TECHNOLOGY FACTSHEET

Hydrogen storage - large-scale underground storage in salt caverns

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Sector	Hydrogen
ETS / Non-ETS	Non-ETS
Type of Technology	Storage
Description	The basic principle of salt cavern storage is the injection of hydrogen into suitable underground salt caverns using compressors. Typically, used pressures range from 80 to 200 bar. The above ground support facilities typically consist of, most importantly, compressors and, next to that, of drying and purification units for the conditioning of extracted hydrogen. These units also make the hydrogen suitable for injection into gas transmission systems and/or end use applications. Depending on the storage concept and end-use targets, above-ground ancillary facilities such as electrolyzers for hydrogen production or combined-cycle gas turbines for electricity production may also be integral parts of salt cavern storage sites. Geometric volumes of 500,000 - 1,000,000 m3 are typical for salt caverns in Europe. Average volumes are reported to be 680.000 m3 (Laban_2020). In the Netherlands, storage sites for hydrogen will likely be connected to the gas transmission system (as it is commonly the case for analogous natural gas storage sites). There are currently no storage facilities combined with hydrogen production or power generation anywhere in the Netherlands, but plans for such hubs are being made (TNO_Internal info).
TRL level 2020	TRL 7 Technologically, it is a mature technology for long term H2 storage. The deployment is very limited so far due to economic constraints. There are three large hydrogen caverns in operation in Texas, USA, and some smaller caverns at Tesside (UK). (Laban_2020, Gammer_2015). The technology has not been proven in combination with frequent charge/discharge cycles at high H2 flows, which may be required when hydrogen production and demand are subject to weather-controlled variations (TNO_2021). Therefore the TRL has been set at 7.

TECHNICAL DIMENSIONS

	Functional Unit		Value and Range								
Capacity	MW		600								
			98			-			600		
			Current			2030			2050		
Potential	NL	MW	-			6.000			30.000		
			-	–	-	6.000	–	6.000	30.000	–	30.000
Market share	Tangible market share estimates are not provided in the consulted refs.	%	-			-			-		
			Min	–	Max	Min	–	Max	Min	–	Max

Capacity utlization factor	1,00
Full-load running hours per year	8.400,00
Unit of Activity	PJ/year
Technical lifetime (years)	30,00
Progress ratio	-
Hourly profile	No
Explanation	An important dimension characterizing hydrogen storage facilities in salt caverns are the injection and withdrawal capacities. Here, the injection (compressor) capacity is chosen as the functional unit since the compressors are the dominant factor in the overall cost. With modern, powerful compressors, injection rates of close to 20 t H2/h can be realized (TNO_Internal info). This corresponds to a capacity of ~ 600 MW H2, as recorded in the table above, considering 33 MWh/ton as LHV for H2. Potentials in NL for salt cavern storage are high. There are currently 6 operational large caverns at Zuidwending (they are used for natural gas storage though, which is why the 2020 potential is set to 0). Based on existing caverns, the medium-term (2030) potential for the Netherlands is about 10 caverns (6 GW H2). The long-term (2050) potential is much larger due to the large multitude of suitable salt formations in NL (TNO_2018). The potential is then limited by the H2 transport infrastructure and estimated to be about 50 caverns (30 GW H2).

COSTS

Year of Euro	2015

	Euro per Functional Unit	Current			2030			2050		
Investment costs	mln. € / MW	0,17			-			0,07		
		0	–	1	Min	–	Max	0	–	0
Other costs per year	mln. € / MW	-			-			0,04		
		Min	–	Max	Min	–	Max	0	–	0
Fixed operational costs per year (excl. fuel costs)	mln. € / MW	0,00			-			-		
		0	–	0	Min	–	Max	Min	–	Max
Variable costs per year	mln. € /	-			-			-		
		Min	–	Max	Min	–	Max	Min	–	Max

Costs explanation	Information about cost is extremely scarce in the literature. (Lord_2014) reports a cost breakdown for sites comparable to those operational in Texas (US). The total investment cost in Lord's publication amounts to ~ 65 mln. $ (53 mln. €). This includes costs for compressors (which is the dominant cost factor), site preparation and cushion gas. Total O&M costs for salt cavern storage sites are estimated to be ~ 2% of the total investment costs (Reuss_2017). In terms of specific costs this translates into 0,51 mln. €/MW (H2) for the investment and ~0,01 mln. €/MW (H2) for the operation. There is no substantiated information about future cost degressions in the literature. A recent TNO report (TNO_2021) shows that much lower investment costs are realistic when using very powerful, state-of-the-art hydrogen compressors because the specific cost of the compressors - which dominate the overall CAPEX - decreases with increasing power.

