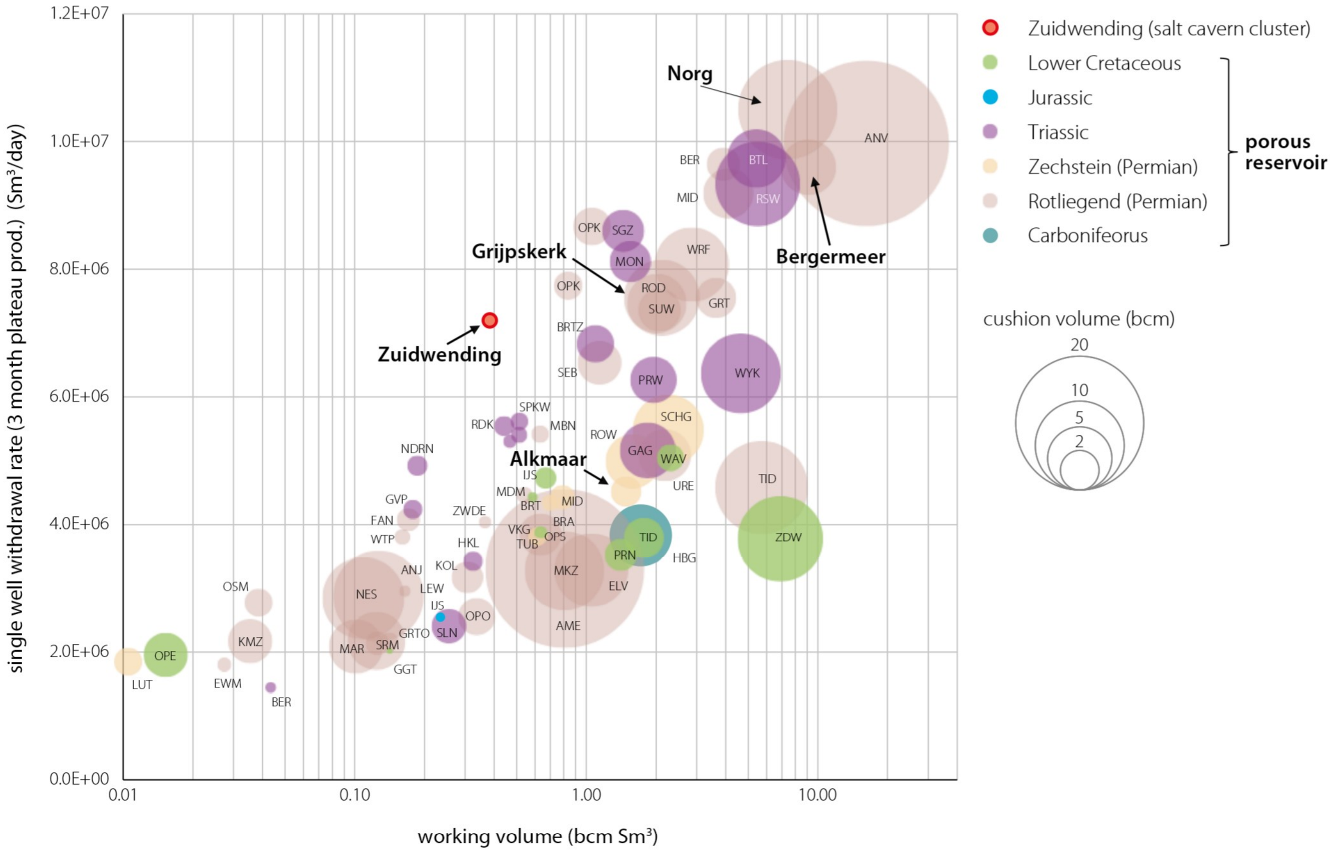


Figure 20.6. Working volume plotted against single well 3-month withdrawal rates calculated by Juez-Larré et al. (2016). The size of the corresponding cushion volume is given by the bubble size. The codes identifying the reservoirs shown in this plots are: AME = Ameland-East; ANJ = Anjum; ANV = Annerveen; BER = Bergen; BRA = Boerakker; BRT = Barendrecht; BRTZ = Barendrecht-Ziedewij; BTL = Botlek; ELV = Eleveld; EWM = Engwierum; FAN = Faan; GAG = Gaag; GGT = Grootegast; GRT = Groet; GRTO = Groet-East; GVP = Geestvaartpolder; HBG = Hardenberg; HKL = Hekelingen; IJS = IJsselmonde; KMZ = Kommerzijl; KOL = Kollumerland; LEW = Leeuwarden 101 RO; LUT = De Lutte; MAR = Marum; MBN = Middelburen; MDM = Middenmeer; MID = Middelie; MON = Monster; MKZ = Munnekezijl; NDRD = Noorderdam; NES = Nes; OPE = Opeinde; OPK = Oude Pekela; OPO = Opende-East; OPS = Opeinde-Zuid; OSM = Oostrum; PRN = Pernis; PRW = Pernis-West; RDK = Reedijk; ROD = Roden; ROW = Rossum-Weerselo; RSW = Roswinkel; SCHG = Schoonebeek-gas; SEB = Sebaldeburen; SGZ = 's-Gravenzande; SLN = Sleen; SPKW = Spijkenisse-West; SRM = Schermer; SUW = Suawoude; TID = Tietjerksteradeel; TUB = Tubbergen; URE = Ureterp; VKG = Vinkega; WAV = Wanneperveen; WRF = Warffum; WTP = Witterdiep; WYK = De Wijk; ZDW = Zuidwal; ZWDE = Zuidwending-East.

gas produced in the Netherlands (Hammond & O'Grady, 2017; Juez-Larré et al., 2018). This is because the energy required for transport of pipeline gas and regasification of LNG leads to higher GHG emissions (Patrahau & Van Geuns, 2021). All of this reinforces the need to implement renewables and to use UGS sites to secure supply for as long as natural gas remains an important source of energy.

Underground Hydrogen Storage (UHS)

Hydrogen is expected to play an important role in our future energy system, as it has the potential to take over (part of) the role of natural gas in securing energy supply (Den Ouden,, 2020). Hydrogen in pure form can be found in geological environments such as ancient continental shields, but it is not found in such large and concentrated quantities as natural gas (Prinzhofer et al., 2018). Global hydrogen is currently primarily produced by steam methane reforming (SMR: $CH_4 + H_2O$ + heat $\rightarrow CO + 3H_2$), but also by partial oxidation of heavier hydrocarbons and coal gasification (Gupta, 2009). Hydrogen from SMR is termed as 'grey hydrogen', because the CO_2 that is produced from the reaction of CO and steam ($CO + H_2O \rightarrow H_2 + CO_2$) is released to the atmosphere. If the CO_2 produced is captured and (permanently) stored in underground reservoirs or reused, this hydrogen becomes 'blue hydrogen'. Unless in the near future there is a successful upscaling and widespread commercialization of 'turquoise' hydrogen production via methane pyrolysis, which has carbon as by-product instead of CO_2 (Upham et al., 2017), CO_2 storage may well be associated with (blue) hydrogen production.

Hydrogen can also be produced through electrolysis. This is a process that uses electricity to split water into hydrogen and oxygen. Where renewable electricity is generated from wind and solar farms or nuclear power plants – with no or fewer CO_2 emissions – the hydrogen produced is referred to as 'green hydrogen' and 'pink hydrogen', respectively (Gahleitner, 2013). This type of production gives hydrogen the potential to act as a bridge between electricity and the gas grids, and hence to replace part of the role that natural gas plays in the energy system. Today, the efficiency of converting electricity into hydrogen through electrolysis is between 63-81% (Ajanovic et al., 2022) and the re-electrification in fuel cells or combined cycle gas power plants has an efficiency of ~50 and ~60%, respectively (Johansson et al., 2022).

To date, in the Netherlands, hydrogen is mainly used as a feedstock in the chemical industry and for the production of ammonia and methanol and to crack heavier crudes in refineries. It is not yet clear how a market for hydrogen as energy carrier will develop, even if the production, transport and storage are technically feasible and the overall societal benefits outweigh the overall societal costs (Mulder et al., 2019; Staffell et al., 2019). In Europe, hydrogen accounts for less than 2% of the current energy consumption (EnTEC, 2022), and although demand for hydrogen storage is expected to increase from ~23 x 10^9 m^3 (70 TWh) in 2030 to around ~150 x 10^9 m^3 (450 TWh) in 2050 (Cihlar et al., 2021), the actual future demand will depend on factors such as the level of production and demand, the interconnection between national and international hydrogen markets and the availability of other sources of flexibility (Breitschopf et al., 2022).

There are only four operational UHS facilities for pure hydrogen worldwide. In all four cases, the hydrogen is stored in salt caverns, with storage volumes ranging between 10 and 100 million m^3 (Evans & Holloway, 2009; Kruck et al., 2013; Table 20.3). This hydrogen is stored as a feedstock for industry in the event of a supply chain disruptions, which means that storage cyclicity is low (Panfilov, 2016). If hydrogen storage is to be used to balance energy supply and demand, much higher injection and withdrawal rates and an increase in storage cyclicity are expected. Fast-cycling operation brings with it specific challenges that require further research, particularly with regard to geomechanical stability of salt caverns and well integrity (Groenenberg et al., 2020a; Eising, 2021; Ugarte & Salehi, 2021; De Bresser et al., 2022; IEA, 2022a). The total estimated storage capacity for hydrogen in all existing salt caverns in Europe is 50 TWh, which would be insufficient to meet future storage needs (Cihlar et al., 2021). Even with the development of new clusters of salt caverns, the time required for their commissioning, and the limited geographical distribution in a handful of countries in Europe, clearly indicates the need for storage sites in depleted gas fields and aquifers.

Underground storage of hydrogen in porous reservoirs is in many ways similar to underground natural gas storage (Tarkowski, 2019). However, due to hydrogen's smaller molecular size and different chemical properties, further research is still required to demonstrate that hydrogen can be safely stored in porous reservoirs with caprocks that have sufficient sealing properties (Kruck et al., 2013; Heinemann et al., 2020; Zivar et al., 2021,IEA, 2022a; Muhammed et al., 2022). UHS is not expected to cause more significant surface subsidence or induced seismicity than UGS, if operated within the same pressure ranges (Van Eijs et al., 2006; Muntendam-Bos et al., 2008, 2022; Van den Bogert et al., 2016; Van Wees et al., 2017). Hydrogen has a lower volumetric energy density (~10.8 MJ/m^3) relative to natural gas (~39 MJ/m^3) and a lower compressibility (by a factor 0.8-0.9; H_2/natural gas), which implies that the required storage volumes and/or the wv:cv ratio will have to be greater than for natural gas if the same amount of energy is to be provided at the same pressure (Juez-Larré et al., 2020, 2023). In contrast, hydrogen can be withdrawn (discharged) 2 to 3 times faster than natural

Table 20.3. *Overview of current operational UHS in salt caverns outside the Netherlands.*

	Clemens Dome (USA)	Moss Bluff (USA)	Spindletop (USA)	Teeside (UK)
Geology	salt pilar	salt pilar	salt pilar	layered salt
Operator	Conoco Phillips	Praxair	Air Liquide	Sabic Petrochemicals
Start year	1983	2007	2016	1972
Geometrical volume (m^3)	580,000	566,000	906,000	3 x 70,000
Average depth (m)	1000	1200	1340	365
Pressure range (bar)	70–135	55–152	68–202	46
Working volume (10^6 m^3)	27.3 (82 GWh*)	41.5 (124 GWh*)	92.6 (277 GWh*)	9.12 (27 GWh*)

* Estimated energy content of the working volume assuming a low heating value (LHV) of 10.8 MJ/Nm^3 for hydrogen (source: DBI-GUT, 2017).

Table 20.4. Storage capacity parameters of candidate fields for natural gas and hydrogen, including theoretical capacity, effective capacity, working volume (wv) and corresponding energy content (see Fig. 20.7 for location). The Groningen natural gas field was excluded from this study due to its large volume. Theoretical capacity corresponds to the total storage capacity (Gas-Initially-In-Place, GIIP) that meets primary technical preconditions for (safe) storage. The effective capacity fulfills techno-economic criteria for efficient and cost-effective storage. The part of the effective capacity that is available for production/injection is known as the working volume. The working volumes obtained were converted to thermal energy content (TWh_t), using the energy factor 3.0E-9 TWh_t/m^3 (10.79 MJ/m^3) for hydrogen. OFF NH & OFF SH = proximal (nearshore) offshore North Holland and South Holland; OFF distal = offshore distal. From Juez-Larré et al. (2019).

