Assessment of underground energy storage potential to support the energy transition in the Netherlands

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demonstrate the large potential storage capacity for natural gas and hydrogen in depleted gas fields, and natural gas, hydrogen and compressed air in salt caverns.

Introduction

With the Paris Climate Agreement, the world faces the important task of reducing CO_2 emissions to 95% below 1990 levels in 2050. In the Netherlands various measures are being designed for this task, including a transition from fossil fuels towards clean and sustainable energy sources, implementation of energy saving and efficiency measures, and Carbon Capture Utilization and Storage (CCUS). Underground storage can play an important role in delivering solutions. The subsurface is probably the best place for the temporal storage of vast amounts of various forms of energy and the only space for permanent storage of large volumes of CO_2.

The Ministry of Economic Affairs and Climate commissioned in 2018 a technical assessment on the various options for underground storage in the Netherlands. The technologies investigated were those that can support the large-scale increase of renewables, secure energy supply, and can be implemented in the subsurface (depths >500 m) and deployed within the next 10-30 years. This paper presents part of the results showing the large potential storage capacity for natural gas (1939 Twh$_t$) and hydrogen (456 Twh$_t$) in depleted gas fields, and natural gas (184 TWh$_t$), hydrogen (43 TWh$_t$) and compressed air (0.58 TWh) in salt caverns.

Present-day large scale storages in the Netherlands

Until recently the Netherlands was one of the largest producers and exporters of natural gas in Western Europe. This was the result of the discovery of the Groningen gas field in 1959, the largest field in Europe and the tenth-largest in the world, containing ~2900 billion m^3 of natural gas reserves (28000 TWh$_t$) (MEAC, 2018a). The exploitation of natural gas led to the discovery of new gas/oil fields (so-called small fields, Figure 1) and the development of a national gas transportation and distribution network during the 1960s and 1970s, including connections to surrounding countries to allow export and transit of natural gas. The annual consumption of natural gas in the Netherlands has remained fairly constant for the past half a century. Today, 41% of primary annual energy consumption (877 TWh$_t$) is still being generated with natural gas (359 TWh$_t$/year or 36 billion m^3/year), covering the demands from the built environment (85%), agriculture and land use (47%), power plants (45%), industry (24%) and transportation (<1%) (CBS, 2019). The national demand for natural gas has a strong seasonal fluctuation, especially in the built environment where demand in the winter triples as natural

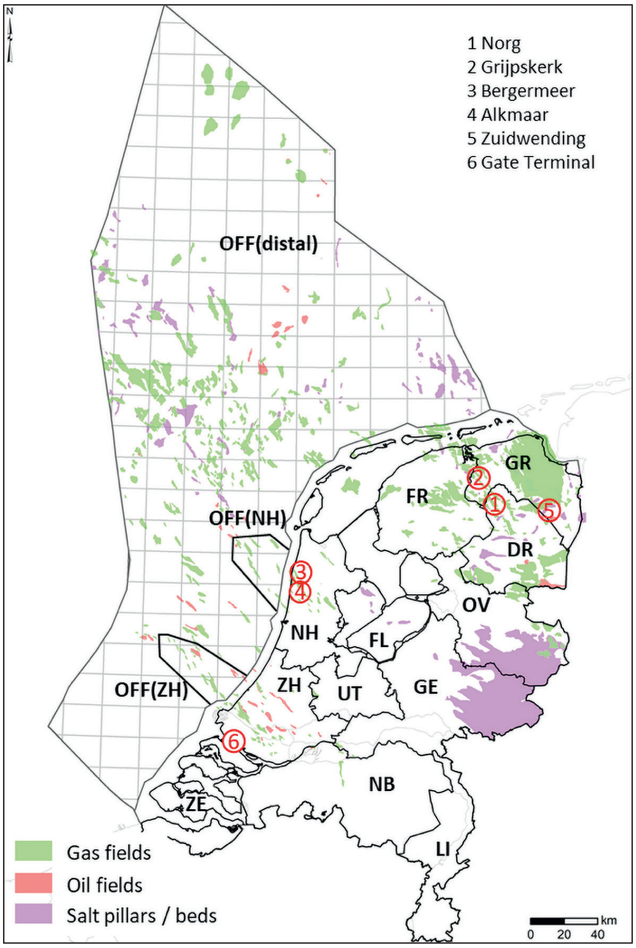

Figure 1 Demarcation of the Dutch provinces and the three offshore areas for which the underground storage capacity was assessed (see Table 3 for province names-acronyms). The contours of the gas/oil fields, rock salt formations — potentially suitable for cavern development — and the current gas storages are also shown.

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Location	Storage	Start year	Working/cushion volume (billion m³)	Production/injection capacity (million m³/day)	Number of wells
Norg	Gas field	1997	6.0/22.3	76/36	6
Grijpskerk	Gas field	1997	2.5/11.4	50/12	10
Bergermeer	Gas field	2015	4.1/4.3	57/42	12
Alkmaar	Gas field	1997	0.5/3.1	36/4	9
Zuidwending	Salt cavern	2011	0.3/0.3	43/26	10
Gate Terminal	LNG tanks	2011	0.3/-	23/-	-

Table 1 Some technical details of the current five underground gas storages and one surface storage in the Netherlands (see location in Figure 1).

