Case Study Germany

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Revision History

Revision	Revision date	Summary of changes
0	04 April 2023	Initial version
1	14 April 2023	Adapted methodology of LCOS & NPV calculation
2	07 June 2023	Streamlined parameter set between all case studies

Checked by:

Name	Institute	Date
Gianluca GRECO WP8 Leader	FHa	12 April 2023
Arnaud REVEILLERE Project Coordinator	Geostock	12 April 2023
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1. Introduction

The general objective of Work Package 8 of the Hystories project[1] is to assess the feasibility of implementing large-scale storage of renewable hydrogen in salt caverns, depleted gas fields and other types of geological stores at selected sites in the EU. To do so, a joint methodology was developed in Hystories task 8.1, which serves as a toolbox to analyse profitability of various large-scale hydrogen storage technologies and business models from the perspective of a single operator. Within this task 8.2, selected case studies of five hydrogen storage sites in different countries are performed by different partners, including France (Geostock), Germany (LBST), Italy (FHa), Spain (FHa), Poland (MEERI).

Each case study consists of the following steps:

1. Selection of a (generic) site
2. Fine-tuning of data, taking local / national aspects into account (with input of national members of Advisory Board)
3. Site-specific profitability analysis / business model valuation considering site-specific costs (standard case)
4. Sensitivity analyses

In Task 8.3, a comparison of the different national case studies will be done.

This document contains the analysis of the case study for Germany. Chapter 2 gives an overview of the storage market in Germany, summarizing aspects of the storage potential, future demand and regulatory framework based on previous work packages of the Hystories project. The choice of key parameters for this case study is laid out in chapter 3, covering common (i.e. valid for all case studies) as well as case-specific parameters. The results of the model application are shown and discussed in chapter 4, focussing on a reference case and additional sensitivity analyses. Finally, the conclusions in chapter 5 summarise key results.

[1] Please see https://hystories.eu/ for information about the project and all public deliverables.

2. Storage market in Germany: an overview

The following section is intended to give an overview on the existing natural gas market in Germany as a basis for the future transformation pathway towards a hydrogen gas infrastructure.

2.1. Brief overview of existing gas storage market in Germany

The geographical position of Germany in the centre of Europe gives it a pivotal role in the European gas transport infrastructure. Today, the natural gas storage market in Germany is characterised by a regional separation into two highly different geographic zones. While in the northern part, salt deposits enable (highly flexible) gas storage in salt caverns, such geological settings do not exist in the southern part. Instead, gas storage in porous media is the only storage option in southern Germany. Figure 1 shows the existing natural gas storage facilities (salt caverns and porous media storages) and the respective working gas volumes as of January 2023.

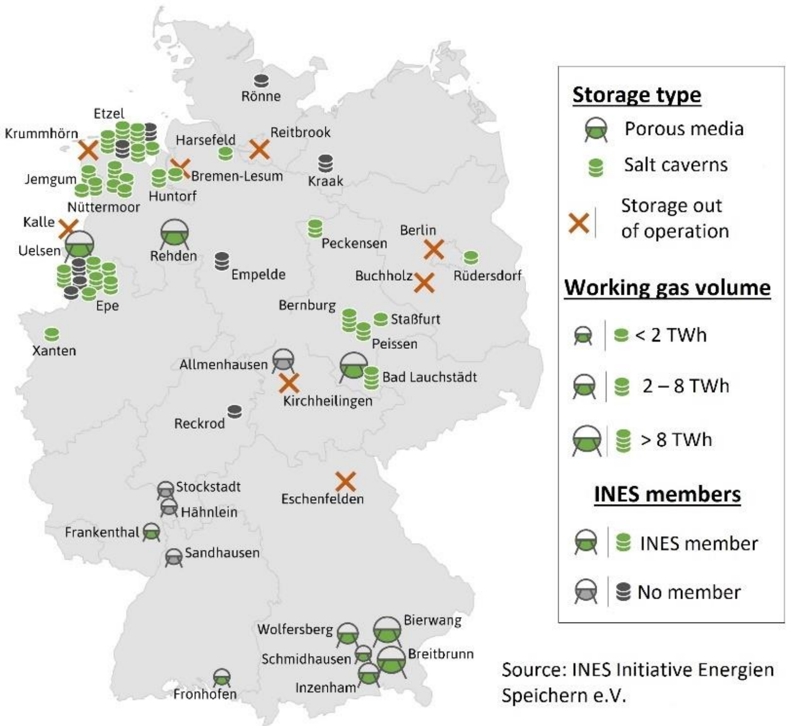

Figure 1: Existing natural gas underground storage sites in Germany (January 2023)
(Source: Initiative Energien Speichern e.V. (INES))

The total natural gas storage of all active underground storage sites in Germany is around 250 TWh, with a maximum daily injection and withdrawal capacity of 4.3 and 7.0 TWh, respectively [GIE 2023]. With this, Germany has the highest storage capacity in the EU.

According to data of the Aggregated Gas Storage Inventory (AGSI), overall storage capacity in underground natural gas storage sites has been rather constant since 2016, varying between 245 and 250 TWh [GIE 2023].

[LBEG 2022] lists 45 natural gas storage sites in Germany, of which 30 are salt cavern storages and 15 gas storages in porous reservoirs. The latter can be further differentiated into 11 depleted gas or oil fields and 4 aquifer sites. While salt caverns account for about 63% of all storage capacity, porous reservoirs make up for about 37% (for details see Table 1)[2]. In 2021, two storage sites were decommissioned, namely the cavern in Krummhoern und the aquifer Eschenfelden. Finally, additional salt cavern storage capacities are in planning, with an overall working gas capacity of 2.5 to 3.0 billion Sm^3 (2.4 to 2.8 billion Nm^3)[3].

Table 1: Key parameters of German natural gas underground storage sites (December 2021) (Source: LBST based on [LBEG 2022])

Parameter	Unit	Porous media	Salt caverns	Total
No. of underground storage sites		15	30	45
Working gas volume	billion Sm^3	9.0	15.6	24.6
	TWh (LHV)[1]	91.1	158.7	249.8
No. of storage sites in planning		0	5	5
Working gas volume (in planning)	billion Sm^3	0	2.5	2.5
	TWh (LHV)[1]	0	25.7	25.7

[1]Assuming a LHV of natural gas of 10.16 kWh/Sm^3.

It is a broad industry consensus that the existing natural gas transport and storage infrastructure will also be the basis for the development of a future hydrogen infrastructure (see e.g. [EHB 2022] and [GIE 2023b]). While repurposing of existing storage sites might have economic advantages compared to new facilities[4], the currently tense natural gas supply situation in Europe could promote building up new facilities for hydrogen gas storage in the upcoming years. The main reason is that existing natural gas storage sites are continuously required for the functioning of the natural gas market. Accordingly, new long-term storage sites will be required to accompany the development of a national hydrogen pipeline grid. In

[2] Please note that this situation is not representative of the average EU, or global situation where most of the natural gas storage capacity is found in porous reservoirs.

[3] Gas volumes in this study are reported as standard cubic meters (Sm^3) at T = 288.15 K, p = 0.1013 MPa, while normal cubic meters (Nm^3) at T = 273.15 K, p = 0.1013 MPa) are used in some sources. Conversion factor: 1 Sm^3 = 0.948 Nm^3.