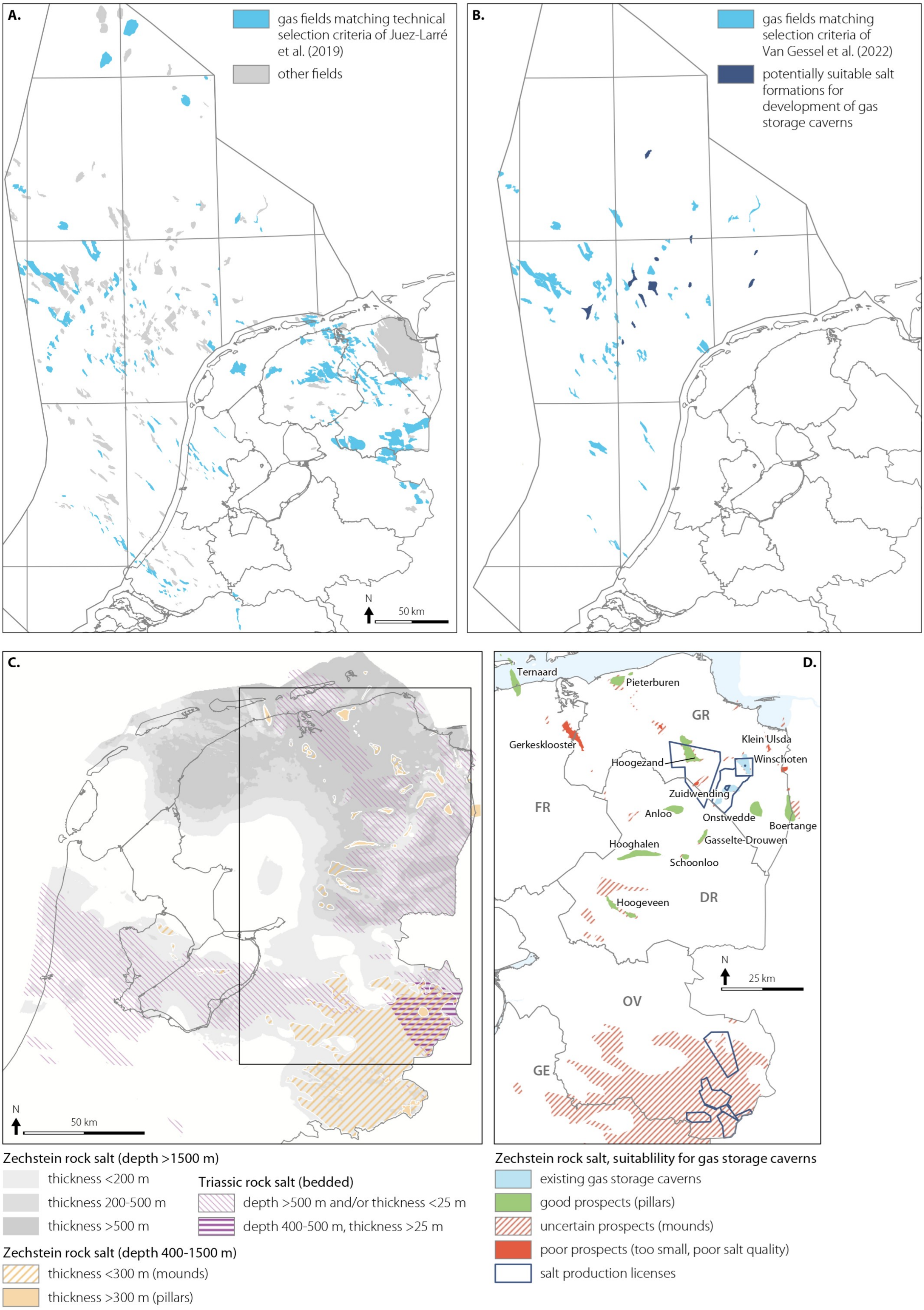
Province/area name (code)	Natural gas			Hydrogen	
	# fields (theoretical capacity) in $x10^9$ m^3	# fields (wv/effective capacity) in $x10^9$ m^3	Energy content wv in TWh_t	wv in $x10^9$ m^3	Energy content wv in TWh_t
Friesland (FR)	39 (216)	21 (34/125)	372	29	88
Groningen (GR)	27 (191)	11 (12/63)	130	10	31
Drenthe (DR)	19 (128)	10 (20/82)	217	17	51
Overijssel (OV)	7 (22)	3 (4/16)	45	3	10
North Holland (NH)	15 (38)	11 (16/35)	177	14	42
South Holland (SH)	17 (57)	17 (22/57)	237	19	56
Rest onshore	6 (5)	0 (0/0)	0	0	0
Total onshore	**130 (657)**	**73 (109/378)**	**1178**	**93**	**277**
Offshore (OFF NH)	6 (31)	3 (8/25)	85	7	20
Offshore (OFF SH)	11 (41)	10 (10/37)	104	8	24
Offshore (OFF distal)	69 (564)	54 (53/414)	572	45	134
Total offshore	**86 (636)**	**67 (71/476)**	**761**	**60**	**179**
TOTAL	**216 (1293)**	**140 (180/854)**	**1939**	**153**	**456**
Current UGS	4 (63)	4 (13/63)	134	11	33

gas, as a result of its (8-10 times) lower density and (1.3-3.0 times) lower viscosity. These high withdrawal velocities can partly compensate for the lower volumetric energy content, but in turn can be limited by technical integrity issues, such as erosion in the production tubing and wellbore damage (Juez-Larré et al., 2023).

Today, many screening studies are looking for potential UHS sites around the world (e.g. Mouli-Castillo et al., 2021; Zivar et al., 2021; Muhammed et al., 2022). In addition, various pilot and demonstration projects in depleted fields are underway to increase the technical maturity of the UHS technology and to make it ready for deployment (IEA, 2022a). Town gas, a mixture of gases containing 50-60% hydrogen, was stored safely in salt caverns, depleted gas fields and aquifers in the past (Bourgeois et al., 1979; Kruck et al., 2013; Reitenbach et al., 2015). Two more recent field projects in depleted fields also show that hydrogen can be stored blended with natural gas, with no adverse effects on installations and the environment (hychico.com.ar; www.underground-sun-storage.at). However, there are still accounts of diffusion, dissolution (into formation water), reactions with rocks and interaction with microbes in reservoirs that can degrade hydrogen purity and/or lead to loss of hydrogen, thus impacting recovery (e.g. Amid et al., 2016; Laban, 2020; Dopffel et al., 2021; Thaysen et al., 2021). To meet quality standards, gas cleaning post-withdrawal may be required, which would significantly impact economics (Taylor, 1986; Yousefi, 2021; Yousefi et al., 2023). This is why research is still needed on many aspects of UHS (Heinemann et al., 2020; IEA, 2022a; Muhammed et al., 2022).

Effective UGS and UHS capacity in the Netherlands

Since 2012, the Dutch Ministry of Economic Affairs and Climate has funded several national (pre-)feasibility studies aimed at estimation of the underground storage potential of depleted gas fields and salt caverns; first for natural gas and in recent years also for hydrogen (Fig. 20.7; Juez-Larré et al., 2016; STRONG, 2018; Van Gessel et al., 2018, 2021, 2022; Groenenberg et al., 2020a). Juez-Larré et al. (2019) estimated the effective storage capacity in still producing gas fields with a minimum depth of 1000 m, a permeability higher than 0.1 mD and with no significant amounts of H_2S (<<1 x 10^4 ppm): the result gave a total cumulative effective capacity of 1178 TWh (onshore) and 761 TWh (offshore) for natural gas and 277 TWh (on-


A.
gas fields matching technical selection criteria of Juez-Larré et al. (2019)
other fields
N
50 km
B.
gas fields matching selection criteria of Van Gessel et al. (2022)
potentially suitable salt formations for development of gas storage caverns
C.
N
50 km
D.
Ternaard
Pieterburen
GR
Gerkesklooster
Klein Ulsda
Hoogezand
Winschoten
Zuidwending
FR
Anloo
Onstwedde
Boertange
Hooghalen
Gasselte-Drouwen
Schoonloo
Hoogeveen
DR
N
25 km
OV
GE
Zechstein rock salt (depth >1500 m)
thickness <200 m
thickness 200-500 m
thickness >500 m
Triassic rock salt (bedded)
depth >500 m and/or thickness <25 m
depth 400-500 m, thickness >25 m
Zechstein rock salt (depth 400-1500 m)
thickness <300 m (mounds)
thickness >300 m (pillars)
Zechstein rock salt, suitablility for gas storage caverns
existing gas storage caverns
good prospects (pillars)
uncertain prospects (mounds)
poor prospects (too small, poor salt quality)
salt production licenses

← ***Figure 20.7.*** *a) Overview of gas fields matching the technical selection criteria for the storage of hydrogen of Juez-Larré et al. (2019) (onshore and offshore) and (b) Van Gessel et al. (2022) (only offshore and including salt formations). c) Distribution of the Zechstein and Triassic rock salt formations in the north of the Netherlands. d) Detail of (c) showing the suitability of salt caverns for storage of gas. The areas where Zechstein salt pillars have a suitable depth and thickness for the development of salt caverns for gas storage are coloured in green (Juez-Larré et al., 2019; www.nlog.nl/en/rock-salt-0). Provinces in (d): GR = Groningen; FR = Friesland; DR = Drenthe; GE = Gelderland; OV = Overijssel.*

shore) and 179 TWh (offshore) for hydrogen (Table 20.4). Onshore, this capacity can be reduced by up to 60% if surface limitations related to urban, natural and groundwater areas are considered (Van Gessel et al., 2021).

Van Gessel et al. (2018) evaluated the storage capacity of salt caverns in the northeastern part of the Netherlands, where large salt pillars of the Zechstein Group are present (Fig. 20.7d). For the construction of clusters of salt caverns, a depth range between 1000 and 1500 m is considered optimal, with a standard geometric volume of each individual cavern of 600,000 m^3 (radius ~25 m x height ~300 m). This size is similar to that of the salt caverns in the Zuidwending underground gas storage facility (Crotogino et al., 2001). The maximum theoretical number of caverns that could be fitted in each salt pillar was calculated based on the directive described in German salt mining regulations. These regulations specify a minimum distance of 100 m between the cavern wall and the flank and 150 m between the cavern wall and the top of the salt pillar structure (ABVO, 1966) and a distance of 160 to 210 m between neighbouring cavern walls (IfG, 2008). The effective number of caverns was assumed to be a conservative 50% of the theoretical number, resulting in a total of ca. 321 possible caverns onshore, although the actual effective number of potential salt caverns could be much smaller if there are surface limitations and subsidence restrictions. The maximum operational cavern pressure considered was 180 bar, with a working to cushion gas volume ratio of 1:1. For a single cavern, this yields a working volume of about 53 x 10^6 m^3 (0.572 TWh) of natural gas or 45 x 10^6 m^3 (0.135 TWh) of hydrogen. Based on all assumptions above, a total potential working volume of 17.0 x 10^9 m^3 for natural gas (184.3 TWh) and 14.5 x 10^9 m^3 for hydrogen (43.3 TWh) was estimated for the onshore Netherlands in yet to be constructed salt caverns, distributed over the provinces of Groningen, Friesland and Drenthe (Table 20.5, Fig. 20.7d).

As it is the case for the current natural gas storage, studies show that the total cumulative capacity for hydrogen storage onshore and offshore is much larger than the current and expected hydrogen demand in the Netherlands (Van Gessel et al., 2021). In 2030 the demand for hydrogen storage is expected to lie between 42 and 475 GWh (14-16 x 10^6 m^3 hydrogen). For 2050, there are different storage scenarios for storage demands based on different weather patterns: low-case 1.3-4.3 TWh (0.43-1.5 x 10^9 m^3), mid-case 15-26 TWh (5-8.7 x 10^9 m^3) and high-case up to 32.9 TWh (11 x 10^9 m^3). In the event that 25% of the annual consumption would be stored as strategic reserves, as it is currently done for oil in the Netherlands and Europe, the total equivalent storage capacity needed could increase to 51 TWh by 2050. Considering the development time of approximately 3-6 years for the leaching of a single one million cubic metre (geometric volume) salt cavern and assuming 9 sites can be developed simultaneously, a maximum of 60 caverns with a total storage capacity of 15 TWh could be developed between 2030 and 2050 (Van Gessel et al., 2021). Therefore, it is likely that depleted gas fields will be required for hydrogen storage to match hydrogen demand with supply in the Netherlands.