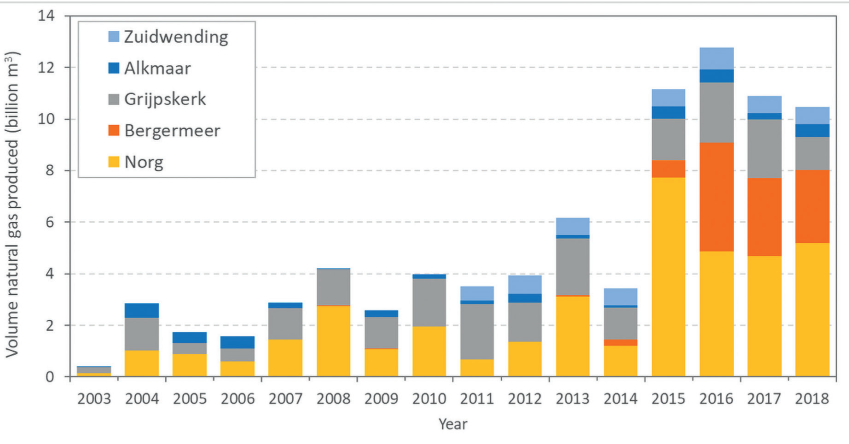

Figure 2 Annual natural gas volumes withdrawn from the 5 underground storages in the Netherlands since 2003. The ramp up since 2015 is due to the replacement of the Groningen swing capacity.

gas is used as a source of heat (from ~5 billion m^3 in summer to ~15 billion m^3 in winter).

Since 1973 the Groningen field has fulfilled the roles of both volume producer and balance producer. In particular its swing production pattern, with ca.10 billion m^3 in the summer to 30 billion m^3 in the winter, has been key to guaranteeing the seasonal demand in the Netherlands and neighbouring countries. However, recent concerns surrounding recurrent induced seismicity in the Groningen field area, have led to the decision to gradually reduce its annual and swing production capacity from 2014 onwards and to cease production by 2030 (MEAC, 2018b). Hence its role as balance producer has been taken over by the existing underground gas storages in the Netherlands (Figure 2).

Since the late 1990s a series of underground natural gas storages have been constructed in the Netherlands: four large ones in depleted gas fields (Alkmaar, Bergermeer, Grijpskerk and Norg) and a smaller one in a cluster of five salt caverns in Zuidwending (Figure 1, Table 1). Two different gas qualities are used in the Netherlands. Low-calorific gas (L-gas, Groningen quality), mainly used for heating of the built environment and greenhouses, is being stored in Norg, Alkmaar and Zuidwending. As the production restrictions on the Groningen field continue, larger volumes of pseudo-Groningen gas need to be fabricated by mixing imported high-calorific natural gas (H-gas) with nitrogen. H-gas is stored in Grijpskerk and Bergermeer and is mainly used for industrial purposes and the generation of electricity in gas-fired power plants. H-gas quality derives from the gas production of the small fields and imported gas. The Netherlands also has an LNG import terminal (Gate Terminal) in Rotterdam with three storage tanks (Figure 1, Table 1). The total current storage capacity of natural gas in the Netherlands is considerable (13 billion m^3) when compared to the cumulative natural gas storage capacity in Europe, which is around 145 billion m^3 spread over 148 locations in 28 countries (GIE, 2018).

Energy transition and underground storage

Despite the desire to phase out the use of natural gas and other fossil fuels in the Netherlands (Dutch Central Government 2013 and 2018), current developments show that the pace at which renewables are being implemented is not fast enough to cover the large energy demands, specifically heat demand during winter. Hence, underground energy storage is expected to continue playing a key role in balancing fluctuations in the seasonal heat demand. In addition to these fluctuations, the energy availability is also influenced by an increasing volatility in electricity generation from wind and solar. This is especially the case in periods of low wind and sun lasting from a few days up to a week. These periods of energy shortage may not be mitigatable with above ground storage solutions, which are typically characterized by much lower power rates and capacities than their subsurface counterparts (Figure 3). In this paper, as part of a larger assessment, we focused on three of the largest forms of underground energy storage: natural gas and hydrogen storage in depleted fields and salt caverns, and compressed air storage (CAES) in salt caverns.

Despite the growing development of district heating networks, various studies suggest hydrogen as a potential candidate to replace natural gas as a source for balancing peak and seasonal demand (Van Wijk, 2017; Weeda and Gigler, 2018; Gasunie, 2018). It can be a clean and sustainable energy carrier, easy to transport, and store underground in large quantities (Figure 3). Currently the Netherlands annually produces ca. 10 billion m^3 of hydrogen for the feedstock industry. This hydrogen is fabricated from natural gas by means of steam methane reforming (SMR). This hydrogen is known as 'grey hydrogen' since during production greenhouse gases are emitted as by-products. Future initiatives consider combining SRM and carbon capture and storage (CCS) to produce 'blue hydrogen', and ultimately 'green hydrogen', generated by water electrolysis powered by renewables (e.g. wind and solar) with no greenhouse gas emissions. Increases in the use of blue and green hydrogen are foreseen in many sectors such as transport and mobility (fuel cells), industry, the built environment and possibly also for production of electricity. Green hydrogen can also serve as a more cost-efficient energy carrier for transporting large quantities of energy from distal offshore wind farms (molecules instead of electrons).

Underground (pure) hydrogen storage is a proven technology. Examples are found in salt caverns in the United States (e.g. Clemens Dome, Moss Bluff) and the United Kingdom (e.g. Teeside) serving as a secure buffer for industrial feedstock demand. Methane mixtures with different percentages of hydrogen (so-called city gas) have been successfully stored in aquifers (e.g. Beyne in France). There are also some recent pilot projects on hydrogen storage in gas fields (e.g. SunStorage project (Austria), HyChico project (Argentina)). In the Netherlands some research have been conducted on the effects of hydrogen injection in natural gas networks (DBI-GUT, 2017).