[4] According to [DBI et al. 2022], average costs for repurposing existing salt caverns is about 16 percent of the costs of newly built facilities (Other sources (e.g. [NWR 2022]) estimate minimum costs of at least 30% and or even costs comparable to new sites, depending on investment requirements for the assets.). The overall (cumulative) transformation costs to achieve an overall storage capacity of 72.8 TWh in 2050, according to [DBI et al. 2022], sum up to 12.8 billion €. This value considers repurposing of 31 existing salt caverns and 4 porous media storages to hydrogen as well as the development of 40 new salt caverns.

scenarios with decreasing natural gas demands until 2030, there will, however, also be the potential to start rededication of natural gas storage sites to hydrogen [NWR 2022]. Still, overall project timelines of at least 5-10 years need to be considered, until a UHS can start operation.

First (pilot) projects in Germany focus on hydrogen storage in salt caverns, as technical feasibility has been investigated in several projects (including FCHJU/CHJU-funded projects HYUNDER or HYPSTER). Due to the geographical location of storage reservoirs described above, these storage sites are located in the northern part of Germany. Figure 2 provides an overview of underground hydrogen storage (UHS) projects announced in the last years (blue numbers) and the indicative development of a German hydrogen transport grid until 2050.

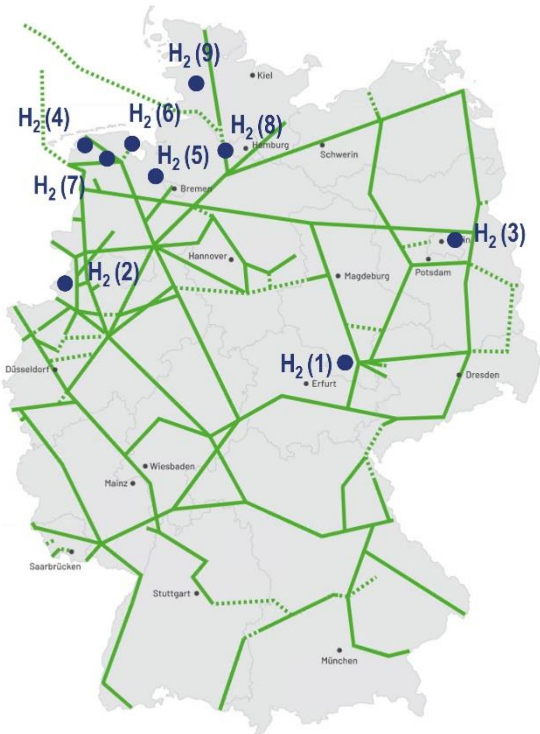

Figure 2: Indicative development of a German hydrogen transport grid (2050) [Source: FNB Gas e. V] and selected announced pilot projects for hydrogen underground storage in salt caverns

Table 2 describes the mapped UHS pilot projects in more detail. They are all salt cavern based and most at this stage are either only announced or in early project stages. Two of the projects have project partners with refinery or steel production background. Due to the advantage of relatively easy soling of new caverns, no project at this stage considers repurposing of existing storage sites - although some projects consider repurposing existing wells that were generally drilled in the idea of developing natural gas storages, such as the Krummhoern pilot project.

Table 2: Publicly announced H_2 storage projects in Germany (Status: December 2022)

	Company (Project)	Location	Techno-logy	Capacity (WGV)	Start of Operation (planned)	Further Comment	Source
1	VNG	Bad Lauchstädt	Salt cavern	50 million Nm^3	2028	Part of project "Reallabor Energiepark Bad Lauchstädt"	[Energiepark Bad Lauchstädt 2022]
2	RWE (GETH2)	Gronau Epe	Salt cavern	28 million m^3 H_2	2027	2023 onwards construction	[RWE 2022]
3	EWE (HyCAVmobil research project)	Ruedersdorf	Salt cavern	up to 65,000 Nm^3	2023	Test site	[EWE 2022]
4	Uniper (Hydrogen Pilot Cavern)	Krummhoern	Salt cavern	250,000 m^3	2024	Demonstration plant at NG storage facility (out of use since 2017)	[Uniper 2022]
5	EWE / Uniper	Huntorf	Salt cavern	No information	2025	Announced as part of Clean Hydrogen Coastline / IPCEI	[EWE 2021]
6	STORAG ETZEL (H2CAST)	Etzel	Salt cavern	No information	2026	Pilot project until 2026	[H2Cast2021]
7	Astora	Jemgum	Salt cavern	Up to 48 million m^3	2030	Time horizon: engineering and permitting (2024), construction (2026 onwards),	[Asotra2022]
8	Storengy (SaltHy)	Harsefeld	Salt cavern	30 to 100 million Nm^3	2027-2030	Project idea in context of HyExpert project	[Storengy 2021]
9	OGE and others (Westküste 100)	Hemmingstedt	Salt cavern	No information	2025	As part of project Westküste 100	[Westküste 100 2021]

Please note: most projects were announced as parts of research projects and depend on positive funding grant decision.

2.2. Germany's hydrogen storage potential

2.2.1. Storage potential for Germany

The potential development of the future hydrogen storage market was subject to different research projects. While some analyses focus on the overall hydrogen storage potential in existing natural gas storage sites, others consider the theoretical contributions of salt caverns and/or porous reservoirs only (e.g. Hystories or HyUSPRe).

By comparing these results, the overall storage potential based for hydrogen storage sites in Germany will be briefly summarized.

Possible transformation pathways of the existing natural gas underground storage sites in Germany towards hydrogen were analysed in a study by [DBI et al. 2022]. The study projects that the rededication of all existing 31 salt caverns in Germany would result in a storage capacity (working gas) of 30.7 TWh_{LHV}. In addition, the authors assumed that four existing UHS in porous reservoirs would be suitable for future hydrogen storage application, providing an additional storage capacity of 1.7 TWh_{LHV}. Accordingly, the overall storage capacity of existing underground storage sites in Germany sums up to 32.4 TWh_{LHV}. By taking all existing natural gas storages in porous reservoirs into account, the CHP-funded project HyUSPRe found the potential capacity for hydrogen storage to be between 24 and 48 TWh [HyUSPRe 2022].

The overall storage potential for hydrogen in porous media for all European countries has also been analysed in work package 1 (WP1) (Geological assessment) and WP2 (Reservoir engineering and geochemistry) of the Hystories project.[5] To do so, several screening criteria and H_2-relevant parameters were defined in order to assess if porous media (i.e. aquifers and depleted hydrocarbon fields) have the potential for hydrogen storage in the future. Based on this data, regional performance in terms of capacity (volumes) and deliverability (storage performance of injection and withdrawal) for pure UHS was deviated[6]. According to the estimations in Hystories D2.2-1, the theoretical potential for hydrogen in porous media in Germany is around 4,675 TWh_{H2}, of which nearly the complete potential is located onshore. This figure is about 2 orders of magnitude higher than the one given by the HyUSPRe project, since while both projects consider the conversion of existing natural gas storages, Hystories also considers the potential of depleted oil and gas fields, and of identified aquifer structures. In contrast to that, theoretical storage capacity in salt caverns is much higher at around 9,400 TWh (onshore only) [Caglayan et al. 2020].