Gasunie has already drawn plans to develop the first large-scale hydrogen storage site in a cluster of salt caverns in the Netherlands. These plans include the development of four new caverns at the current UHS storage site in Zuidwending, with a total storage capacity of 20 kilotonnes (HyStock, 2022), corresponding to ~235 million m^3 H_2 and ~667 GWh. In 2022, a feasibility study was successfully carried out in which the injection and withdrawal of hydrogen in a small salt cavity in an observation well in Zuidwending was tested over short periods. The first cavern is expected to be operational by 2028 (Energystock, 2022).

Hydrogen storage performance for the UHS sites of Grijpskerk, Norg and Alkmaar has also been investigated in detail, as the existing storage facilities could potentially be considered for reuse as UHS (Juez-Larré et al., 2023). The study shows the importance of estimating the storage capacity in terms of volume and energy based on a range of working pressures. This is because hydrogen has a much lower energy density than natural gas (Fig. 20.8). Current research on the possible reuse or retrofit of parts of existing natural gas infrastructures for hydrogen is also an important aspect for the technical development of UHS sites and grids (EBN, 2016; DBI-GUT, 2017; also see www.gasunietransportservices.nl). Another topic for investigation is the societal acceptance of underground activities on land in the Netherlands (e.g. Winters et al., 2020; Mendrinos et al., 2022; Sprenkeling et al., 2022). The possibilities for UHS in the North Sea are currently also being investigated, both for depleted gas fields and salt caverns, as they

Table 20.5. Results of the estimated storage potential of salt caverns (from Juez-Larré et al. (2019), www.nlog.nl). Listed are the number of effective salt caverns, the working volume (wv) and corresponding energy contents for natural gas and hydrogen results are given per salt pillar and grouped per province (see Fig. 20.7 for location). The working volumes obtained were converted to thermal energy content (TWh_t), using the energy factor 3.0E-9 TWh_t/m^3 (10.79 MJ/m^3) for hydrogen.

Province/ salt pillar	# effective caverns	Storage natural gas wv (10^9 m^3)	Storage natural gas Energy content (TWh_t)	Storage H_2 wv (10^9 m^3)	Storage H_2 Energy content (TWh_t)
Groningen	**230**	12.2	132.1	10.4	31.0
Zuidwending	52	2.8	29.9	2.4	7.0
Winschoten	22	1.2	12.6	1.0	3.0
Pieterburen	39	2.1	22.4	1.8	5.3
Onstwedde	66	3.5	37.9	3.00	8.9
Boertange	51	2.7	29.3	2.3	6.9
Friesland	**31**	**1.6**	**17.8**	**1.4**	**4.2**
Ternaard	31	1.6	17.8	1.4	4.2
Drenthe	**60**	**3.2**	**34.4**	**2.7**	**8.1**
Anloo	14	0.7	8.0	0.6	1.9
Hooghalen	37	2.0	21.3	1.7	5.0
Hoogeveen	1	0.1	0.6	0.04	0.1
Schoonloo	8	0.4	4.6	0.4	1.1
Total	**321**	**17.0**	**184.3**	**14.5**	**43.3**

could be an alternative to onshore developments (e.g. NSE, 2022; Van Gessel et al., 2022; poshydon.com; see Fig. 20.7).

Underground Oil Storage (UOS)

The purpose of oil storage sites is to meet strategic and long-term demand. In the case of the European Union all member states are obliged to maintain a strategic oil reserve amounting to 90 days of consumption in critical sectors (Directive 2009/119/EC). As domestic oil production in the Netherlands is only ~5% of the national consumption, most of the oil is imported (CBS, 2022). Oil arrives at the Maasvlakte Oil Terminal (MOT), where it is distributed through pipelines to various surface storage sites and processing facilities in the harbour areas of Rotterdam, Vlissingen and Antwerp. The MOT has 39 oil tanks each with a diameter of 85 m and a height of 22 m, resulting in a total aboveground storage capacity of approximately 4 to 5 x 10^6 m^3.

The Netherlands Petroleum Stockpiling Agency (COVA) is responsible for organizing the storage of strategic petroleum reserves in the event that production and/or trade are interrupted for a longer period of time due to exceptional circumstances such as geopolitical conflicts and trade crises. COVA does not own any storage facilities and therefore its task is to select suitable storage companies and locations at the lowest possible cost for the emergency stock of crude oil for the Dutch state. Therefore, the stock of oil for the Netherlands is stored in several surface facilities in the Netherlands and Belgium. Crude oil is stored in some salt caverns in Etzel, northern Germany (www.storag-etzel.de) and diesel is stored in salt caverns in De Marssteden (Enschede). The Marssteden facility, commissioned in 2016, stores diesel (and home heating oil) in two salt caverns in the Röt Formation and has a total storage capacity of 250,000 m^3 (SodM, 2022). Unlike the deeper salt pillars of the Zechstein Group in the northern part of the Netherlands, the salt caverns at Marssteden were developed horizontally with a height of ~20 m and a diameter of ~130 m in flat salt layers (up to 100 m thick) at depths of 300 to 500 m. In general, salt caverns mined in layered salt formations are much smaller than in salt pillars. This is to ensure cavern stability as the degree of heterogeneity of the salt formation is much higher (Han et al., 2006).

Underground Nitrogen Storage (UNS)

Gas feedstocks like nitrogen can be stored in salt caverns in a similar way as for natural gas and hydrogen. In Heiligerlee (province of Groningen), nitrogen is being stored in a salt cavern of 860,000 m^3 in the Winschoten salt dome. This solution-mined cavern was commissioned in 2010 and was selected as the most suitable cavern among those within the Heiligerlee and nearby Zuidwending cavern clusters (RVO, 2010). The nitrogen stored in this cavern is extracted from air at the Zuidbroek facility (zuidbroek.gasunie.nl). Most of the nitrogen produced from this facility is directly blended with (imported) high-caloric natural gas to produce a Groningen (low-caloric) composition

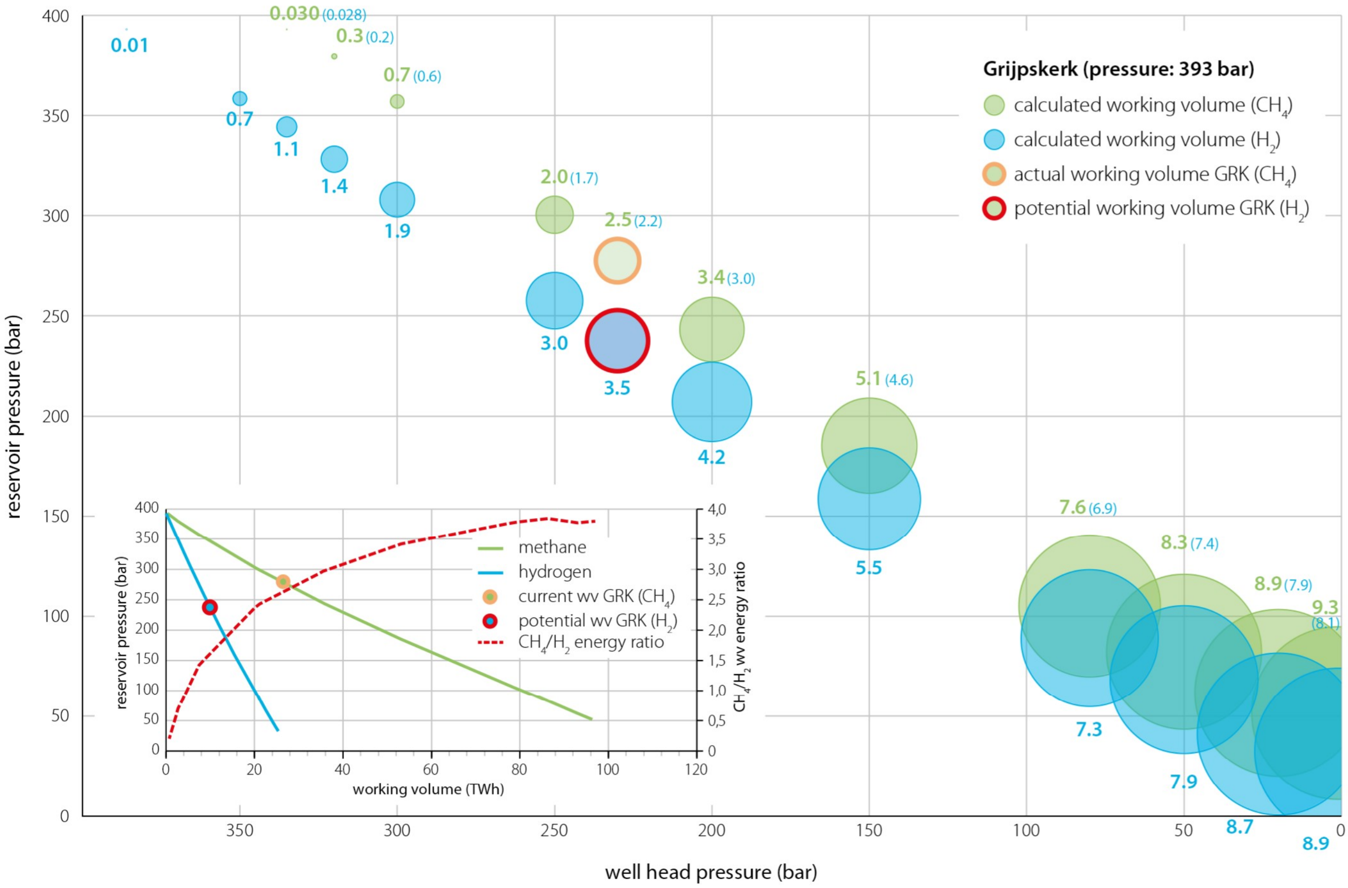


Figure 20.8. Working volumes (wv) of hydrogen (blue bubbles and numbers) and pure methane as proxy for natural gas (green bubbles and numbers) in billion Sm³ calculated by Juez-Larré et al. (2020, 2023) for the Grijpskerk (GRK) reservoir at 393 bar (max. storage pressure), considering a wide range of reservoir depletion pressures (min. storage pressure) and wellhead pressures. A cut-off withdrawal rate of 1 million Sm³/day was enforced. Next to the value for each working volume of methane, the equivalent volume of hydrogen at the same temperature and pressure is indicated in blue numbers between brackets. The graph in the lower left corner shows the corresponding energy content of the calculated working volumes (absolute and ratio) between hydrogen and methane. Modified from Juez-Larré et al. (2023).

gas (also known as pseudo-Groningen gas) suitable for domestic use in the residential sector and for export. The remaining nitrogen is transported via a pipeline (10 km) to the Heiligerlee salt cavern, where approximately 128 x 10^6 m³ can be stored annually, with a minimum available volume of at least 45 x 10^6 m³. This storage facility, along with a recent upgrade of the nitrogen facility at Zuidbroek, was initially realized to partially offset the loss of production capacity from the Groningen field by approximately 7 x 10^9 m³ per year (Gasunie, 2022). There are three other nitrogen facilities in the Netherlands (Ommen, Wieringermeer and Pernis). Although the Ommen and Wieringermeer facilities do not have an underground nitrogen storage, they are directly linked to pseudo-Groningen gas production facilities and are connected to the Grijpskerk and Alkmaar UGS, respectively.

Other gases, such as helium, can also be stored as feedstock. There are very few underground helium storage (UHeS) sites worldwide. Those that are in operation are mostly associated with the natural production of helium as byproduct in natural gas fields, as it is the case in the USA and Russia (e.g. Tade, 1967; Khan et al., 2012; Golovachev & Starokon, 2020). To date, there is no underground helium storage in the Netherlands. The nearest storage facility is in Gronau-Epe in Germany where helium is stored in a salt cavern at a depth of 1300 m. Helium is primarily used to liquefy nearly any other gas, mostly nitrogen and methane, that is, in cryogenic applications.

Compressed Air Energy Storage (CAES)

A CAES system stores electrical energy 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 when non-dispatchable electricity is produced from Variable Renewable Energy (VRE) such as wind and solar (Fig. 20.9). The compressed air is stored in underground reservoirs, commonly salt caverns, at high pressure. At discharge, electricity is regenerated by employing compressed air from the reservoir(s) to drive a turbo-expander or a gas turbine, that drives an electricity generator and delivers 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; Fuchs et al., 2015), air volumes in the order of 50-100 x 10^6 m^3 are required to conduct CAES at large-scale (power outputs typically between 100-500 MW and discharge durations of 6-12 hours). This type of storage can play a role in delivering short-to-medium-term and high power flexibility services to the electricity grid (Eckroad & Gyuk, 2003).