Another form of large-scale underground energy storage that could contribute to the security of supply is CAES. At times of excess production of electricity, this may be used to store compressed air in salt caverns (Succar and Williams, 2008). During periods of power shortages, the compressed air can be released driving high-pressure turbines with a capacity of several hundreds

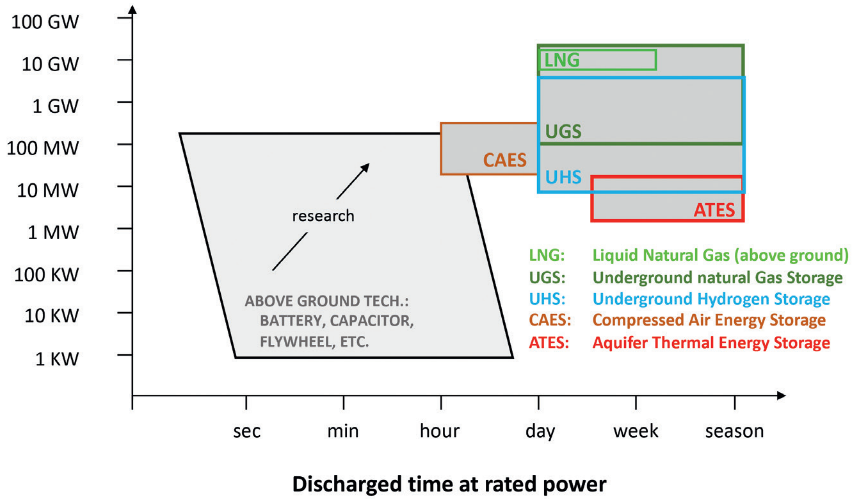

Figure 3 Overview energy storage techniques and indicative power ratings and discharge time (after TNO & EBN, 2018).

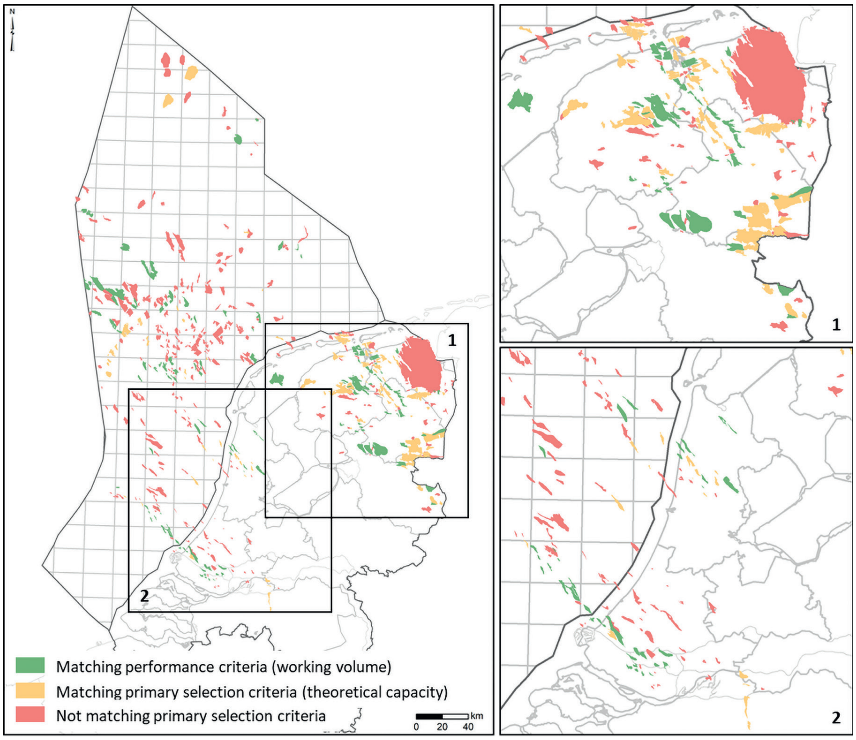

Figure 4 (Left) Overview of the selected fields based on the criteria for theoretical capacity and working volume. (Right) Zoom in of areas 1 and 2.

Input parameter	Value	Units	Remarks
Reservoir layering	Single layer	-	All reservoirs are modelled as homogenous single layered reservoirs.
Type flow	Radial flow (dry gas)	-	Towards a single centered well.
Drainage radius	500	meters	Area of ~0.8 km^2
Wellbore radius	$8^{3/8"}$	inches	
Perforation	1	fraction	Full reservoir perforation.
Tubing internal diameter	7	inches	
Tubing external diameter	$7^{5/8}$	inches	
Tubing inner roughness	0.0006	inches	
Tubing length	See remark	meters	Equal to reservoir's depth at mid reservoir thickness.
Reservoir temperature	See remarks	Degrees Celsius	Initial temperature measured in the reservoir. This is assumed constant throughout the entire withdrawal of the working volume.
Mechanical skin factor	+1	-	A +1 skin is used to simulate some average formation damage due to the high operational flow rates. No well stimulation (negative skin) is considered in this study.
Dietz reservoir shape factor	31.62	-	Circular reservoir with a centered well
Wellhead pressure	(Pi-150)	bars	A constant wellhead pressure of 150 bar below the initial reservoir pressure (Pi), except for reservoirs with initial pressures below 150 bar where a wellhead of 50 bar is used instead.
Withdrawal decline rate (type)	Exponential	-	
Withdrawal threshold/cut-off (base load)	1	million m^3/day	Reservoirs with lower initial withdrawal rates were discarded as potential candidates.
Composition gas stored	High calorific	-	(89% mole methane)

Table 2 Reservoir and well input parameters and assumptions used to estimate the working volume per each field.

of MW over periods from a few hours up to a day (Figure 3). This storage capacity is significantly higher than the largest battery systems that are currently operational in the world (Tesla's lithium-ion battery in South Australia, 100 MW/129 MWh) (Figure 3). CAES is currently operational at two sites: Huntorf in Germany and McIntosh-Alabama in the US since 1970s and 1980s respectively (Crotogino et al., 2001). The relevance of compressed air storage as a peak shaver in the Netherlands can increase with the growth of variable renewable electric power (wind and solar).