ENERGY IN- AND OUTPUTS

	Energy carrier	Unit	Current			2030			2050		
Energy carriers (per unit of main output)	*Main output:* Hydrogen	PJ	-1,00			-			-		
			-1	–	-1	Min	–	Max	Min	–	Max
	Hydrogen	PJ	1,00			-			-		
			1	–	1	Min	–	Max	Min	–	Max
	Electricity	PJ	0,07			-			-		
			0	–	0	Min	–	Max	Min	–	Max
		PJ	-			-			-		
			Min	–	Max	Min	–	Max	Min	–	Max

Energy in- and Outputs explanation	Electricity consumption for the compressors is reported to be ~2,2 kWh/kg H2 (Lord_2014, Michalski_2017). Considering a H2 LHV of 0,033 MWh/kg, the value listed in the table above is obtained. The lower value reported in TNO_2021 is based on expected improvements of the compression process.

MATERIAL FLOWS (OPTIONAL)

	Material	Unit	Current			2030			2050		
Material flows			-			-			-		
			Min	–	Max	Min	–	Max	Min	–	Max
			-			-			-		
			Min	–	Max	Min	–	Max	Min	–	Max
Material flows explanation	0										

EMISSIONS (Non-fuel/energy-related emissions or emissions reductions (e.g. CCS)

	Substance	Unit	Current			2030			2050		
Emissions			-			-			-		
			Min	–	Max	Min	–	Max	Min	–	Max
			-			-			-		
			Min	–	Max	Min	–	Max	Min	–	Max
			-			-			-		
			Min	–	Max	Min	–	Max	Min	–	Max
			-			-			-		
			Min	–	Max	Min	–	Max	Min	–	Max
Emissions explanation											

OTHER										
Parameter	Unit	Current			2030			2050		
Hydrogen injection rate	t/h	18,00			-			-		
		3	–	18	*Min*	–	*Max*	*Min*	–	*Max*
Hydrogen extraction rate	t/h	18,00			-			-		
		5	–	18	*Min*	–	*Max*	*Min*	–	*Max*
Maximum extraction per year		-			-			-		
		Min	–	*Max*	*Min*	–	*Max*	*Min*	–	*Max*
Maximum extraction per year		-			-			-		
		Min	–	*Max*	*Min*	–	*Max*	*Min*	–	*Max*
Explanation										

REFERENCES AND SOURCES	
1	Laban_2020, "Hydrogen storage in salt caverns", Master's thesis, TUD, 2020
2	Gammer_2015, "The role of hydrogen in a clean responsive power system", Report, Energy Technologies Institute, 2015
3	Lord_2014, "Geological storage of hydrogen", Int. J. of Hydrogen Energy (39), p.15570-15582, 2014
4	TNO_Internal info (based on communication with expert Remco Groenenberg from research group "Applied Geosciences")
5	Michalski 2017 - „Hydrogen generation by electrolysis and storage in salt caverns," Int. J. Hydrogen Energy (42) p.13427-13443, 2017
6	HYUNDER 2014 -„Assessment of potentials, actors, business cases for large-scale longterm green H2 storage in EU," EU project HyUnder , 2014
7	Reuss 2017 - Reuss, „Seasonal storage and alternative carriers: a flexible hydrogen supply chain model," Applied Energy (200), 2017
8	Crotogino 2010 - „Large scale hydrogen underground storage for securing future energy supplies", Proceedings WHEC, 2010
9	TNO_2021, "Large Scale Energy Storage: WP 2: Techno-Economic Modelling of Large-Scale Energy Storage Systems", Report, 2021