There are two main technology concepts: diabatic CAES (D-CAES) and advanced adiabatic CAES (AA-CAES). In a D-CAES system, the heat generated on compression of the air is not stored but is dissipated in the air. Therefore, to enhance discharge power and economics, an external fuel is normally used to heat up the air before driving the turbine. Natural gas is used conventionally, but its combustion generates CO_2 and NOx emissions (indicated with 'exhaust' in Fig. 20.9). 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. Worldwide, there are two operational D-CAES plants in salt caverns, one in Germany (Huntorf, 321 MW/2.5 GWh, since 1978) and one in the US (McIntosh, 110 MW/2.6 GWh, since 1991) with round-trip efficiencies of 42% and 54%, respectively (Matos et al., 2021). Round-trip efficiencies approaching 60% are deemed feasible with efficient utilization of waste heat of the generation process.

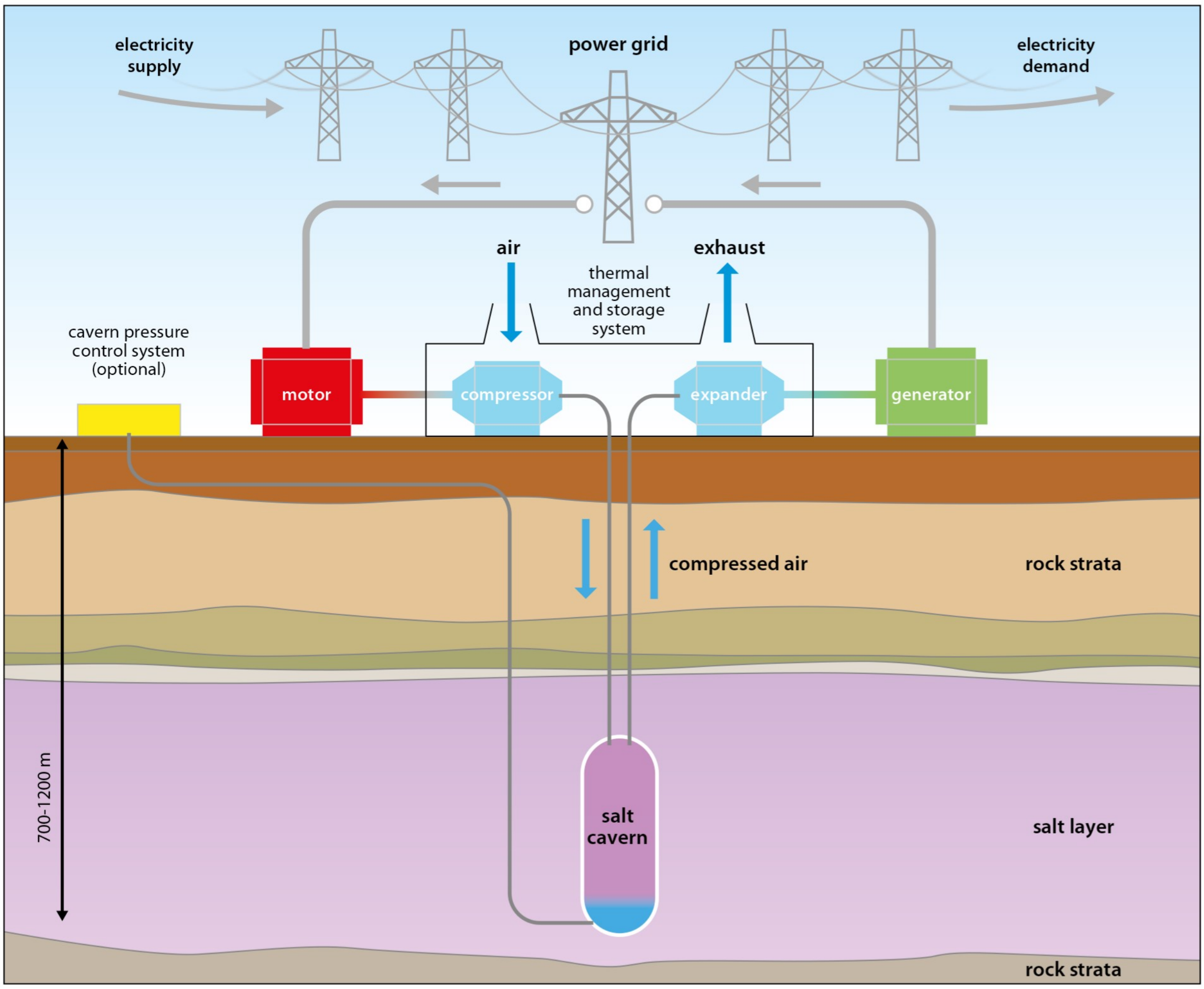


Figure 20.9. Schematic diagram of a CAES system (from Groenenberg et al., 2020b; after storelectric.com). In a diabatic CAES system, a fuel must be burned during (re-)generation of electricity to heat the air in the expander (turbine), which generates flue gases containing e.g. CO_2, NO_x and SO_2 (given natural gas) or water and NO_x (given hydrogen) leaving the system through the exhaust. In an adiabatic CAES system, the thermal storage and management system is capable of storing the heat lost during compression long enough to reuse it to heat the air, thus requiring no fuel.

In an AA-CAES system, the heat produced during compression is stored in a TES (Thermal Energy Storage device) and reused during the discharging process, which eliminates the need to use fuel to heat up the expanding air. With this method, 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 current level of technological maturity is not high enough for the technique to be commercially applied (King et al., 2021). In 2010, RWE Power and partners General Electric, Zublin and DLR launched the Adele project in Staßfurt – Germany (RWE, 2010) as the world's first large-scale AA-CAES demonstration project. Although the concept and design have been established (200 MW up to 5 hours with a 70% round-trip efficiency), this project was placed on hold in 2016 citing uncertain business conditions. Despite all these issues some major projects are underway on CAES (King et al., 2021).

The Dutch subsurface has a large potential for CAES in salt caverns. To estimate the total CAES capacity onshore, Van Gessel et al. (2018) used the same geometric volume of 0.3-0.6 x 10^6 m^3s for potential development in salt caverns as used for hydrogen storage. In the study, a notional CAES facility was used with a discharge power of 300 MW for a period of 6 hours at assumed operational pressures up to 180 bar, which equals an approximate required energy storage capacity of 1800 MWh (1.8 GWh). With these conditions the total technical potential for developing CAES in salt caverns in the Netherlands was estimated to lie at around 0.58 TWh (Van Gessel et al., 2018). Table 20.6 shows the storage capacity estimated for each province and salt pillar. In recent years various demonstration and commercial projects have been developed, mainly based on the D-CAES concept. This indicates a strong renewed interest in CAES (King et al., 2021), probably sparked by the increasing need for flexibility services to integrate a growing share of variable renewables (wind, solar) into the energy system. In the Netherlands, project developer Corre Energy intends to build a 320-MW D-CAES plant with a storage capacity of 3-4 GWh (Corre Energy, 2022). The project obtained the status of European Project of Common Interest (PCI) in 2017 and receives financial support from the Connected Europe Facility (CEF) 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.

Table 20.6. *The total number of (effective) caverns and corresponding energy storage for CAES per province and salt pillar (see location in Fig. 20.7). The effective number of caverns is a conservative estimate based on 50% of the theoretical number of caverns that could be mined in a salt structure. From Juez-Larré et al. (2019).*

Province/ salt pillars	#Effective salt caverns	Energy storage (TWh)
Groningen	**230**	**0.414**
Zuidwending	52	0.094
Winschoten	22	0.039
Pieterburen	39	0.069
Onstwedde	66	0.119
Boertange	51	0.092
Friesland	**31**	**0.056**
Ternaard	31	0.056
Drenthe	**60**	**0.108**
Anloo	14	0.025
Hooghalen	37	0.067
Hoogeveen	1	0.002
Schoonloo	8	0.014
Total	**321**	**0.577**

Underground Pumped Hydro Energy Storage (UPHES)

This technology is used to store electricity in the form of gravitational potential energy. Large amounts of water are pumped from a lower to a higher elevation basin using low-cost surplus off-peak electric power. In periods of peak electrical demand, the water collected in the upper basin is released into the lower basin through a turbine generating electric power. The round-trip efficiency of a PHES system varies from 60 to 80% (Letcher, 2016). The storage capacity is proportional to the product of the total mass of water and the difference in height between the two basins.

The aboveground variant of the pumped hydro energy storage, located in mountainous areas, is the most widely used electricity storage technology worldwide since the early 20th century (i.e. it has the largest installed capacity). In Europe, about 190 aboveground pump-accumulation systems are currently operational or are under construction (DOE, 2022). The total power of all these systems is approximately 60-70 GW. The average discharge time is 6 to 12 hours. The biggest systems have a capacity of 1 to 2 GW. Aboveground PHES are more difficult to build in areas with lower topographical gradient. In flat regions, a height difference can only be created by placing at least one of the two basins underground. However, the underground excavation and material handling costs, construction risk and the time required to complete the project can hinder the economics of an UPHES project. As a result, most developers around the world are considering utilizing existing subsurface structures such as abandoned mines (e.g. Madlener & Specht, 2020). Preconditions for underground structures are the absence of large fractures and that the UPHES is operated unpressurized to ensure mechanical stability. There are no UPHES in operation today, although many sites and projects have been proposed (e.g. Kitsikoudis et al., 2020). There is only a 500 MW pumped hydro power station in preparation in Paldiski, Estonia (zeroterrain.com).

In the case of the Netherlands, besides the Lievense plan for an aboveground pumped hydro storage in the Markermeer (Rijkswaterstaat, 1982) and the DELTA21 concept next to the Tweede Maasvlakte (www.delta21.nl), there has been a proposal to build a UPHES (OPAC group) in Graetheide in the southeast of the Netherlands (Limburg) since the 1980s. The planned UPHES with a power of 1400 MW could execute about 250 cycles a year, each lasting six hours, storing up to 2.1 TWh annually (Huynen, 2018; Kramer et al., 2020). The design includes a surface water basin (~500 x 500 m) connected to an underground reservoir and machine hall at 1400 m depth, with three mineshafts to collect the water. The underground reservoir could be constructed in the thick succession of the lower Carboniferous (Dinantian) carbonates of the Carboniferous Limestone Group (700 m thick in exploration borehole Geverik-1), as it is a strong and stable rock formation (Müller & Hereth, 1987; Kramers et al., 2011). The construction of shafts, machine hall and tunnels would make use of proven technology. Although underground constructions are common in the Netherlands at shallow depths, the realization of this project at 1400 m depth would be new to the country. The absence of a 'tradition' in hydroelectric energy storage investments, creates an obstacle that has yet to be overcome (Kramer et al., 2020).

Underground Thermal Energy Storage (UTES)

Thermal energy storage (TES) uses the thermal properties of materials to store heat and/or cold. Thermal energy sources are abundant and include industrial waste heat, solar heat, geothermal heat or heat converted from excess wind or solar (photovoltaic) electricity by heat pumps or an electric boiler. Sources of cold are related to industrial processes, low ambient temperatures and surface waters. Where thermal energy storage takes place underground (UTES) in geological formations, it involves significantly larger volumes of sedimentary rock and water than in surface installations. For UTES, water is the most preferred medium because it has one of the highest specific heat capacities (~4.17 MJ/(m^3 °C)), about 3 times larger than that of most rock formations (Cabeza, 2021). The prospect of easily storing large amounts of energy underground is the reason why the number of UTES projects is rapidly expanding in Europe, especially in the Netherlands.

A large variety of UTES concepts are being applied or are in the development phase, among others: Aquifer-TES, Borehole-TES, Tank-TES, Mine-TES and Pit-TES. Other concepts of underground heat storage are still in the conceptual phase, such as depleted oil reservoirs, and will not be further discussed in this chapter (Stricker et al., 2020). The scale at which UTES is applied can vary from the very local (e.g. single house) to city scale (e.g. large heat networks), depending on the temperature ranges and volumes provided by the heat/cold source, the type of demand and the properties of the underground reservoirs. The principles of each of the UTES concepts is briefly described next and is linked to specific underground formations in the Netherlands that have favourable heat storage properties. In particular, many Aquifer-TESs and Borehole-TESs are currently installed in the Netherlands and there is great potential for further development.