Assessment of the potential underground storage capacity

In this paper we present the results from the national scale assessment carried out on potential underground storage capacity for natural gas, hydrogen and compressed air (TNO and EBN, 2018). We report the estimated capacity per province (onshore) and for three offshore areas in the Dutch sector of the North Sea (Figure 1). We report two types of storage capacities: i) theoretical capacity, corresponding to the total storage capacity (Gas-Initially-in-Place, GIIP) that meets primary technical preconditions for (safe) storage and ii) effective capacity, which in addition 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 remaining GIIP is the cushion volume (cv), as this remains in the reservoir or salt cavern for pressure support.

The Dutch subsurface in principle holds a large potential for underground storage in its large portfolio of (depleted) gas fields and well-mapped extensive rock salt formations wherein caverns may be constructed. Natural gas fields are considered appropriate because of their proven containment of most gases (natural gas, CO_2, nitrogen), widespread occurrence and developed capacity and infrastructure for natural gas production. However, the effective containment of hydrogen is not yet fully proven and it is currently under research (e.g. SunStorage project Austria).

We selected potential suitable candidates for underground storage based on: i) technical preconditions for safe storage, ii) favourable properties for minimal techno-economic performance (e.g. high permeability, not too large volumes); and iii) accessibility and presence of infrastructure which support storage deployment.

Natural gas/hydrogen storage in depleted fields

The potential production capacity and working volume for gas storage in natural gas fields were calculated on the basis of empirical functions that describe the flow behaviour and pressure development in porous reservoirs and wells (Juez-Larré et al. 2016). The entire portfolio of onshore/offshore natural gas fields in the Netherlands, with their corresponding reservoir properties, was used and a single well standard configuration was applied (Table 2). The theoretical storage capacity was estimated only for those gas fields fulfilling the following criteria: i) developed and accessible through production wells at the time of evaluation, ii) a minimum depth of 1000 m, iii) no significant amounts of H_2S (<<10.000 ppm), iv) a permeability higher than 0.1 mD (i.e. no stimulation required), and v) not being used for storage as yet. For the working volume the fields had to satisfy additional requirements: i) a transmissivity >100 mD.m, ii) a GIIP volume of less than 30 billion m^3 (due to the likely required large cushion gas and geological complexity of large fields), iii) have an initial well productivity higher than 1 million m^3/day. GIIP volume minus the working volume gave the resulting cushion gas. The working and cushion volumes for hydrogen storages were derived from results on natural gas using an average expansion factor of 0.85, which is valid for the range of pressures (100-300 bar) and temperatures (80-140°C) of all the gas fields investigated.

The initial portfolio of gas fields contained a GIIP volume of 1483 billion m^3. Applying the above-mentioned criteria we estimated a theoretical and effective capacity of 1293 billion m^3 and 854 billion m^3 respectively. Note that all m^3 are reported at normal conditions (0°C and 1 atm). The geographical distribution of the fields is displayed in Figure 4, and their total number, corresponding storage capacities and energy contents are depicted for each province and offshore area in Table 3, for both natural gas and hydrogen. From the total effective capacity we estimated that only 180 billion m^3 could be used as a working volume, which is about 20%. This shows that compared to the current working volume (wv) available of 13 billion m^3, there is potential for ~15 times higher storage (of which about two thirds is onshore). Geographical spread of the storage capacity is within the currently operational gas extraction areas; especially in the northeast of the Netherlands, and the provinces of South Holland and North Holland. The working volumes obtained were also converted to thermal energy content (TWh_t), using the energy factor of $1{,}1e^{-8}$ TWh_t/m^3 (39 MJ/m^3) for natural gas and of $3.0e^{-9}$ TWh_t/m^3 (10.79 MJ/m^3) for hydrogen.

Figure 5 shows the number of fields per working volume class and province, with the small fields generally being more abundant. In most provinces, there are up to five options per volume class, which offers opportunities for various business cases both for peak and seasonal buffers. Among the candidates there is a large spread of wv:cv ratios (Figure 6). Fields with high wv:cv ratios are preferred, since the cushion gas is one of the most expensive items in an underground gas storage project. In order to reduce the volume of cushion to be injected, a natural gas field can be converted into an underground gas storage even before this is fully depleted. However, for hydrogen the mixing with the unrecovered natural gas may be an issue in view of the quality requirements for hydrogen in some applications. The expectations are that large-scale developments of hydrogen buffering, in particular, will be mostly linked to heat demand and generation of electricity. Unlike applications in the transport sector and industry, heat and power plants have the least high-quality requirements since they can easily tolerate changes in the hydrogen:methane mixture.