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[5] Please note: a map with existing porous media traps and salt deposits in EU27+UK can be found on Hystories website: https://hystories.eu/map/.

[6] See Hystories Deliverables D1.1-0 – Selection criteria for H_2 storage sites and D1.2-0 – Geological database report for details. https://hystories.eu/publications-hystories/

2.2.2. Hydrogen storage demand for Germany

While section 2.2.1 described the hydrogen storage potential in existing German storage sites as well as the theoretical storage capacities in suitable porous media and salt caverns, the following summary serves as an indication for German long-term storage demand.

The analysis in the context of Hystories WP5 (Energy System Modelling) provides a profound overview of the development of the European energy system until 2050. Depending on the scenario, the overall hydrogen demand is expected to increase from around 350 TWh by 2025 to 1,700-1,900 TWh/year by 2050 (see Hystories D5.5). For Germany, the model calculations result in an estimated hydrogen demand of between 340 and 360 TWh in 2050 [LBST 2022].

The development of the optimal hydrogen storage capacities for Germany in the different scenarios are shown in Figure 3. According to the modelling results, the storage demand in Germany is expected to increase to up to 0.5 TWh_{H2} in 2030, 4.6-25.2 TWh_{H2} in 2040 and 35.0-66.0 TWh_{H2} in 2050[7]. Salt caverns are identified as the key storage technology in most of the scenarios in Germany. Although porous media are considered as viable option only in scenarios B and D, only in scenario D they account for about 40% of storage capacity [LBST 2022].

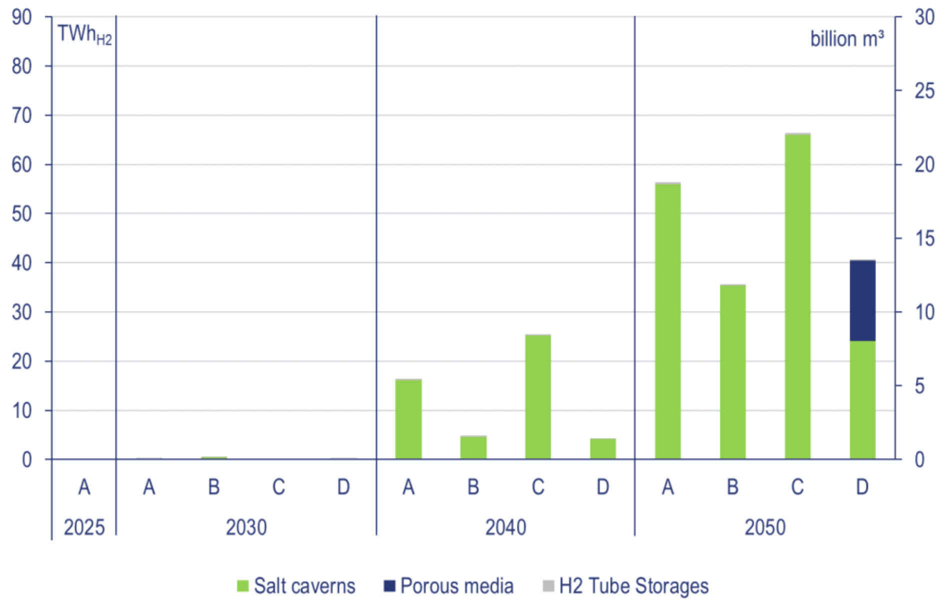

Figure 3: Optimal storage capacity for hydrogen storage in Germany (Source: Hystories D5.5)

[7] As described in Hystories Deliverable D5.1, scenarios A and B mainly focus on domestic production of hydrogen, while scenarios C and D also consider significant hydrogen imports to Europe. With regard to storage technologies, only salt caverns are applied for hydrogen underground storage in scenarios A and C, while scenarios B and D also take hydrogen storage in porous media into account. In line with the announcement of the European Commission in the context of RePowerEU, it was decided to select scenario D (with high hydrogen imports and the use of porous media storages in addition to salt caverns) as reference scenario.

Please note for EU27+UK results: While sensitivity analysis showed that the model results for the overall storage capacity in Europe is quite robust (see Hystories D5-6), the regional distribution of underground storage infrastructure in the different countries is strongly impacted by input parameters like import volumes, transport capacities and costs and admissible technologies. As an example, the scenarios show very limited demand for hydrogen storage technologies in Germany in 2030, while the overall demand for EU27+UK is in a range of 29-42 TWh_{H2}. Instead of Germany, the overall system optimization allocates storage volumes into specific countries like France, Spain, Denmark, Sweden and UK. One reason is that certain (electricity and gas) grid limitations on the regional level are not considered in the model to limit complexity. As discussed in D5-6 for scenario B, most of H_2 storage capacities for storage media in 2050 are located in Italy. Applying capacity limitations, however, results in a shift towards other European countries like France where porous media capacities are increased (for details, see Figure *16* and Figure *17* in the Annex).

The overall modelling results, however, are in line with the analysis by [DBI et al. 2022] and [BMWK 2022], which assume a hydrogen storage demand in Germany of 2 TWh (2030) and between 47 TWh (electricity dominated scenario) and 73 TWh (hydrogen dominated scenario) in 2050. The German National Hydrogen Council (*Nationaler Wasserstoffrat*), on the contrary, expects a demand for hydrogen storage in Germany of 5 to 15 TWh already in 2030 [NWR 2022].

Comparing this long-term hydrogen storage demand with the hydrogen storage capacity in all existing German salt caverns (around 30.7 TWh_{LHV}), a gap of up to 43 TWh can be identified. Accordingly, in addition to repurposing existing salt caverns, further storage capacities are needed (either by newly built salt caverns or by hydrogen storage in suitable porous media).

In total, however, storage demands are significantly lower than theoretical storage potentials described in chapter 2.2.1.

2.3. Regulatory framework

The following chapter shall give a brief overview over the existing regulatory framework for hydrogen storage in underground storage sites in Germany. Basis for the chapter are analyses that were already done within the Hystories project as well as external literature sources.

Hystories D6.1-1 summarizes key elements of the regulatory framework for UHS in Europe in general and for most Member States in detail, covering both regulation and legislation [FHa 2021].

From a European point of view, the most relevant regulatory requirements are described in the Gas Directive 2009/73/EC and Gas Regulation (EC) No 715/2009, defining rules for the European natural gas market. With the proposal of the Hydrogen and Decarbonised Gas Market Package (COM(2021) 803 final and COM(2021) 804 final), the European Commission has provided a draft for a revised version of both documents in December 2021. Based on an analysis of [Oxford Institute 2023], the proposed regulation for hydrogen infrastructure does – to a large extent – replicate the existing framework for natural gas infrastructure. One major difference for hydrogen storage sites is the implementation of a regulated third-party access (rTPA) for hydrogen storage (compared to negotiated third-party access (nTPA) for natural gas storages). The regulated third-party access for hydrogen storage and line pack shall be based on published tariffs which are approved by regulators (see Gas Directive Article 32). The reason is that hydrogen storages are, on the one side, likely to be more limited than natural gas storage. On the other side, the European Commission also highlights the importance of underground storage for hydrogen systems due to the highly volatile and intermittent renewable electricity generation. The proposal includes rules in Gas Directive Articles 64 and 69 that hydrogen network, terminal and storage operators, and hydrogen system operators must keep separate accounts (unbundling). Finally the proposal also foresees a transition period in which e.g. new storage facilities can apply for exemptions from regulated third-party access under specific conditions for a predefined time period (Gas Regulation Article 60). The trialogue process between European Commission, Parliament and Council has not been concluded as of March 2023.