Types of Underground Thermal Energy Storage

Aquifer-TES (ATES) is the storage of heat or cold in aquifers typically found at depths of several hundreds of metres. In the Netherlands the Water Act regulates all subsurface activities at depths shallower than 500 m (below ground surface). At greater depths, the Mining Act applies, with strict regulations for ATES, as this type of storage requires specialized drilling equipment and techniques. Storage in an ATES system is carried out through one or several wells that extract groundwater and reinject it into aquifers (Fig. 20.10a). The ATES design needs to meet some requirements such as specific sequences of interbedded sand and clay formations with certain thicknesses and permeabilities. Most of the targeted shallow aquifers are made of unconsolidated sand or gravel formations which are tens of metres thick, with a good permeability (>7 Darcy) and overlain by a layer of clay (aquiclude). Currently, there are more than 2800 ATES systems in operation worldwide, 99% of which are Low-Temperature ATES (<25°C) and 85% of which are located in the Netherlands (Fleuchaus et al., 2018). They can contain between 10,000 and 500,000 m^3 of water (to max. 5×10^6 m^3 for multiple systems in a network) with temperatures of up to 25°C (Bloemendal & Hartog, 2018). The power of small- and large-scale systems is 100-300 kW and 5-30 MW, respectively (Fleuchaus et al., 2018). Where water is stored at higher temperatures (up to 90°C), systems typically become cost-effective when the thermal power is more than 5 MW (Kallesøe & Vangkilde-Pedersen, 2019) and where associated storage capacity is more than 10 GWh.

Borehole-TES (BTES) utilizes one or several boreholes with depths from tens of metres up to 250 m. Each borehole contains a 'U' shaped pipe that is inserted into the borehole and then filled with a grouting material to anchor the pipe and to provide good thermal contact with the surrounding formation. The working fluid carrying heat or cold is circulated through the borehole, working as an underground heat exchanger as the heat (or cold) is transferred from the borehole to the surrounding rock formation in a closed loop. Geological formations used for BTES

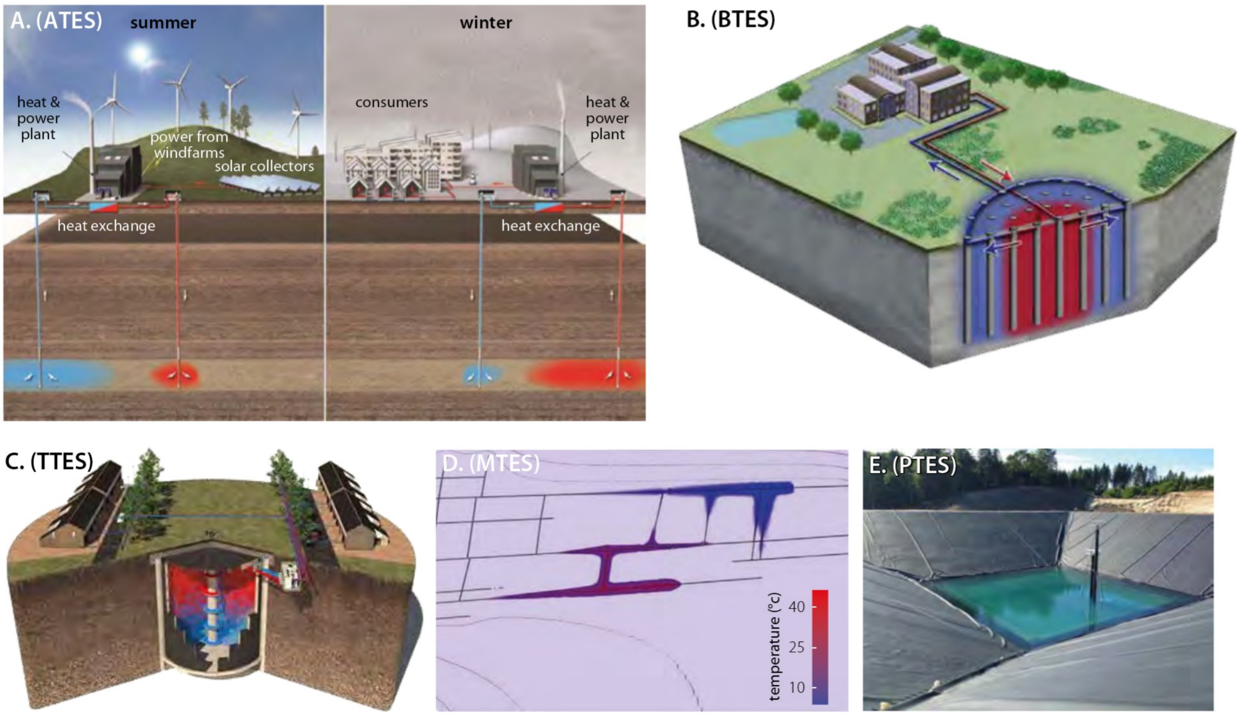


Figure 20.10. *Overview of different UTES storage types: a) Aquifer-TES (© Carsten E. Thuesen, GEUS 2017), b) Borehole-TES (© Underground Energy LLC), c) Tank-TES (© Ecovat), d) Mine-TES (© HEATSTORE 2021a, www.heatstore.eu), e) Pit-TES (© PlanEnergi).*

can range from unconsolidated material to rock (e.g. tight limestone or unfractured crystalline rocks) with or without groundwater, and in order to retain heat efficiently ideally have high heat capacity, low thermal conductivity, limited natural groundwater flow and/or low permeability. Single or small low-temperature BTES systems are typically connected to a single household or utility building. They can provide power of up to 10 kW per individual low-temperature BTES system, while multi-borehole systems can deliver power between 70 and 200 kW. About 75,000 small BTES systems are installed in the Netherlands (wkotool.nl). Large-scale high temperature BTES systems are often designed in radial clusters, with hot water circulating from the inner to the outer boreholes, or vice versa for cold water (Fig. 20.10b). In the Netherlands, an example of a relatively large-scale HT-BTES system is located in Beijum (Groningen), which was built in 1985. It stores solar heat at 60°C with a storage capacity of 600 MWh at a depth of 20 m in the Boxtel and Eem formations (Kallesøe & Vangkilde-Pedersen, 2019). Outside the Netherlands, an example of a large scale BTES system can be found in Brædstrup (Denmark), which stores 400 MWh with a water volume of more than 20,000 m^3 (HEATSTORE, 2021a).

Tank-TES (TTES) systems are (semi-)underground tanks or vessels storing hot water. Small aboveground/underground tanks, with volumes typically up to 12,000 m^3, are commonly used for daily or weekly storage. One of the largest aboveground thermal energy storage tanks is located in Berlin, Germany and has a storage volume of 56,000 m^3 and storage capacity of 2.6 GWh (Vattenfall, 2021). It can run at a maximum thermal output of 200 MW for 13 hours. In the Netherlands, there is a large aboveground storage tank in Diemen, 50 m high and 26 m in diameter, with a storage capacity of 22,000 m^3 that can supply heat to 75,000 homes in Amsterdam, Amstelveen and Almere (Vattenfall, 2013, 2022). Larger tanks may be required for long-term seasonal storage, and although they can be buried underground, they are not designed to take advantage of the thermal properties of subsurface geology. Underground TTES simply needs an easily excavatable soil. Tanks consist of an outer concrete vessel containing a highly insulated inner vessel (Fig. 20.10c). The energy is exchanged by pumping the hot or cold water from the vessel through a centrally located heat exchanger. The heated (or cooled) water is then returned to the vessel through diffusers at different heights, in such a way that the thermal stratification of the water in the vessel is preserved. This allows for high efficiency, as no water is pumped out of the vessel. An example of a large conceptual underground TTES is the one being designed by GroeneWarmte with a diameter of 30-48 m, a depth of 29-54 m and a storage capacity of 1.7 to 8 GWh (Ecovat, 2022).

Mine-TES (MTES) is the storage of excess heat in mine shafts at depths between a couple of hundred metres and up to 2 km, which are naturally or intentionally flooded with groundwater. Hot water (heated at the surface) is injected and maintained at a temperature higher than that of the rock in-situ (Fig. 20.10d). MTES is primarily limited by the availability and integrity of existing shallow-to-deep shallow mine shafts in heat- or cold demand areas. Systems already exist in which water is extracted from deep and shallow flooded mine shafts as a source of heat and cold. Examples of such systems are found in Heerlen, Saxony, Bochum and Essen in eastern Germany (HEATSTORE, 2021b). The Mijnwater project in Heerlen (southeast Netherlands) provides heating and cooling for 350 homes and 9 large utility buildings (mijnwater.com). In Bochum (Germany) a MTES is currently being designed (HEATSTORE, 2021b) and in the city of Kuusikonmäki in Vantaa (Finland), there are plans for the construction of a storage cavern in bedrock at a depth of a 100 m (Cavern-TES). It will store one million cubic metres of water heated up to 140°C by waste heat, and will have a total storage capacity of 90 GWh (Vantaan Energia, 2021).

Pit-TES (PTES) consists of a large shallow pit with walls that slope gently (~27°C) towards the centre and are covered with an impermeable plastic liner (Fig. 20.10e). This technology requires a stable soil to avoid bank instability and a low groundwater table and low natural groundwater flow to reduce heat losses. The water in the pit can reach a maximum temperature of up to 95°C. Like TTES, pit storage is also stratified by temperature and can be used as inter-seasonal storage for heat and cold, but also for daily or weekly use. A PTES usually stores volumes of 6×10^4 to 2×10^5 m^3. There are no plans yet for the construction of a PTES in the Netherlands. Six PTES systems have already been built in Denmark and more systems are planned (HEATSTORE, 2021b), such as a large one in Aalborg (5×10^5 m^3) which has a thermal power potential of between 10 and 40 MW and a storage capacity of 3-12 GWh (Danish Energy Agency, 2018; Fyhn, 2021). Table 20.7 summarizes the requirements and performance indicators for the five types of UTES discussed.

Suitable (hydro)geology for low- to high-temperature ATES and BTES

According to the current Dutch Water Law, the maximum temperature for subsurface injection is limited to 25°C at depths shallower than 500 m. This is labelled low-temperature (LT) and includes most of the ATES and BTES systems installed in the Netherlands so far. Medium (MT: 25-60°C) to high (HT: 60-100°C) temperature ATES and BTES require an exemption from the current legal framework.

ATES and BTES are considered very promising UTES technologies for the Netherlands. From an economic point of view, ATES and BTES have one of the lowest investment costs per unit of energy delivered and require a small surface area. They offer a wide range of market services and storage capacities (Yang et al., 2021), although their current application and future potential are greatly influenced by the suitability of the subsurface and potential interference issues with other activities in the shallow subsurface (e.g. drinking water production).

Future development of MT and HT storage systems can provide larger amounts of hot water to reduce peak demand (currently supplied by natural gas) and/or optimize renewable energy production. In particular, HT-ATES sourced with geothermal, waste or solar heat can be connected to a network to provide a stable supply of heat during the winter. This has an added value when combined

***Table 20.7** Summary of the requirements and key performance indicators for different underground thermal energy storage types (high and low temperature). Source: Van der Stoel (2022).*

	ATES	BTES	TTES	MTES	PTES
Subsurface requirements	***	**	*	***	*
Pre-investigation	***	***	**	**	**
Surface area[a] [m^2]	*	*	** ≤2500	*	*** ≥10^4
Storage volume [m^3]	250,000–10^6	>20,000	1000–98,000	25,000–10^6	50,000–500,000
Storage capacity [MWh]	15,000–55,000	>250	100–5000	1000–90,000	5000–40,000
Power [MW]	≥1	0.1–1.5	1–17	≤200	10–40
Investment costs [€/m^3]	5–10	20–50	150–280	≥80	25–40
Operation and maintenance[b] [%]	4–5	0.5	0.5	n.a	1
Recovery efficiency [%]	50–80	40–60	70–95	n.a.	70–90
Scalability	***	***	**	*	**

*** = high; ** = medium; * = low
[a] This excludes physical space needed for a technical room, as this is always required. [b] As share of investments cost per year.