The candidate fields onshore and in the two near-shore areas, were further classified based on qualitative characteristic of their

Natural gas				Hydrogen	
Province/area name (code)	**# fields (theoretical capacity) billion m³**	**# fields (wv/effective capacity) billion m³**	**Energy content wv TWht**	**wv billion m³**	**Energy content wv TWht**
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

Table 3 Results showing the candidate fields storage capacity for natural gas and hydrogen: theoretical capacity, effective capacity, working volume (wv) and corresponding energy content.

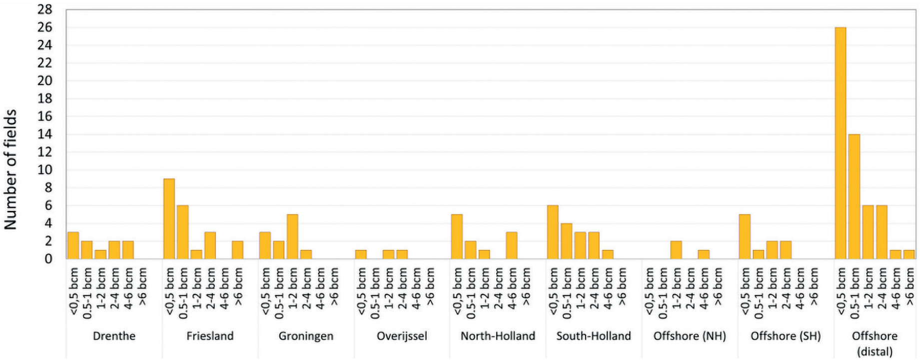

Figure 5 Results showing the number of candidate fields and associated total working volume of natural gas per province, and subdivided by working volume class, (bcm = billion m^3).

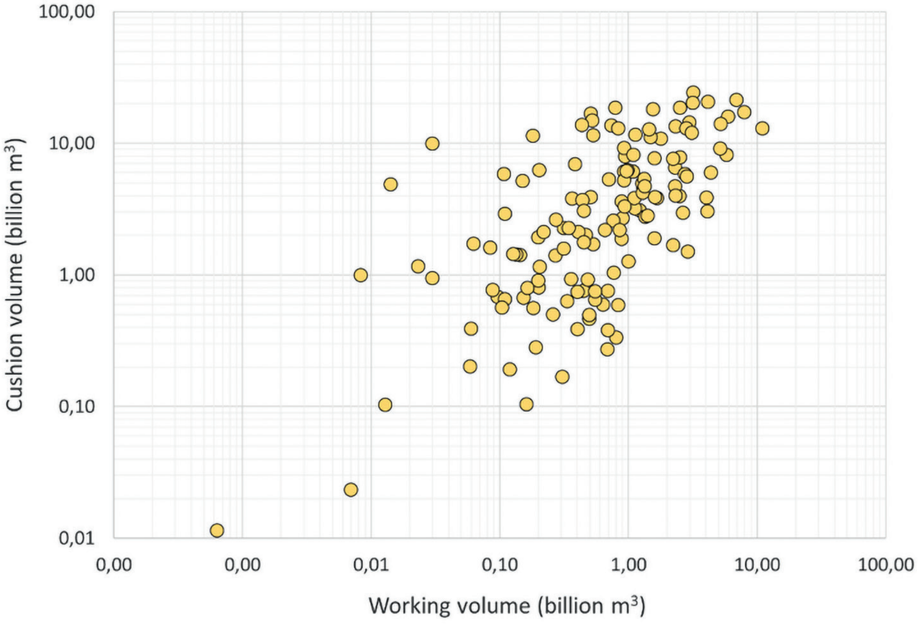

Figure 6 Distribution of estimated working vs. cushion volumes of all candidate fields.

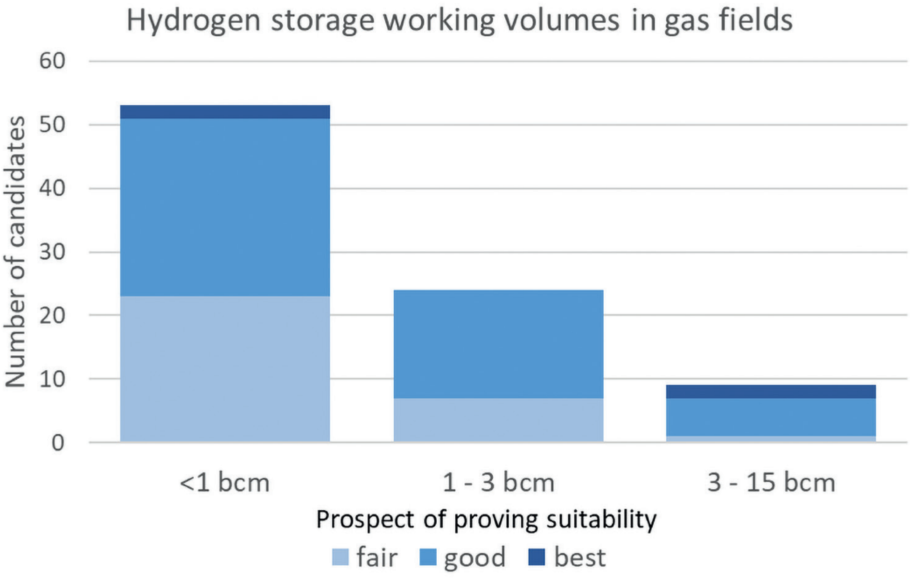

Figure 7 Number of candidate fields per class of working volume and suitability. Only fields from onshore and the two near-shore areas (South and North Holland) are included.

sealing formation (salt being preferred over clay), transmissivity (>4000 mD.m as best and <1000 mD.m as worst) and wv:cv ratio (>1 as best and <0.5 as worst). Figure 7 gives the number of fields and cumulative working volume per working volume and suitability class (best, good and fair). The availability of the gas fields for storage purposes will depend on the expected cessation of production (COP) date. Figure 8 shows that currently more than 90% of the natural gas production is expected to terminate before 2030, eventually releasing its working volume for storage. It is important to note that the COP date is an estimate and may shift in time depending on changes in the production strategy (based on technical and/or economic changes).