Key information about the German regulation and political perception of underground (hydrogen) gas storages are summarized in the following.

The national hydrogen strategy (2020) does not define a clear blueprint for a strategy regarding large-scale UHS. However, the strategy considers underground storage as an important subject, but no special attention has been given to caverns, aquifers, or others [Watson Farley & Williams 2021] [BMWK 2020].

A leaked version of a revised national hydrogen strategy (11/2022) does, however, explicitly announce that the federal government will develop a concept for hydrogen storage within the next years, that will cover the rededication of existing natural gas storage sites to hydrogen as well as the required development of new UHS. Besides enforcement of the future energy system and increasingly relying on intermittent renewable energy, only large-scale storage systems enable the temporal decoupling of energy production and demand. The draft also mentions the possible requirement for a national reserve for hydrogen and hydrogen derivatives to increase security of supply. As one key political measure, also the short-term support for different infrastructure projects in line with the IPCEI Hydrogen are announced, including 1,800 km pipeline network and three UHS in salt caverns (with operation starting 2026/2027). As of March 2023, the final document, however, has not been published by the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

The German National Hydrogen Council (*Nationaler Wasserstoffrat, NWR*)[8] has also underlined the requirement for a hydrogen storage roadmap 2030 in a position paper in 2022 [NWR 2022]. While announced UHS have an overall capacity of below 0.5 TWh, the hydrogen storage demand may add up to 5 TWh already in 2030. Key proposals in line with the roadmap are:

Short-term (until 2024)

- Implementation of a regulatory framework for hydrogen storage projects
- Shortening of timeline for approval procedures by including hydrogen into the existing rules for natural gas in "UVP-V Bergbau"
- Transitional rules for pilot plants to allow the use of non-renewable hydrogen as cushion gas to lower CAPEX
- CAPEX and OPEX subsidies for pilot projects

Mid-term (until 2030):

- Exemption of entry/exit fees and gas grid fees
- Exemption of electricity grid fees for injection and compression work (as a relevant part of storage OPEX)

Based on the recommendations above, two main aspects regarding the existing regulative framework for UHS can be derived:

1) There is no regulatory framework in place for hydrogen storage projects in Germany and
2) Approval procedures for hydrogen storage projects so far do not follow existing rules for natural gas underground storage projects, which are laid out in "UVP-V Bergbau".

The reason why existing rules for natural gas do not directly apply to hydrogen mainly lies in the way hydrogen was introduced into existing energy law in Germany. With the revisions of the German Energy Act (*Energiewirtschaftsgesetz, EnWG*)[9] in 2021, hydrogen was included as an additional grid-bound energy carrier beside electricity and gas (§3 Nr. 14, EnWG) [CMS 2021] [TaylorWessing 2022]. By doing so, existing rules for (natural) gas infrastructure do not apply for pure hydrogen transport and storage. Instead, definitions for a hydrogen grid and hydrogen storage units were included in §3 Nr. 39a and 39b, EnWG, respectively. Specific

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[8] « The German National Hydrogen Council was appointed by the German government and acts as an independent, non-partisan advisory board. The board consists of 25 high-ranking experts in the fields of economy, science and civil society. The German National Hydrogen Council's objective is to assist and advise the State Secretaries' Committee on Hydrogen in the further development and implementation of Germany's National Hydrogen Strategy » (https://www.wasserstoffrat.de/en/) .

[9] German Energy Act (*Energiewirtschaftsgesetz, EnWG*) 2023. https://www.gesetze-im-internet.de/enwg_2005/BJNR197010005.html#BJNR197010005BJNG000100000

rules for the regulation of hydrogen grids are defined in §28j-q, EnWG. As a consequence of separate hydrogen and natural gas regulation, the whole regulative and legislative environment needs to be newly defined for hydrogen, either by creating a new framework or referring to the existing framework for natural gas.

With regard to the existing legislative environment and permitting procedures for natural gas underground storage in Germany, further details were collected and discussed in Hystories D6.1-1 (Assessment of the Regulatory Framework) [FHa 2021] and therefore not reproduced in the present report. In summary, there is no uniform European approach to the legal framework for underground gas storage in European countries. As stated in Hystories D6.1-1, *“current legal requirements can be part of mining law, energy law, construction law, environmental law, labour protection law, health, and safety regulations.”*

In conclusion, it can be stated that the regulatory framework for hydrogen underground storages in Germany is in a development phase. The hydrogen infrastructure market in Germany, as in all other European countries, is only starting to emerge with first infrastructure projects (including underground storages) being implemented. Therefore, further definition and adjustments to the existing framework can be expected within the next years.

3. Input parameters and main assumptions

The cost analysis in this case study was performed by applying the cost model for UHS developed in Hystories WP2 (see D7.2-1) and the economic tool developed in Hystories D8.1 on a hypothetical salt cavern storage site in Germany. The storage technology selection for salt caverns was done based on the important role of salt caverns in the German gas storage market (see chapter 2.1) and their high suitability for the operation with hydrogen compared to porous media storages [DBI et al. 2022]. Since in general, salt caverns in Germany differ from each other in depth, size and number of caverns per storage site, the chosen case study should also reflect an average and representative facility.

Aim of the case study is the estimation of the levelized costs of hydrogen storage (LCOS), including the discussion of key economic parameters like CAPEX (development costs or capital expenditures), OPEX (costs of operating the storage facility over its life cycle) and ABEX (abandonment expenditures).

Key boundary conditions for parameter selection were also predefined by the ranges for main design parameters given in Hystories WP7 (D7.2-1) (see Table 3) [Geostock 2022] to allow for a high validity of the model application. In addition, discussions with key stakeholders from the projects' advisory board were used to set key parameters for the case study. The tool developed in Hystories task 8.1 for the qualitative assessment of different UHS sites was not applied in this case study.

Table 3: Main design parameters range for salt caverns described in the cost model in Hystories D7.2-1.

DESIGN PARAMETER	RANGE	REMARK
Minimum storage operating pressure (minOP)	60 barg – 70 barg	Geology dependent
Maximum storage operating pressure (MOP)	100 to 240 barg	Geology dependent
H_2 stream minimum operating pressure at compression inlet	From 30 barg, 30 °C To 60 barg, 30 °C	Electrolysis input dependent or Transportation network pressure dependent
Maximum total design withdrawal flowrate	0 to 30 million Sm^3/d (0 to 2500 tons_H2/d)	Geology dependent
Withdrawal-to-Injection Capacity Ratio (WTIR)	1 to 5 (usually around 2)	Techno-economical choice
Total installed compression brake power (TICBP)	1 to 80 MW	Techno-economical choice

Table 4: Conceptional design cases for salt caverns storage in Hystories D7.2-1.