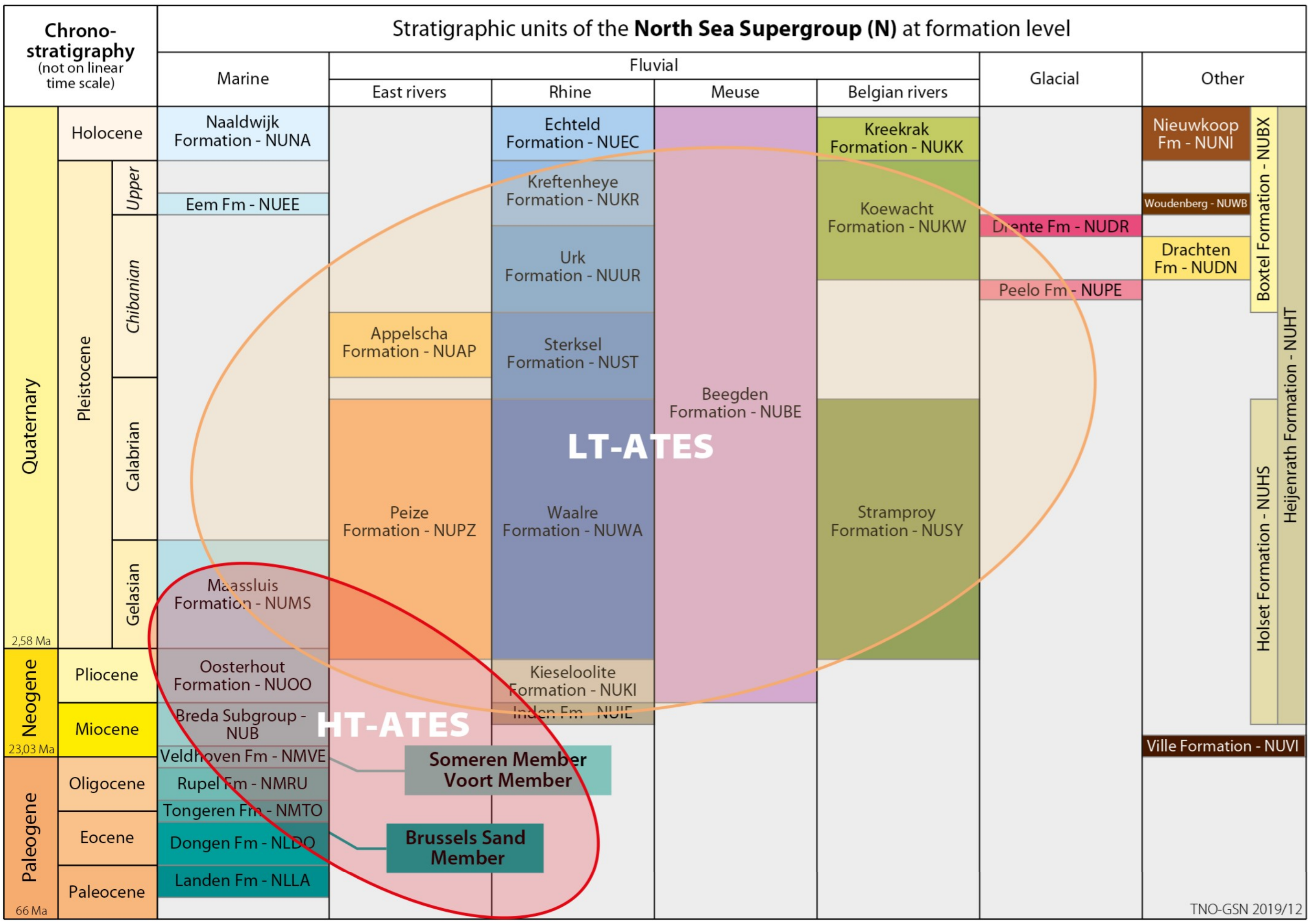


Figure 20.11. Stratigraphic units of the North Sea Supergroup (N) at formation level, with an indication of suitable formations for LT- and HT-ATES (modified from www.dinoloket.nl). Suitable formations for MT-ATES overlap with both LT- and HT-ATES, as this is highly dependent on the applied temperature level and local circumstances.

with geothermal heat, as the geothermal doublet can be used as a baseload, avoiding a suboptimal fluctuating production profile (Van Gessel et al., 2021; Mijnlieff et al., 2025, this volume).

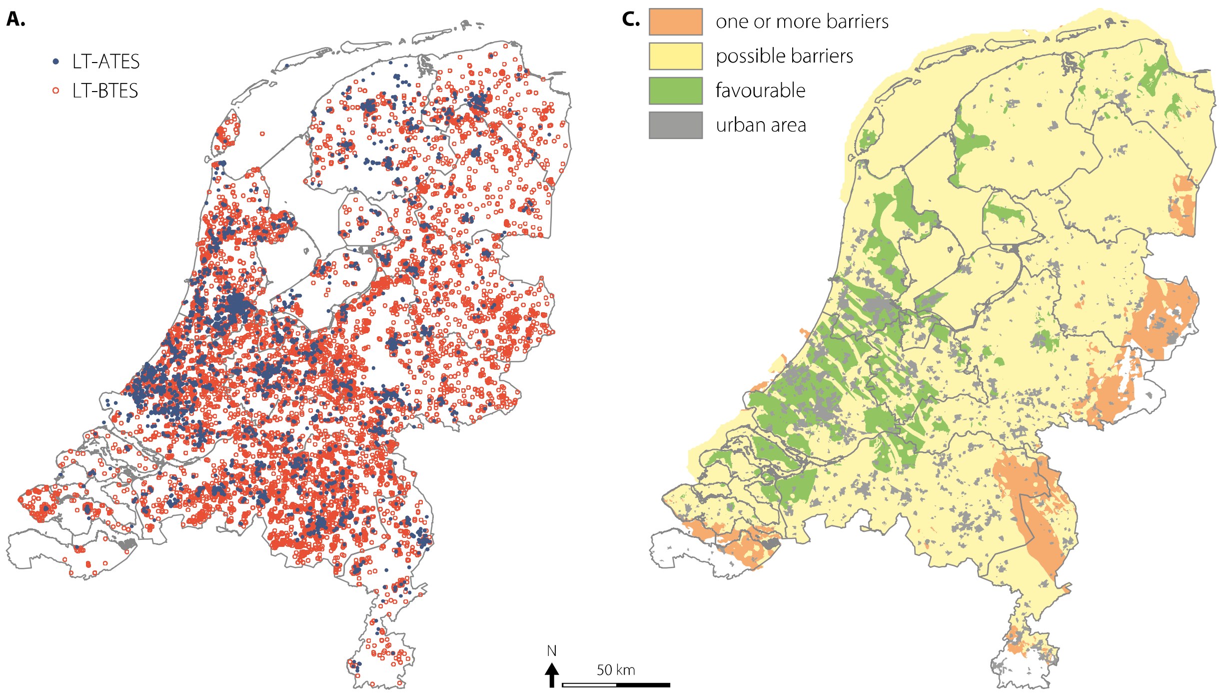
The Dutch subsurface has a great potential for the development of LT-ATES due to the large availability of aquifers with good permeability. These aquifers belong to deltaic depositional systems with marine, coastal and fluvial sediments deposited during the Paleogene, Neogene and Quaternary (Busschers et al., 2025; Munsterman et al., 2025, both in this volume). Successions of coarse-grained unconsolidated sands with high permeability (>30-40 Darcy) and thicknesses greater than 15 m intercalated with clay layers, provide the perfect confined stratified porous medium for the storage of large amounts of low-temperature thermal energy (LT-ATES). The targeted geological formations of the LT-ATES systems are mostly found in fluvial formations (Kreftenheye, Appelscha, Sterksel, Urk, Beegden, Peize- and Waalre, Kieseloolite) and glacial formations (Peelo, Drente; Fig. 20.11). Very few ATES systems have been installed in shallow marine formations such as the Maassluis and Oosterhout formations (Fig. 20.11), as they are known to have greater vertical heterogeneity and to contain an abundance of fine-grained sediments, which tend to migrate towards the producing well causing severe fines production and/or clogging (Cabeza, 2021).

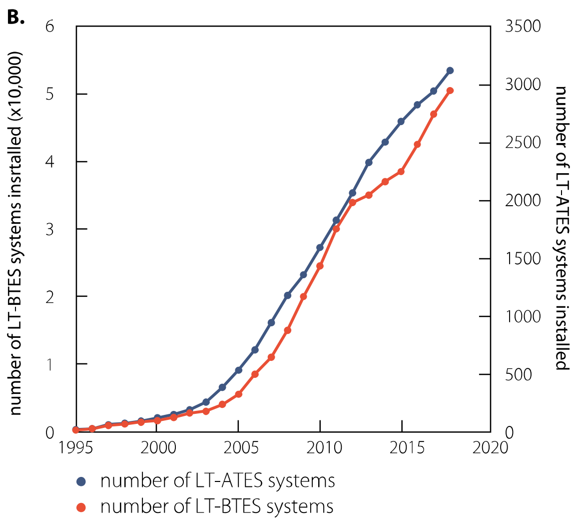
However, the Maassluis, and Oosterhout formations, and the Breda Subgroup seem to have the largest potential for HT-ATES, as they lie deeper (~200-500 m), are hotter and have medium- to fine-grained sediments with relatively low permeability, which can significantly reduce the 'buoyancy flow effect' that causes a reduction in the effective recovery (Marif, 2019).

Technically, HT-ATES systems could be drilled to a depth of at least 700 m with shallow drill rigs, but for greater depths more expensive drill rigs are required. The economic viability of HT-ATES systems also relies on the flow rate that can be achieved (Wesselink et al., 2018). Flow rate depends on reservoir permeability, which in deeper sand reservoirs is expected to be lower due to, among other things, compaction. In addition, some legal aspects will have to be considered, since these systems must comply with the regulations of the Mining Act rather than the Water Law. Shallow aquifers (<50 m) are mostly ruled out for HT-ATES as they lie above the freshwater/to brackish/salt water transition and as such are often part of the (strategic) groundwater reserves.

Subsurface potential maps for existing systems

The potential for LT-ATES and LT-BTES in the Netherlands has already been demonstrated with the large number of systems installed during the last 25 years (Fig. 20.12a and b). HT-ATES uses deeper formations for which the subsurface potential is less well known and the requirements are slightly different. Dinkelman et al. (2020) applied a pre-defined set of subsurface criteria to assess and map





D.

Parameter	Barrier	Possible barrier	Favourable
Lithology	no data available on national scale		
Depth		<50, >500 mbgs*	50-500 mbgs*
Thickness sand layer	<10 m	10-15 m	>15 m
Horizontal hydraulic conductivity – Kh value	<5 m/d		≥5 m/d
Presence of confining cap layer (clay)		thickness <5 m	thickness >5 m
Faults		<1 km	>1 km
Groundwater flow velocity		>25 m/yr	<25 m/yr
Chloride concentration		<1 g/l	>1 g/l

Figure 20.12. *a) ATES and BTES systems in the Netherlands (wkotool.nl). b) Cumulative amount of LT-ATES and LT-BTES installed (STOWA, 2020). c) Potential map for areas with favourable geological formations for the development of HT-ATES in the Netherlands shown as favourable (green), less favourable due to presence of possible barriers (yellow) and unfavourable (one or more barriers). This is based on the criteria depicted in the table (d) such as depth, thickness, hydraulic conductivity of the aquifer and the presence of a confining layer (aquitard) (Dinkelman et al., 2020). (*) mbgs: metres below ground surface.*

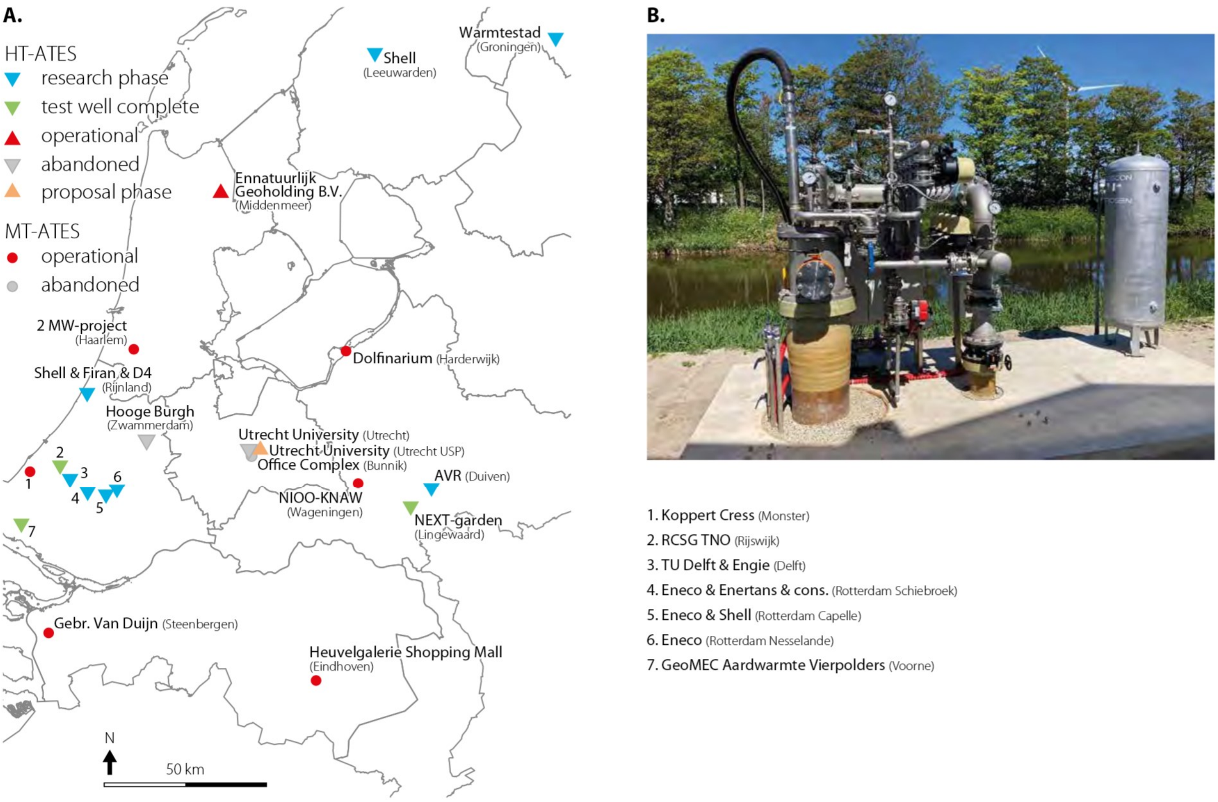


Figure 20.13. *a) Status of MT-ATES and HT-ATES (research) projects in the Netherlands (from publicly available information as of 2023). b) Hot well surface equipment of the HT-ATES installation of Ennatuurlijk Aardwarmte in Middenmeer developed in the HEATSTORE project (source: IF Technology).*