		Storage natural gas		Storage H_2	
Province/ salt pillar	# effective caverns (50% of theoretical)	wv (billion m^3)	Energy content (TWh_t)	wv (billion m^3)	Energy content (TWh_t)
GRONINGEN	230	12.2	132.1	10.37	31.0
Zuidwending	52	2.76	29.9	2.35	7.0
Winschoten	22	1.17	12.6	0.99	3.0
Pieterburen	39	2.07	22.4	1.76	5.3
Onstwedde	66	3.5	37.9	2.98	8.9
Boertange	51	2.7	29.3	2.30	6.9
FRIESLAND	31	1.64	17.8	1.39	4.2
Ternaard	31	1.64	17.8	1.39	4.2
DRENTHE	60	3.2	34.4	2.69	8.1
Anloo	14	0.74	8.0	0.63	1.9
Hooghalen	37	1.96	21.3	1.67	5.0
Hoogeveen	1	0.05	0.6	0.04	0.1
Schoonloo	8	0.42	4.6	0.36	1.1
Total	321	17.01	184.3	14.46	43.3

Table 4 Results of the estimated potential total number of salt caverns (50% of theoretical), working volume (wv) and corresponding energy contents for natural gas and hydrogen per province and salt pillar (see location in Figure 9).

Natural gas and hydrogen storage in salt caverns

For the storage of natural gas and hydrogen in salt caverns, this paper focused only on salt structures onshore, since these are considered most relevant for storage demands in the near future. Offshore salt structures may become relevant as a result of the expansion of offshore wind farms and generation of green hydrogen. In order to estimate the gas storage capacity in salt caverns (working volume), we evaluated salt pillars within the Zechstein Group. Differently from the Triassic salt deposits, Zechstein salt deposits are ubiquitous in the northeastern part of the country and are the most suitable for the construction of salt caverns because of its thickness, of more than 300 m, and a depth range between 1000 and 1500 m (Figure 9) (Krombrink et al., 2012). We only selected the largest salt pillars that would provide enough volume for the construction of caverns and had no indications of anhydrite benches (based on drilling and seismic data) (Figure 9).

We assumed a standard cavern size of 600,000 m^3 (radius ~50 m x Height ~300 m), similar to those found in the Zuidwending underground gas storage. To calculate the maximum theoretical number of caverns that could be constructed in each salt pillar, we considered the directive described in the German salt mining regulations (ABVO § 224). These regulations specify a minimum required distance of 100 m and 150 m between the cavern wall and the flank and top of the salt dome structure respectively, and a distance of 160 to 210 m between neighbouring cavern walls (LfG, 2008). For our assessment we estimated the effective number of caverns to be a conservative 50% of the theoretical number. We also considered a maximum operational cavern pressure of 180 bar, and a wv:cv ratio of 1:1. This gives a wv for a single cavern of about 53 million m^3 of natural gas, and based on the conversion factor 0.85, of 45 million m^3 of hydrogen. All the parameters assumed and the working volume obtained are representative for salt caverns in Zuidwending and Moss Bluff gas storages.

Based on all the above, we estimated that a total of ca. 321 salt caverns could be constructed in the selected salt pillars (Table 4), with a total working volume of 17 billion m^3 of natural gas and of 14.5 billion m^3 of hydrogen. This implies an associated energy content of 184 TWht and 43 TWht respectively, distributed over the provinces of Groningen, Friesland and Drenthe (Table 4).

Compressed air energy storage (CAES) in salt caverns

In the case of compressed air storage in salt caverns the evaluation methodology used was the same as for the storage of natural gas and hydrogen, barring the lower operational pressure range. The maximum pressure of 70-100 bar is commonly used [Crotogino et al. 2001], since for higher pressures excessive amounts of energy (heat) are lost during compression. To compensate for the restrictions on the maximum operational pressures, the minimum pressures used are also lower (50 to 80 bar). These lower operational pressures require salt caverns to be placed at shallower depths (700-1200 m) in order to reduce the rate of convergence of the cavern walls due to lithostatic pressure.

For the national assessment a notional adiabatic CAES facility (i.e. including heat storage) was assumed with a discharge power of 300 MW for a period of six hours (Figure 3). This is equal to an approximate energy storage capacity in one cavern