DESIGN PARAMETER		Unit	Salt caverns storage LOW	Salt caverns storage MID	Salt caverns storage HIGH
Development wells count	n_{WH} or n_{WHprod}	[-]	4	8	16
Observation wells count	n_{WHobs}	[-]	NA		
Free gas volume per cavern	V_{cavern}	X 1000 m_3	815	380	185
Working Gas Volume per cavern	-	[million Sm^3] Per cavern	62.5	31.25	15.625
Cushion Gas to Total Gas ratio	x_{CG}	[-]	47%	43%	41%
Total Working Gas volume (for the site)	V_{WG}	[million Sm^3]	250		
Last Cemented Casing Shoe depth	$LCCS$	[m]	1 000		
Maximum storage operating pressure	MOP	[barg]	180		
Minimum storage operating pressure	$minOP$	[barg]	70		
Maximum withdrawal flowrate per cavern	-	[million Sm^3/d]	5.91	2.79	1.36
Maximum total design withdrawal flowrate (for the site)	Q_w	[million Sm^3/d]	23.6	22.3	21.8

The following sections briefly define scope of the case study (chapter 3.1) and summarize key parameter definitions of general and country/site-specific parameters (chapter 3.2).

3.1. Case study Germany - Scenario definition

The overarching scenario for cost model calculation is the following. The case study focusses on the development and operation of a new salt cavern and does not take any repurposing activities into account.

The availability of hydrogen storage facilities from 2030 onwards require short-term investment decisions on location and storage characteristics. Accordingly, the case study assumes a preparation, investment, and development phase between 2022 and 2029. By doing so, storage operation is assumed to start in 2030 and to continue over a 30-year lifetime until 2059.

To enable high utilization of the UHS from the beginning, the early connection to a hydrogen transport pipeline (see also Figure 2) is assumed. In addition, the salt cavern facility consists of several caverns from the beginning (with one well each). In case, storage demand increases over time, no further extension of the existing plant will be done. Instead, additional separate storage sites would be built outside the scope of this case study. Accordingly, these additional UHS are not considered in this case study, as well as potential synergies and scaling effects in surface facilities.

As described in Figure 4, surface facilities covered by the model include all components within the gas plant fence like filters and metering, compression and decompression units as well as dehydration and gas treatment units. In addition, all subsurface components of the UHS are considered (see Figure 5) [Geostock 2022b].

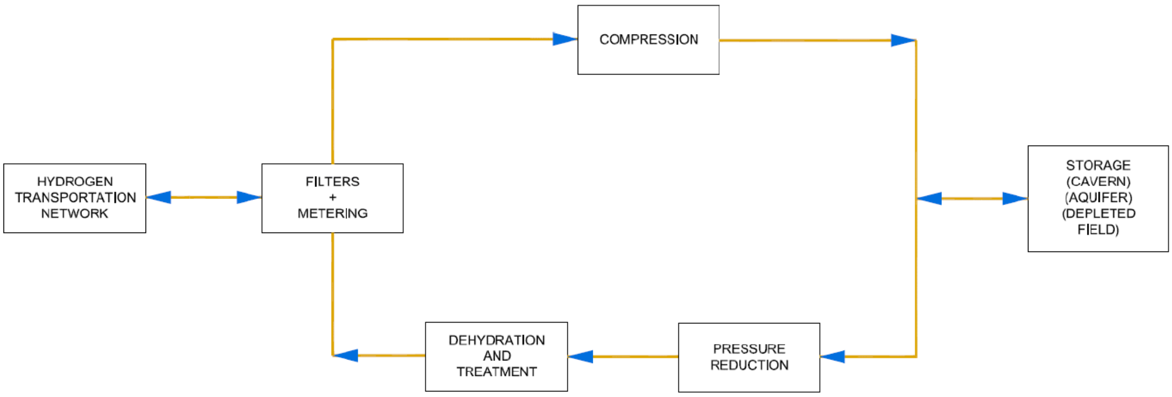

Figure 4: Battery limits of CAPEX model for surface facilities (source: Hystories D7.1-1)

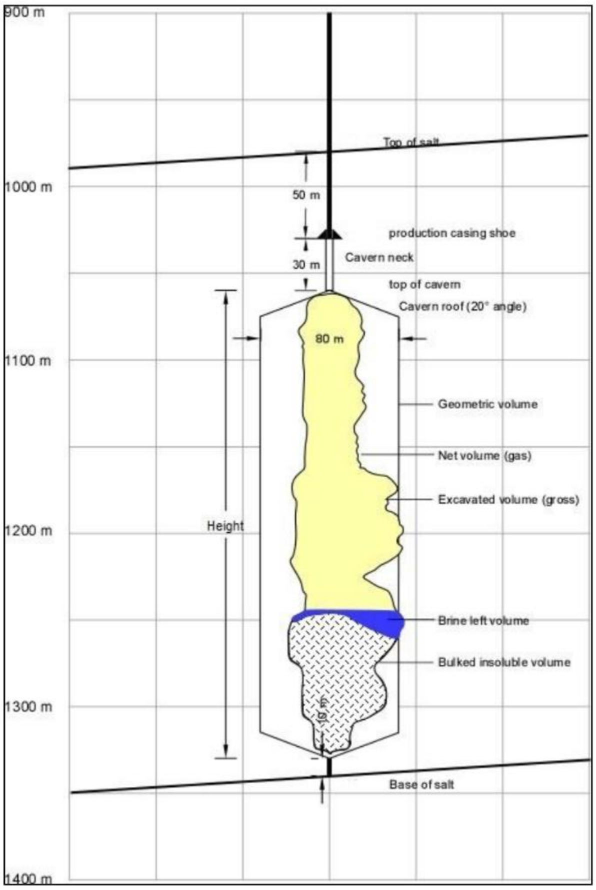

Figure 5: Schematic representation of cavern geometry (source: Hystories D7.1-1)

Further technical site-specific characteristics of this case study were derived by taking some publicly announced plans of the Hydrogen Cavern in Bad Lauchstädt, Germany into account (see pilot project No. 1 in Table 2). The project partners are terawatt, Uniper, VNG Gasspeicher, ONTRAS, VNG and DBI. Responsible partner for the gas storage facility is VNG Gasspeicher.

Key announced parameters of the project Energiepark Bad Lauchstädt are summarized in Table 5. The cavern is located in Saxony-Anhalt, Germany, in close vicinity to the middle German chemistry area around the cities of Leuna, Merseburg and Bitterfeld. The region is not only characterized by an existing high hydrogen demand, but also by an existing hydrogen pipeline with a length of about 150 km connecting key chemical locations. According to [VNG 2019a], the regional hydrogen demand will increase to up to 9 billion Nm^3 by 2050. The salt cavern announced in the context of the project "Energiepark Bad Lauchstädt" is planned to have a working gas capacity of up to 50 million Nm^3 hydrogen [VNG 2019b]. Beside the salt cavern, the project also includes a renewable electricity production capacity of 40 MW (wind onshore), 35 MW electrolyser capacity and a gas pipeline connection with an hourly throughput of around 100,000 Nm^3/h [GIE 2021]. A connection to the existing hydrogen pipeline system in Leuna is planned to be created by repurposing an existing, 25 km long natural gas pipeline. According to current plans, pipeline operation shall start already in 2024, with a pipeline pressure of around 30 bar and a maximum pressure of 63 bar [Energiepark Bad Lauchstädt 2022]. Today, already 17 caverns for natural gas storage are in operation at the site. Accordingly, potentially also the rededication of an existing cavern is a realistic perspective.