potential obstacles for HT-ATES. The most favourable areas for HT-ATES projects are concentrated in the west of the Netherlands (Fig. 20.12c and d). Less favourable areas are areas where one or more barriers may be present due to less good properties of the subsurface. In addition to the subsurface potential, other factors are important for the successful development of an HT-ATES system. The technical requirements are a good heat recovery efficiency (minimum 60-90%), the availability of a heat source and heat demand (HEATSTORE, 2021b). During the production or recovery period, the produced water temperature will drop over time and a heat pump may be required to raise the temperature of the water produced. Scaling and corrosion issues in the wells can also complicate operations. The economic requirements of a HT-ATES system are determined by the seasonal variations in the volumes and temperatures of heat demand, combined with the presence of heat sources with low marginal costs of production (e.g. waste, geothermal or solar heat; see HEATSTORE, 2021b). The operating temperature of the heating network is especially important, since it often determines the difference in temperature between the hot and cold wells. This, together with the flow rate and the duration determines the energy capacity of the storage project. Storage with high power and/or storage capacity significantly reduces the cost of storage per unit of energy. Experience from previous projects and feasibility studies indicates that the power of a HT-ATES should be at least 5-10 MW (thermal) and with an energy storage capacity equivalent to 2500 annual hours at full load. For the Netherlands, this equates to the annual heat demand of ~1200-2500 households.

Currently, several MT-ATES and HT-ATES projects are in operation (Fig. 20.13a). Two HT-ATES systems were operational already in the Netherlands in the 1980s, but were eventually shut down due to technical failures, lack of economic incentives due to the competition with low natural gas prices and a general mismatch between supply and demand (Bakema & Drijver, 2019). In the Netherlands, the HT-ATES in Middenmeer is an example of a successful project commissioned in 2021 (Fig. 20.13b). At Middenmeer, the operating geothermal system supplies hot water at ~85°C to nearby greenhouses, but in periods of low demand, the excess heat produced is stored in an aquifer located at a depth of 360-380 m in the shallow marine Maassluis Formation (Oerlemans et al., 2022).

The current energy transition is an incentive for the development of new HT-ATES projects. Many research institutes and industry stakeholders around the world are collaborating to investigate, design and implement HT-ATES systems. Examples are the European HEATSTORE project (HEATSTORE, 2021a,b; www.heatstore.eu) and PUSH-IT (www.push-it-thermalstorage.eu). In the Netherlands, initiatives such as the WarmingUP project continue investigating HT-ATES with the aim of removing technical, legal and economic barriers by 2025 (www.warmingup.info).

Long-term (permanent) underground storage

Storage of production water and filtrate residues

In the Netherlands, two main types of water are injected in the underground for permanent storage. One type is the water produced during oil and gas extraction, and another are the filtrate residues left behind after purification of surface water for drinking purposes.

During oil extraction, some of the deep underground water is brought to the surface. To a lesser extent this also occurs during the final phases of natural gas extraction. Although this so-called 'production water' is separated from the oil and gas at the surface, it still contains trace amounts of oil or gas and radioactive elements. It also contains traces of chemicals used during the production process, such as corrosion inhibitors used in wells or glycol or ethanol used in the gas treatment facility. Production water can be managed in two ways, namely by reinjecting it back into the oil or gas field, into a deep nearby aquifer, or by cleaning it and discharging it to the surface. The balance between these options is made in accordance with strict regulations to protect people and the environment (SodM, 2005). For offshore, the cleaning and disposal of production water in the sea takes place in accordance with the OSPAR convention (Karman & Smit, 2019; www.ospar.org). In practice, it seems that when large volumes are involved, reinjection is the most environmentally friendly form of disposal (Brolsma et al. 2017). Once reinjected into the field, the same top layer that sealed off the oil, gas or adjacent aquifers for millions of years ensures the safe and permanent storage of these waters. Two important factors are considered for the reinjection of water in an oil and/or gas field. In the interest of containment and risk of seal fracture the field used for water injection must not be seismically active and no more water can be injected into the field than the original volume of oil and gas.

Reservoirs used for the injection of production water in the Netherlands are mainly located at depths between 0.7 and 3.0 km. They consist of sandstones belonging to the Rijnland Group and Upper Rotliegend Group and carbonates of the Zechstein Group (Hoving et al., 2023). There are currently nine onshore locations where production water is regularly injected into depleted oil/gas fields. These include the Groningen (Borgsweer), Pernis-West, Rotterdam, Schoonebeek, Rossum-Weerselo, Bergermeer, Starnmeer and Nijensleek fields. In the Schoonebeek oil field, the injected steam, which has allowed the production of the high-viscosity oil since 2011, is re-produced as brine at a rate of 6000-12,000 m^3/day. Part of this brine is reinjected into the field and the rest is transported and injected into the Rossum-Weerselo field. Some water was also injected into the Tubbergen and Tubbergen-Mander fields between 2015 and 2016. From all deep reservoir injection activities in the Netherlands since 1972 (Borgsweer), there have been no reports of chemical reactions in the reservoirs or seal layers or waste causing any negative environmental impact in shallower formations (Hoving et al., 2023). The fact that in all cases the aquifers used for water disposal lie much deeper than any drinking water aquifer (>500 m), means that all these activities are in accordance with the General Provisions Act and are managed under it (WABO, 2022).

As for the permanent storage of filtrate residues in the Netherlands, there is currently one underground storage in Andijk. At this location, the surplus water flow after water purification of the IJsselmeer lake is injected for permanent storage in brackish aquifers at a depth of 200-250 m. The injection flow rates are a few tens of m^3/hour. The reservoirs used are the Peize and Waalre formations of the Upper North Sea Group, composed mainly of stacked fining-upwards fluvial sequences. In the past there have been other permanent water storage systems in shallow reservoirs (100-500 m) in Noordbergum, Ridderkerk and Zevenbergen. Despite the shallow depth at which these waters are injected, the Mining Act also takes into account the permanent underground storage of filtrate residues.

Underground storage of CO_2

The Dutch government has a target to reduce greenhouse gas emissions from the Netherlands by at least 49% by 2030 compared to 1990 levels, and 95% by 2050 (MEACP, 2019a) to align with the increasing EU emission reduction targets (EC, 2023). Underground CO_2 storage (carbon sequestration) is nowadays considered one of the technologies that can help to reduce the emissions of CO_2 into the atmosphere. Despite the current transition to renewable energy sources, 80% of the world's energy supply is still derived from fossil fuels (IEA, 2022b). Large amounts of CO_2 can be captured from large point-source emitters. These sites include power plants, various large industrial facilities (e.g. steel and cement manufacturers) and hydrogen production sites. In power plants and industrial facilities CO_2 can be captured 'post-combustion', while in hydrogen production sites CO_2 is captured 'pre-combustion'. CO_2 can be captured using solvent-based (in liquid) or sorbent-based (on solid particles) methods, through cryogenic separation, oxygen-fired combustion or via membrane separation (Ringrose, 2020). CO_2 can be transported to the storage site using pipelines, ships or trucks, ideally in dense or liquid phase, depending on operating pressure and temperature. A CCS project can be combined with carbon capture and utilization (CCU), when CO_2 can be utilized, for instance in the production of high value chemicals, in greenhouse horticulture or in geo-methanation (Zauner et al., 2022).

For long-term geological storage, CO_2 is injected into suitable porous underground reservoirs (e.g. sandstones or carbonates) beneath thick and continuous overburden formations with good sealing properties (e.g. salt or shale). The suitability of the reservoir depends on the storage resources, injectivity and containment characteristics. Reservoir depth for CO_2 storage should be greater than ~800 m in order to make efficient use of pore space when storing CO_2 in the dense (supercritical) phase. Besides depleted gas and oil reservoirs, and saline aquifers, some CO_2 storage projects have used other reservoirs such as coal seams, volcanic rocks (basalt) and underground caverns (CO2RE, 2022). For the Netherlands in particular, depleted natural gas reservoirs, and to some extent also aquifers, are currently considered the most promising storage sites (CATO, 2022).

Several containment mechanisms contribute to the storage of CO_2 in porous reservoirs (Frykman, 2002; Benson et al., 2005; Fig. 20.14). In depleted gas fields, the primary containment is structural trapping. For aquifers, additional important mechanisms are residual trapping (the CO_2 is kept in pores by capillary forces) and dissolution of CO_2 into the brine. On longer timescales, mineral precipitation also plays a role (dissolved CO_2 reacts with the rock matrix and precipitates as a mineral). Lateral and vertical heterogeneity determines whether a free CO_2 plume forms or whether most CO_2 is captured by capillary forces. The lateral extension of the top seal is a critical factor only for trapping the 'free' CO_2 plume. Once dissolved, the CO_2 remains in the reservoir, since brine with dissolved CO_2 is heavier and tends to sink to the bottom (Zhang et al., 2011).

A significant number of research projects on CCS have been carried out in recent decades. In the Netherlands, the large research program known as CATO (CO_2-Afvang, Transport en Opslag, 2004-2014) investigated many of the fundamental aspects of the capture, transport and storage of CO_2 (Lysen et al., 2005; CATO, 2022). The feasibility of CO_2-enhanced coalbed methane production in the former mining area of Limburg was also considered but was ruled out due to high investment costs (Van Bergen et al., 2005; Van Bergen et al. 2025, this volume). Following extensive research and concerning the fact that CCS is technically feasible and deployable (CO2RE, 2022) and combined with the availability of public funding, several large-scale CCS projects are now underway, with injection scheduled

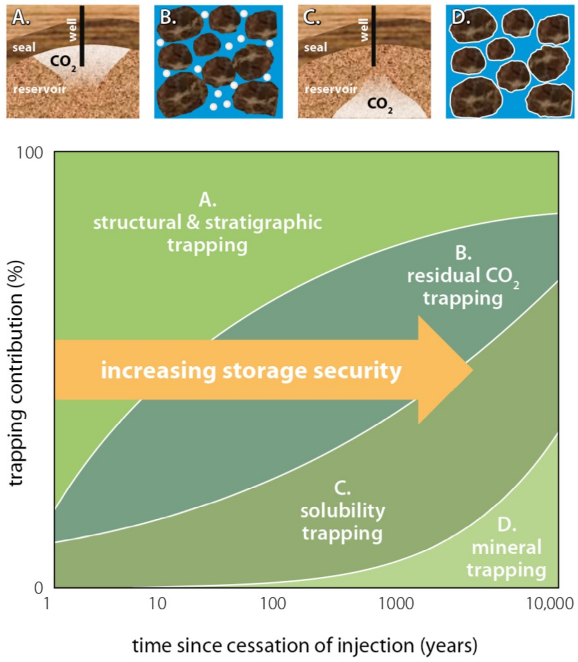


__Figure 20.14.__ Schematic representation of the contribution of trapping mechanisms for aquifers (modified from www.bigskyco2.org/node/127 and Benson et al., 2005).

to start in 2025 to 2027. In the following, we describe the development of CCS in the Netherlands with focus on the scientific, technological, economic and societal aspects and the search for potential suitable underground reservoirs onshore and offshore.