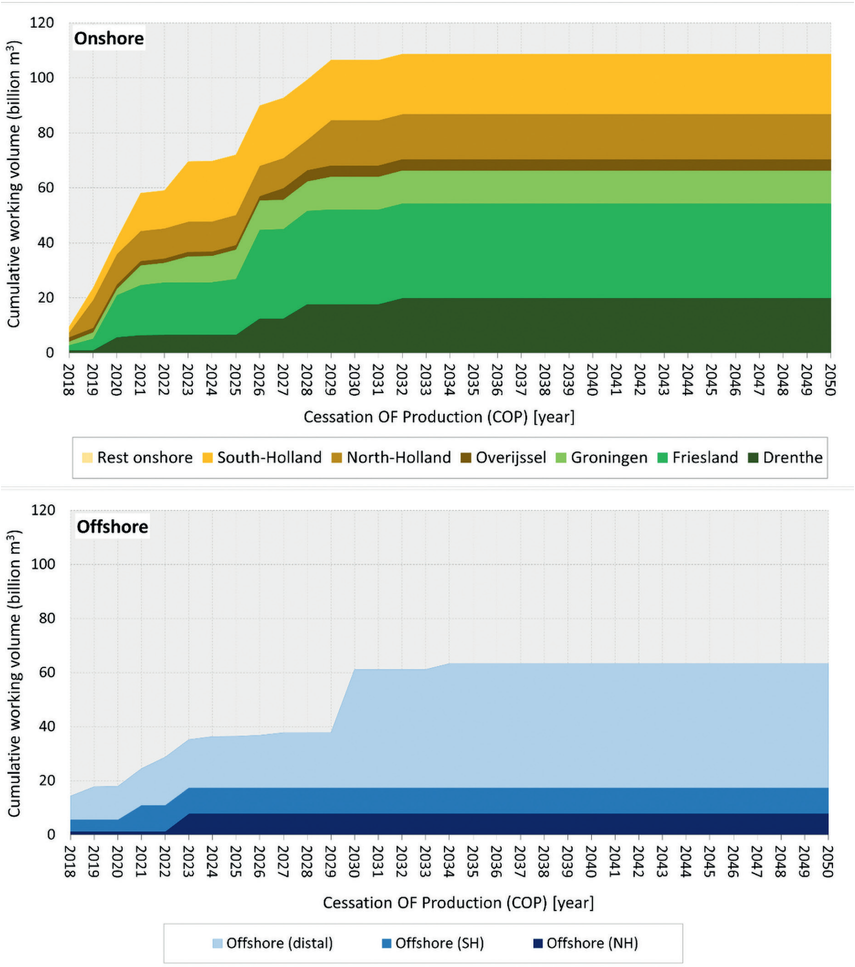

Figure 8 Cumulative availability of working volume (natural gas) over time for the onshore (above) and offshore (below) fields. COP dates were extracted from current production licenses.

Province/ salt pillar	# effective salt caverns (50% of theoretical)	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

Table 5 Results of the total number (effective) of caverns (50% of theoretical) and corresponding energy storage for CAES per province and salt pillar (see location in Figure 9).

(analogous to working volume) of 1800 MWh. Note that a full-scale adiabatic CAES is today not yet a proven technology. The assumed round trip efficiency is ca. 60-70%, which implies that approximately 2800 MWh is required for charging. Results show a total energy storage capacity for the ca. 321 salt caverns onshore of about 0.58 TWh (Table 5).

Discussion

The changing energy landscape in the Netherlands is likely to stimulate additional demand for flexibility. This flexibility can be delivered by various types of energy storages at different scales. However, the implications for the various technologies offering flexibility is still uncertain. The energy transition is in an early phase and many choices regarding the future energy system have not yet been made.

Different studies point out hydrogen as a potential alternative to natural gas. Analogous to natural gas, the necessary supply of hydrogen that would be required to fulfil large-scale demand can only be guaranteed by means of storage, unless alternative future supply routes via import are being set up. Storage can easily balance periods of intermittent production (wind and sun) and a fluctuating demand. Hydrogen storage has not yet been applied in any Dutch gas field and today it is still a subject of intensive research (e.g. DNV-GL, 2017; Jepma and Van Schot, 2017). There are a few pilot projects on injection of hydrogen/methane mixtures in depleted natural gas fields and aquifers (e.g. Sun Storage