Table 5: Key parameters of German H_2 salt cavern pilot project "Energiepark Bad Lauchstädt"

Parameter	Value	Comment
Total cavern volume	560,000 m^3	[HYPOS 2019]
Cavern status	Filled with brine and blanket	[HYPOS 2019]
Cavern neck	850 – 905 m	[HYPOS 2019]
Cavern height	905 – 1108 m	[HYPOS 2019]
Cavern pressure	30 – 140 bar	[HYPOS 2019]
Working pressure	30 – 115 bar	[HYPOS 2019]
Storable H_2 volume	Working gas volume: 49.9 million Nm^3 (52.6 million Sm^3) Cushion gas volume: 15.5 million Nm^3 (16.4 million Sm^3)	[HYPOS 2019], [VNG 2019b]
H_2 injection rate (max)	35,000 Nm^3/h (36,885 Sm^3/h)	[VNG 2022]
H_2 depletion rate (max)	100,000 Nm^3/h (105,491 Sm^3/h)	[VNG 2022]
H_2 quality after cleaning & washing	99.96 % H_2	[VNG 2022]

3.2. Model input parameters and assumptions

Main assumptions for CAPEX (surface and subsurface facilities) and ABEX were taken from the Hystories D7.2-1 (Life Cycle Cost Assessment of an underground storage site).

In addition, the following assumptions for general model input parameters have been selected. To enable comparability between the different case studies in task 8.2, some key parameters were streamlined between the partners (see comments).

Table 6: General parameters – Case Study Germany

Parameter	Value	Comment
Cost of electricity (CoE) [€/MWh]	100	Assumption for Germany (Sensitivity analysis: variation of CoE between 50 – 150 € / MWh)
Hydrogen production costs [€/kg]	6.29	Common assumption for all Case Studies (Renewable hydrogen)
Cost for H_2 cushion gas in salt caverns [€/kg]	6.29	Common assumption for all Case Studies (Renewable hydrogen)
Other costs [€/kg]	1.89	Common assumption for all Case Studies (30 % of hydrogen production costs)
Storage service margin profit (%)	5.75	Common assumption for all Case Studies
Margin profit (%)	15	Common assumption for all Case Studies

Table 7: Financial input parameters – Case Study Germany

Title	Title	Comment
Subsidy [Mio. €]	20	Common assumption for all Case Studies
Venture period [years]	30	Operation period 2030-2059 Common assumption for all Case Studies
Residual value [% of CAPEX]	20	Common assumption for all Case Studies (approximately equal to ABEX/CAPEX ratio)
Corporate tax [%]	25	Assumption for average corporate tax in Germany. Note: Corporate income tax (CIT) Germany 1) Corporate income tax/solidarity surcharge: 15.825% 2) Trade tax: varies between 8.75% to 20.3%, depending on location of the business establishment. Source: [PWC 2022]
Financing fund [% of CAPEX]	none	Common assumption for all Case Studies
Interest rate [%]	5	Common assumption for all Case Studies
Financing duration [years]	30	Set as venture period, common assumption for all Case Studies
Rate of Return [%]	5.75	Common assumption for all Case Studies

In addition to general parameters described in chapter 3.2, several site-specific characteristics are considered in this case study, derived from existing plans for the Energiepark Bad Lauchstädt in Germany (see chapter 3.1).

Table 8: Parameters for geology and subsurface facilities – Case study Germany

Parameter	Value	Comment
Free gas volume per cavern [million m^3]	0.56	Assumption based on parameters for Energiepark Bad Lauchstädt (Average salt cavern Germany: 500,000 m^3, see [DBI et al 2022])
Maximum gas inventory per cavern [million Sm^3]	69	Assumption based on parameters for Energiepark Bad Lauchstädt [HYPOS 2019] (See working gas volume and cushion gas volume below)
Number of caverns (Assumption: one well head per cavern)	4	Assumption. Tool in D7.1 designed for at least 4 caverns
Last cemented casing shoe [m]	850	Assumption based on parameters for Energiepark Bad Lauchstädt [HYPOS 2019]: Cavern neck: 850 - 905 m Cavern height: 905 - 1108 m (Average Germany: 1000 m, see [DBI et al 2022])
Drilling complexity index	1	Common assumption for all Case Studies
Fresh water pipeline length [km]	15	Common assumption for all Case Studies
Brine disposal pipeline length [km]	30	Common assumption for all Case Studies
Working gas volume [million Sm^3]	210	Assumption based on parameters for Energiepark Bad Lauchstädt [HYPOS 2019] 49.9 million Nm^3 (52.6 million Sm^3) per cavern
Cushion gas volume [million Sm^3]	66	Assumption based on parameters for Energiepark Bad Lauchstädt [HYPOS 2019] 15.5 million Nm^3 (16.4 million Sm^3) per cavern
Cushion gas / total gas ratio	0.24	Assumption based on parameters for Energiepark Bad Lauchstädt [HYPOS 2019]
Debrining flowrate per cavern [m^3/h]	200	Common assumption for all Case Studies
Expected number of full cycles per year	1.6	Results of WP5 for Germany 2050. Assumption: same value for 2030, 2040 and 2050
Maximum number of full cycles per year	4.6	Calculated by dividing 365 days by duration of one full cycle in days (here: 80 days)
Load factor	0.35	Calculated by dividing number of full cycles per year by Maximum number of full cycles per year

Table 9: Parameters for operating costs and surface facilities – Case Study Germany

Parameter	Value	Comment
Material cost factor for injection (compression) stream	1	Common assumption for all Case Studies. MCF carbon steel (raw material) = 1 MCF stainless steel 316L (raw material) = 3.5 - 4.5
Material cost factor for withdrawal stream	1	Common assumption for all Case Studies. MCF carbon steel (raw material) = 1 MCF stainless steel 316L (raw material) = 3.5 - 4.5
Total storage maximum withdrawal flowrate capacity [million Sm^3/day]	10.13	Assumption based on parameters for Energiepark Bad Lauchstädt [HYPOS 2019] 100,000 Nm^3/h = 105,491 Sm^3/h per cavern = 10,127,183 Sm^3/day (4 caverns)
Overall compression ratio (ratio of discharging pressure over suction pressure)	2.52	For calculation see D7.2-1.
Number of required compression stages	2	Overall compression ratio: $\tau=(MOP+1)/(netOP+1)$ n=1 if $\tau \leq 2.34$, n=2 if $2.34 < \tau \leq 4.54$ or n=3 if $4.54 < \tau \leq 9.67$
Withdrawal to injection capacity ratio	2.86	Assumption based on parameters for Energiepark Bad Lauchstädt (see chapter 3.1) Withdrawal rate max.: 100.000 Nm^3/h Injection rate max. 35.000 Nm^3/h
Minimum suction pressure of compression stream (pipeline operating pressure) [barg]	55	Common assumption for all Case Studies
Maximum storage operating pressure [barg]	140	Assumption based on parameters for Energiepark Bad Lauchstädt [HYPOS 2019]
Minimum storage operating pressure [barg]	60	Assumption, so that operating pressure > minimum suction pressure. In line with pipeline properties for Energiepark Bad Lauchstädt (see chapter 3.1)
Field lines size [km]	2	Common assumption for all Case Studies
Purification coefficient (only for porous media)	0	Not applicable for salt caverns

4. Results

The following chapters present the results of the Case Study Germany. The results were received by using the country-specific parameters listed in chapter 3 as input data for the economic modelling tool described in Hystories D8.1.