In 2004, a small-scale pilot CCS project began in the offshore K12-B natural gas field located 150 km northwest of Amsterdam (Vandeweijer et al., 2021). The natural gas reservoir (Upper Slochteren Member) lies at a depth of around 4000 m and is sealed at the top by the evaporites of the Zechstein Group. Since 1987, the field has been producing natural gas with a relatively high CO_2 content (13%), which was initially separated and vented at the site. The start of the CCS project involved the capture and reinjection of the CO_2 produced at a rate of 0.02 Mt/yr. A few years later, the Shell Pernis refinery in the Rotterdam harbor area proposed a CCS project to inject CO_2 (as by-product of the production of hydrogen) into two nearby depleted natural gas fields, Barendrecht (Cretaceous at 1700 m depth) and Barendrecht-Ziedewij (Triassic at 2700 m depth), both in sandstone reservoirs. The project plan spanned two phases. Phase-I was a 3-year injection into the Barendrecht reservoir and phase-II a 25-year injection in Barendrecht-Ziedewij, at rates of about 0.4 Mt/yr, resulting in a combined (storage) resource estimated at around 10 Mt. Although technically sound, the project encountered strong societal opposition and was cancelled by the Dutch government in November 2010 (Feenstra et al., 2010). Today, only a relatively small amount of CO_2 (0.5 Mt/yr) from Shell's refinery in Pernis and Alco's bioethanol plant in Rotterdam is fed to nearby greenhouses.

After Barendrecht, other onshore natural gas fields were investigated as potential candidates for CCS, but did not develop into projects, mainly due to strong public opposition. CCS research was then redirected to offshore locations, giving rise to the **ROAD** project (Rotterdam Opslag en Afvang Demonstratieproject; Neele et al., 2011; Read et al., 2019). This project aimed to capture CO_2 from coal-fired power plants on the Maasvlakte and store it in the nearshore P18-4 depleted natural gas field, 20 km off the coast (Arts et al., 2012). The project was suspended in 2017, this time due to the collapse of the CO_2 price, which undermined the original business case.

While a combination of economic, political and social factors has led to the cancellation of Dutch CCS projects so far, this trend seems to be changing. The 2015 Paris Agreement and the more recent Dutch Climate Agreement (2019) have led to an increase in political, industrial and societal support for CCS. The focus of CCS projects has shifted from coal-fired power plants (ROAD) to industrial processes that may have no (near-future) alternatives to fossil fuels. A consortium under the name of **Porthos** (Port of Rotterdam CO_2 Transport Hub and Offshore Storage) was formed in 2017 to continue looking for new opportunities for CCS (www.porthosco2.nl). Porthos continues the work done on the ROAD project by updating the transportation and storage design and expanding the set of offshore natural gas fields considered. The goal of this consortium is to enable the capture and storage of 37.5 Mt (2.5 Mt/yr) of CO_2 from the Port of Rotterdam for a period of 15 years starting in 2026, storing it in the offshore block P18 in Lower Germanic Trias Group sandstone reservoirs at ~3500 m depth.

Athos (Amsterdam-IJmuiden CO_2 Transport Hub and Offshore Storage) was another promising offshore CCS project aimed at the large-scale capture and storage of CO_2 generated from major industrial facilities in the Amsterdam area. The decision of one of the partners (TATA steel) to redirect investment towards new clean steel manufacturing technologies involving the use of hydrogen, halted the project in 2021 (ATHOS, 2022). A new initiative named **Aramis** aims to create synergies between different CCS projects (including Porthos) by collecting CO_2 captured by many emitters and transporting it from Rotterdam to several offshore underground storage locations

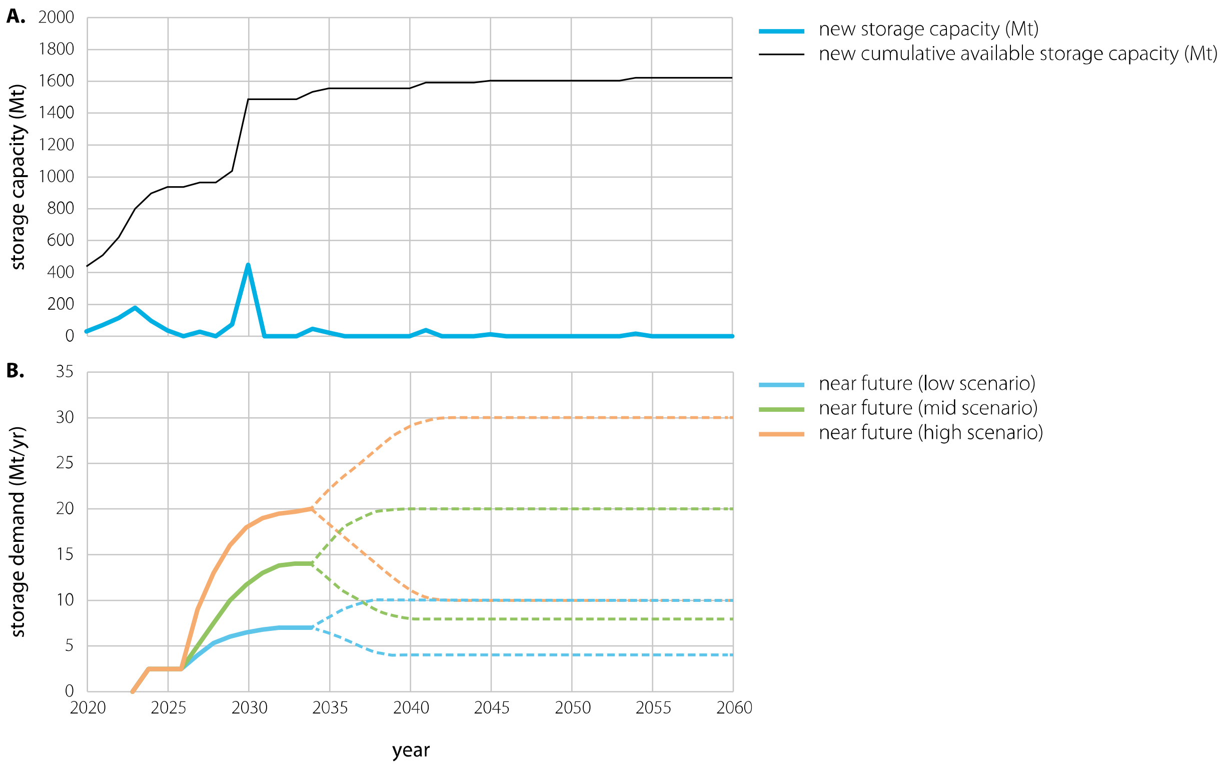


__Figure 20.15.__ a) Projection of available (cumulative) storage capacity in Megatonnes (Mt). Data from EBN and Gasunie (2018). b) Projection of the possible future demand for storage. Numbers for 2030 are based on the Dutch Climate Agreement (49% emission reduction compared to 1990) with upsides created based on the new EU national climate targets (55-60% reduction as compared to 1990). Long-term targets are uncertain, but are estimated based on aggregate scenarios for 2050.

(see www.aramis-ccs.com). The project is intended to be open access, potentially connecting several different emitters and storage operators. Possibly, foreign emitters will also be connected through pipelines or ships. This could be the first time multiple emitters and multiple storage locations are connected in one CCS system. The consortium anticipates that most of the depleted gas field candidates for storage are likely to be located in the K and L quadrants of the Dutch central offshore (approximately 150 km from shore), although other candidates may also be included.

In 2018, EBN and Gasunie conducted a portfolio study to estimate the CO_2 storage resources in depleted offshore gas fields in the Netherlands, (EBN & Gasunie, 2018). The results show an estimated storage potential of about 1.6 Gt (Fig. 20.15a), but the total storage resources do not include aquifers, which have yet to be assessed. The ultimately available CO_2 storage capacity will depend on: i) the timing of the CO_2 supply from onshore; ii) the rate of dismantling of offshore infrastructure; and iii) economic feasibility. Despite these uncertainties, the Netherlands' offshore storage resources are significant considering that the Netherlands produces on average 160 Mt CO_2 each year, of which up to 20% (~30 Mt/yr) can be considered for CCS (EBN & Gasunie, 2018). Therefore, the anticipated availability of storage volume in depleted offshore gas fields over the next 20 years is substantially larger than the expected storage demand (Fig. 20.15b). Exactly when storage potential will be released depends on when production from a platform ceases due to economic considerations such as the technically possible production rates, relevant gas prices applicable at the time and operating costs.

The European Commission has implemented various incentives to stimulate CCS (EC, 2022): i) the Emission Trading Scheme (ETS); ii) subsidies for viability studies and demonstration projects of CCS; iii) Emission Performance Standards, since certain facilities are subject to a maximum emission standard per unit of product. Recently, in the Netherlands, the subsidy scheme called 'Stimulation of Sustainable Energy Production and Climate Transition' (SDE++) was introduced to make CCS affordable by compensating for the difference between the cost price and the market value (RVO, 2022). To date (2022), these incentives have resulted in only a limited number of CCS projects and infrastructure.

Many other countries in Europe have shown interest in CCS. The two most prominent countries are the United Kingdom and Norway. Norway already has two fully operational projects (Sleipner and Snøhvit). Apart from small projects for research purposes, not many industrial-scale projects in Europe have progressed to an operational phase, for reasons very similar to those in the Netherlands.

Summary and outlook

The Dutch subsurface has been a major source of raw materials and energy resources in the form of oil, gas and coal, and will continue to play an important role, unlocking new renewable sources and supporting the transition to a renewable energy system with storage. After more than half a century of self-sufficient supply of natural gas, the decline in hydrocarbon production in the Netherlands is increasing the dependence on foreign energy resources and the need for alternative energy supply sources. Meanwhile, the country is embarking on an energy transition largely driven by important global environmental, climate and geopolitical challenges. The ongoing transition is towards a new energy system powered by large-scale variable renewable sources (solar and wind) complemented by energy imports. Along with already existing fluctuations in energy demand, the inevitable variability in energy supply results in an increased need for energy storage. The Dutch subsurface is very suitable, and has a great potential, for storing not only large amounts of energy, but also feedstocks and waste. Therefore, the role of the subsurface in the energy system is shifting from being an energy provider to being more of a service provider for (energy) storage.

This chapter provides an overview of the most relevant state-of-the-art underground storage technologies for the Netherlands. It shows that, compared to the previous edition of this chapter, a lot of research has already been carried out revealing the large potential of the subsurface as an energy storage services provider for fuel-based energy carriers, electricity and heat. In addition, permanent underground storage options will continue to provide very important services to the energy system, beyond the current permanent storage of production water from oil and gas extraction and filtrate residues. The energy storage potential in general and the storage potential for CO_2 in particular are estimated to be large with projects underway or about to be implemented. This will make the subsurface very relevant in the energy transition beyond the era of fossil fuels.

It is evident that the further implementation and upscaling of current and new underground storage technologies cannot be achieved without a good understanding of the subsurface, as well as an adequate insight into energy systems dynamics, commercial viability and social drivers that steer the need for storage development and integration. In the Netherlands, much of the subsurface knowledge comes from long-standing exploration and production activities for coal, oil, gas and salt, or from dedicated surveys (e.g. geothermal) over the past century. The availability of this enormous amount of data and information is of great benefit for the identification and study of a wide range of natural reservoirs as potential candidates for reuse and development as underground storage. This includes (nearly) depleted oil and gas fields, aquifers and engineered underground cavities. It is important to note that in the Netherlands, the geological setting (and the corresponding levels of uncertainty), as well as land use vary greatly from region to region. As a result, related regional strengths, weaknesses, opportunities and threats are also quite variable. With all this in mind, it is essential to investigate whether specific underground storage technologies can be developed and deployed in a safe, responsible and timely manner to meet the scale of storage demand for a particular energy carrier or feedstock and the disposal of any byproduct. In addition, it will be necessary to examine the potential short- and long-term consequences and risks associated with each particular type of underground storage and also how to limit and mitigate them and assess their impact in case of poor management (Dost et al., 2025; Fokker et al., 2025, both in this volume) and potential conflicts between different subsurface users (e.g. hydrogen storage, CAES and CO_2 storage) and surface users (e.g. spatial claims for nature reserves, groundwater and urban areas).

Local and regional authorities and communities should be involved in all phases of the life cycle of (large-scale) underground (energy) projects to ensure societal embeddedness and support and embrace adequate consideration of changing social needs, interests and opinions on how the subsurface should be used. Due to the difficult societal acceptance of the exploration and production of natural resources onshore, we show how alternative sites for underground storage in offshore areas are currently being investigated, as it is the case for CCS and UHS. Further research should focus on the realization of underground storage pilot and demonstration projects, their integration with aboveground storage technologies (as new hybrid energy storage solutions) and the economic, environmental and societal feasibility in the context of the Netherlands and global energy markets.

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Digital map data

Spatial data of figures in this chapter for use in geographical information systems can be downloaded here: https://doi.org/10.5117/aup.28164377.

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