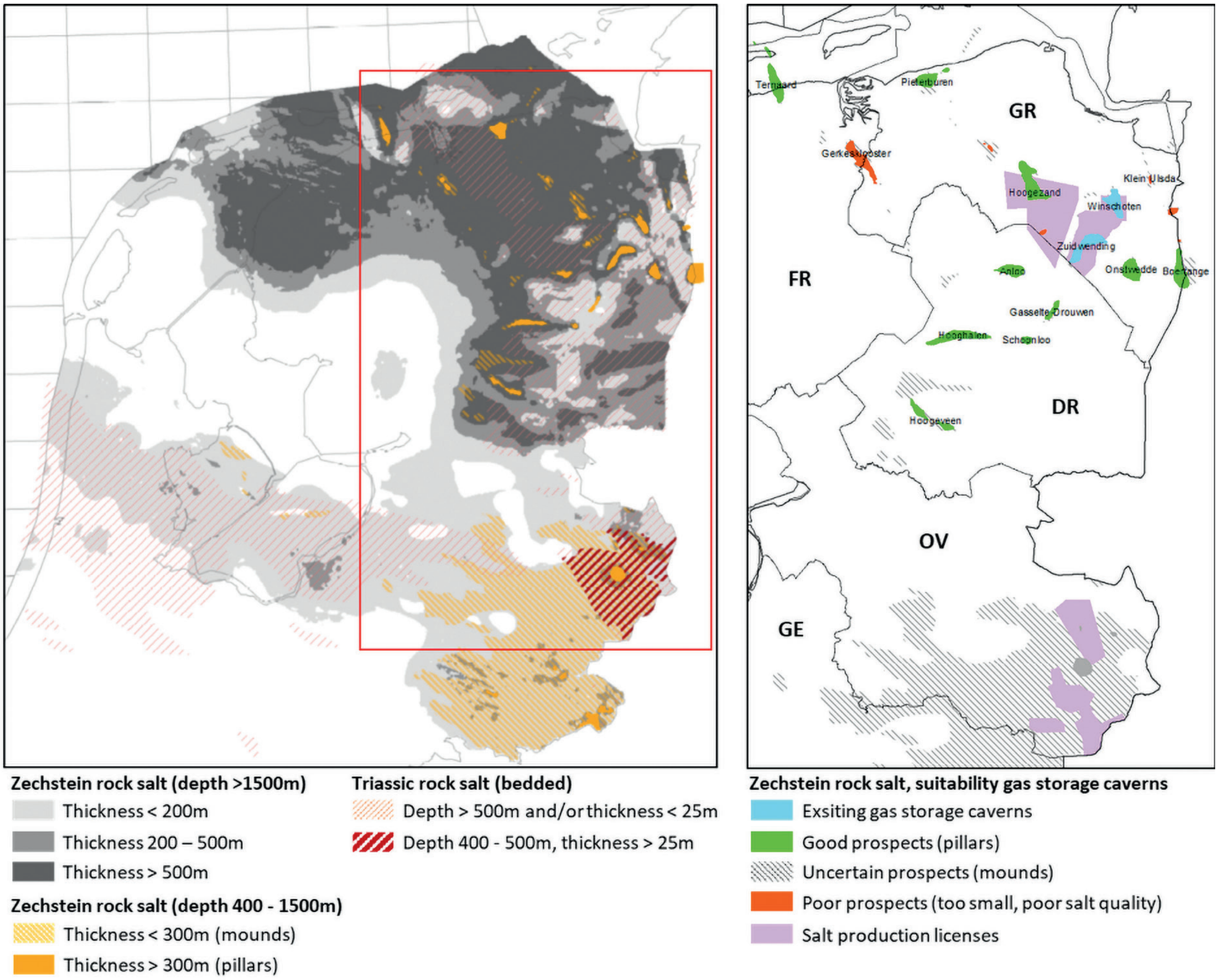

Figure 9 (Left) Regional distribution of the Zechstein and Triassic rock salt formations in the Netherlands. (Right) Zoom in of the northeastern part of the Netherlands. The areas where the Zechstein rock salt has a suitable depth and thickness for the development of salt caverns are coloured in green (pillars).

Project). In addition to the well-known techno-economic aspects that are generally needed for the construction of a gas storage, in the case of hydrogen there are some additional aspects that require further research, in particular: i) degree of sealing of the caprock for varying percentages of hydrogen in the gas mixture, and ranges of reservoir temperatures and pressures; ii) geochemical reaction of hydrogen with minerals and fluids in the reservoir; iii) biochemical conversion processes; iv) hydrogen and formation water mobility and its impact on the fingering and sweep efficiency; v) mixing of hydrogen with residual hydrocarbons; vi) influence of hydrogen on cement quality and bonding of cement); vii) required cushion gas volumes and potential alternatives to hydrogen as a cushion gas; viii) risk of induced seismicity.

The storage of gas in salt caverns, as an energy peak shaver, is an advanced technology. This applies to natural gas as well as to nitrogen, air, hydrogen and even (recently) helium. With the right composition and crystalline structure, salt is a proven barrier for these gases and no adverse geochemical reactions occur that may affect the integrity of the cavern and/or well. The construction of the caverns in itself is an easily controllable process, as long as knowledge about the composition, structure, thermo- and geo-mechanical properties of the salt is present. However there are still important research questions to be addressed such as: i) how does the uptake/delivery of large quantities of renewable energy at high rates affect the integrity of the cavern and the well; ii) how to optimize the spatial integration of a large number of caverns in one location and the effects on surface uplift/subsidence; iii) how to dispose of large volumes of brine, and iv) how to permanently decommission a salt cavern.

Concluding remarks

The large number of (nearly) depleted natural gas fields in the Netherlands offer a wide range of opportunities for buffering energy in gaseous form. Besides the storage of natural gas, these fields have the potential to buffer large volumes of hydrogen (wv): 93 billion m^3 (277 TWh$_t$) on land and 60 billion m^3 (179 TWh$_t$) at sea.

The Netherlands also has a large potential for the creation of up to 321 salt caverns in salt pillars onshore. The estimated working volume for storages of natural gas and hydrogen is 17 billion m^3 (184 TWh$_t$) and 14.5 billion m^3 (43.3 TWh$_t$) respectively. If all these salt caverns were to be used for CAES instead, they could store up to 0.58 TWh. However, the development of storage capacity in salt caverns may prove insufficient to accommodate the volume of energy buffering required in a timely manner. This is because of the limited rate of construction (2 to 3 salt caverns/year), issues on brine disposal and the limited size of the salt cavern clusters due to surface subsidence.

Despite the large potential for underground energy storage in the Netherlands, its future is still uncertain. The type and size of energy storages that may be needed will depend to a large extent on the choices of the future energy system (i.e. production, conversion, transport and consumption). Policy makers should realize the importance of long-term planning in case buffering may be required in the future. Lead times in the required research, planning and development (10+years) of the different underground storage options demand a strong guiding approach. In the coming 10 to 20 years most of the currently producing gas fields will be closed and their infrastructures removed. This together with potential interference with other (sub)surface activities or reuse for other purposes (e.g. CCS) may further hinder their development as storages.

Beside the technical aspects discussed in this study, the future development of underground storages onshore and/or offshore will also make necessary the study of the legal, spatial economical, safety and social aspects for the reuse of depleted fields and construction of new caverns for non-mining purposes. The design of a general energy storage vision and strategy, including the successful set-up of pilot projects, will determine the future role of underground storage in the current energy transition era.

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