Key modelling results for a reference case are shown and discussed in chapter 4.1, followed by an analysis of cash flow indicators in chapter 4.2. Sensitivity analyses of selected input parameters are used in chapter 4.2.3 to check robustness of the model regarding variations in specific input parameters.

4.1. Reference Case

Based on the assumptions for this case study described in chapter 3 above, yearly storage throughput of the assumed storage site is about 29,860 t/year. For perspective, this number can be compared to the key storage parameters in Table 10 and Figure 6, which show projections of the overall German national hydrogen storage throughput that were estimated in Hystories D5.5 (scenario D) [LBST 2022].

Based on these results, the assumed annual throughput in 2030 of the single site would be nearly sufficient to cover the overall storage throughput demand for Germany in 2030. Since hydrogen demand (and hence storage capacity demand) will significantly increase in Germany until 2050, the share of the assumed storage will continuously decrease to about 2% of national demand by 2050. It should be noted that regional distribution of storage demand within a country is not considered in the assumptions that shaped the Hystories WP5 results. Still, these results show that the assumed storage size might be oversized in the first operation phase in the early 2030s, while it can be expected that its storage capacity is needed when the hydrogen market in Germany becomes more mature.

Table 10: Comparison of assumed storage throughput to national storage throughput based on results from Hystories D5.5-2 [LBST 2022]

Parameter	2030	2040	2050
Hydrogen demand per country [TWh/year] *	78.3	189.6	356.2
Capacity of storage per country [TWh] *	0.2	4.2	40.4
Capacity of storage per country [t] *	7,158	125,569	1,211,786
Overall hydrogen storage throughput [TWh/year] *	1.0	5.9	55.6
National hydrogen storage throughput [t/year] (1) *	30,225	176,615	1,666,930
Case Study: Technical storage throughput (t/year) (2)	29,860	29,860	29,860
Case Study: Technical throughput site (2) / national storage throughput (1) (%)	98%	17%	2%
Number of full cycles per year (for salt caverns) *	4.2	1.4	1.6

*: Country-specific modelling results for Germany from Hystories D5.5-2.

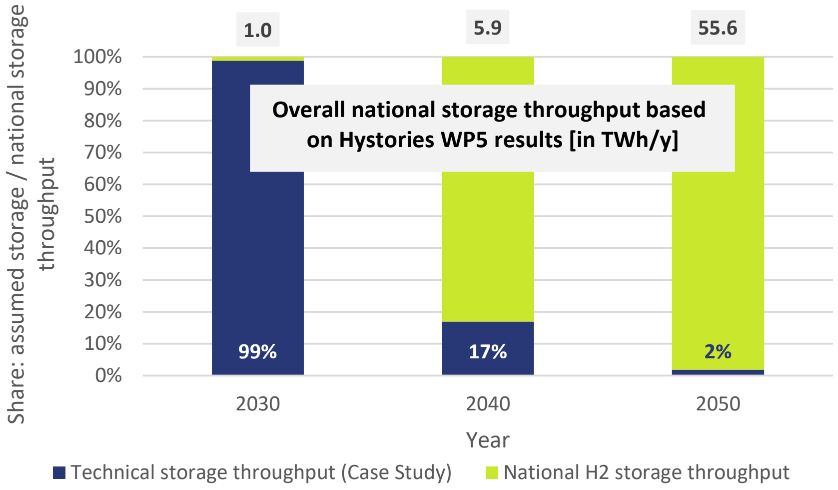

Figure 6: Assumed storage throughput vs. national storage throughput based on Hystories WP5 results in Hystories D5.5 [LBST 2022]

Key modelling results of the business case analysis for the reference case are summarized in Table 11.

Table 11: Key modelling results for CAPEX, OPEX and ABEX of the case study for Germany

Parameter	Unit	Value
CAPEX – subsurface	million €	268.9
CAPEX – surface	million €	199.6
OPEX	million € / year	12.4
ABEX	million €	88.6

In the following, contributions to CAPEX subsurface, CAPEX surface, OPEX and ABEX are analysed in more detail.

Capital Expenditures (CAPEX) for subsurface facilities sum up to 268.9 million €, with main contributions of leaching facilities (33%), leaching operation and maintenance costs (21%) and contingencies related to subsurface facilities (17%). Further cost components are costs for development drilling and leaching completion (8%), salt cavern debrining and conversion costs (8%) and cushion gas investments (13%) (assuming a hydrogen costs of 6.29 €/kg). All values are shown in Table 12 and Figure 7 below.

Table 12: Cost breakdown: CAPEX - subsurface

Costs breakdown	Description	Value [million €]
EPC_1	EPC cost main parameters and cost breakdown for leaching facilities	88.20
EPC_2	Leaching operation and maintenance costs	57.40
EPC_3	Salt cavern debrining and conversion costs	21.86
EPC_4	Development drilling and leaching completion costs	21.12
CG	Cushion gas for salt caverns	35.52
$CONT_{subsurface}$	Contingencies related to subsurface	44.82
Total		**268.9**

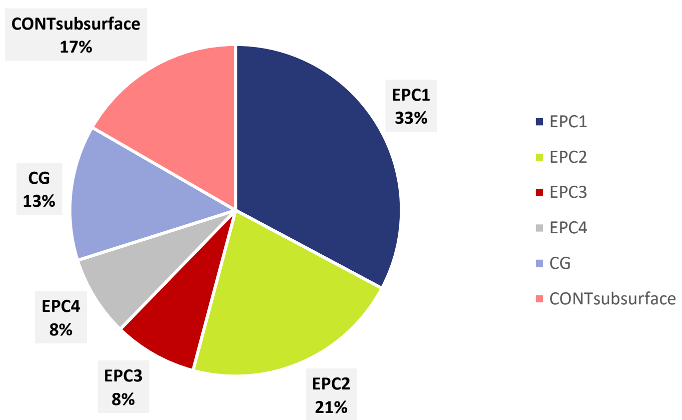

Figure 7: Cost components CAPEX - subsurface

CAPEX for surface facilities sum up to 199.6 million €, with main cost contributions coming from the units for filtering, drying & compression, and metering (61%). Smaller cost shares are connected to contingencies related to surface facilities (17%), EPC costs for gas pipeline interconnection (9%), balance of plant (8%), and additional costs for pipeline interconnection (assumption: 2 additional km) (5%). As this Case Study analyses a UHS in a salt cavern, no costs connected to hydrogen purification are required (in contrast to UHS in porous media). All values are shown in Table 13 and Figure 8 below.

Table 13: Cost breakdown: CAPEX - surface

Costs breakdown	Description	Value [million €]
EPC_1	EPC cost main parameters and breakdown for filtering, drying & compression, and metering units	121.32
EPC_2	EPC costs for interconnection wellhead and gas plant	19.07
EPC_3	EPC cost per additional kilometre between Gas Plant and nearest WH	10.42
EPC_4	EPC cost estimate for hydrogen purification at storage outlet	-
EPC5	EPC cost main parameters and cost breakdown for Balance of Plant	15.54
$CONT_{surface}$	Contingencies related to surface facilities	33.27
Total		**199.61**

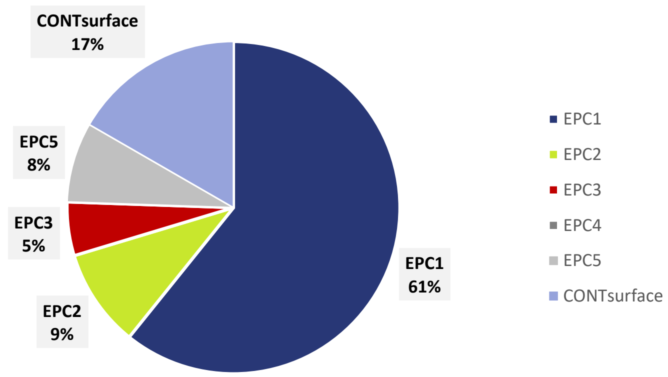

Figure 8: Cost components CAPEX - surface

Storage facilities' Operational Expenditures (OPEX) are listed in Table 14 and Figure 9. Annual OPEX are assumed to be constant over the whole operation period (2030 – 2059) with 12.4 million €/year. Overall OPEX are split up into three components: fixed OPEX (surface) accounting for 70% of total OPEX, variable OPEX (surface) for 25% and further fixed OPEX (subsurface) accounting for 5%. While all fixed OPEX are calculated taking a constant factor of surface and subsurface CAPEX into account, variable OPEX (surface) are impacted by project parameters like e.g. cost of electricity or storage's load factor.

Table 14: Cost breakdown: OPEX

Costs breakdown	Description	Value [million €/year]
$OPEX_{fix, UG}$	OPEX - Subsurface	0.63
$OPEX_{fix, AG}$	Fixed OPEX - Surface	8.75
$OPEX_{var, AG}$	Variable OPEX - Surface	3.04
Total		**12.43**

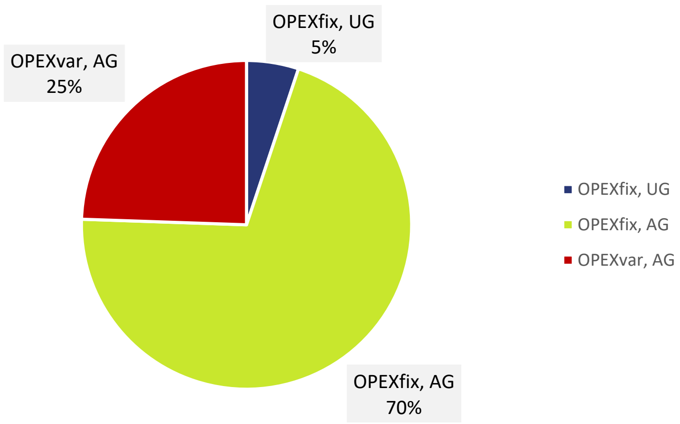

Figure 9: Cost components OPEX

Finally, Abandonment Expenditure (ABEX) of the assumed UHS sum up to 88.2 million €, of which 54% are connected to subsurface facilities and 46% to surface facilities. Results are also listed in Table 15 and Figure 10.

Table 15: Cost breakdown: ABEX

Costs breakdown	Description	Value [million €]
$ABEX_{subsurface}$	Abandonment Expenditure for subsurface	46.67
$ABEX_{surface}$	Abandonment Expenditure for surface facilities	39.92
Total		**86.60**

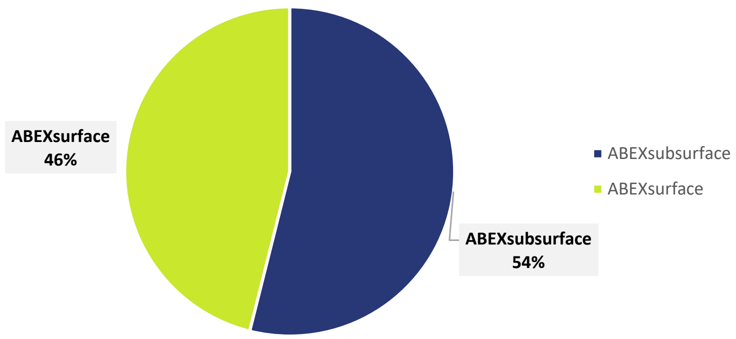

Figure 10: Cost components ABEX

4.2. Cash flow analysis

Key UHS project KPIs include Net Present Value (NPV), Internal Rate of Return (IRR), Net Present Cost (NPC), and Levelized Cost of Storage (LCOS). The definition of each parameter is based on Hystories D7.3 and D8.1.

4.2.1. Methodology

Net Present Cost (NPC) are defined as net present value of the total costs over the project period.

$$NPC = \sum (CAPEX_t + OPEX_t + ABEX_t) \cdot (1 + r)^{-t}$$

The Levelized Cost of Storage (LCOS) is estimated as NPC divided by a net present value of the quantity of H_2 transit over a project lifetime. The operational lifetime is assumed to be 30 years for the case study. Also, the investment period of additional 8 years before the start of operation is taken into account.

The formula used for the calculations is:

$$LCOS = \frac{\sum (CAPEX_t + OPEX_t + ABEX_t) \cdot (1 + r)^{-t}}{\sum H2transit_t \cdot (1 + r)^{-t}}$$

With discount rate r = 5.75%.

Net Present Value (NPV) of the project is defined as the sum of the present values of all cash flows during the project. Beside all project related costs, also e.g. subsidies and revenues are considered.

For the reference case, revenues are calculated based on the following formula, applying a storage service margin profit of 5.75%:

$$Storage\ service\ price \left(\frac{€}{kg}\right) = LCOS \left(\frac{€}{kg}\right) \cdot \left(1 + storage\ service\ margin\ profit\ (\%)\right)$$
$$= 1.71\ \frac{€}{kg} \cdot (1 + 5.75\%) = 1.8041\ \frac{€}{kg}$$

The internal rate of return (IRR) is used to estimate the profitability of the business case. IRR is a discount rate that makes the net present value (NPV) of all cash flows equal to zero in a discounted cash flow analysis.

4.2.2. Results

The above explained KPIs are calculated for the reference case and listed in Table 16. For assumptions related to financial parameters, please see Table 7 above.

Table 16: Key business case results of the case study for Germany (Reference Case)

Parameter	Unit	Value
Yearly stored hydrogen	kt/year	29.9
Net Present Value (NPV)	million €	-19.20
IRR	%	5.31
Net Present Cost (NPC)	million €	460.59
Levelized Cost of Storage (LCOS)	€/kg	1.71

The results show that there is no viable business case for the assumption taken in the reference case. The NPV of the project is -19.2 million €, with NPC of 461 million €. The IRR lies at 5.31 %, which is outside the acceptable investment range of companies. For an overall amount of stored hydrogen per year of 29.9 kt (assumed to be constant over the overall project lifetime), the LCOS are about 1.71 €/kg hydrogen stored.

Figure 11 shows the cumulative net cash flow (without discounting) over the project lifetime.

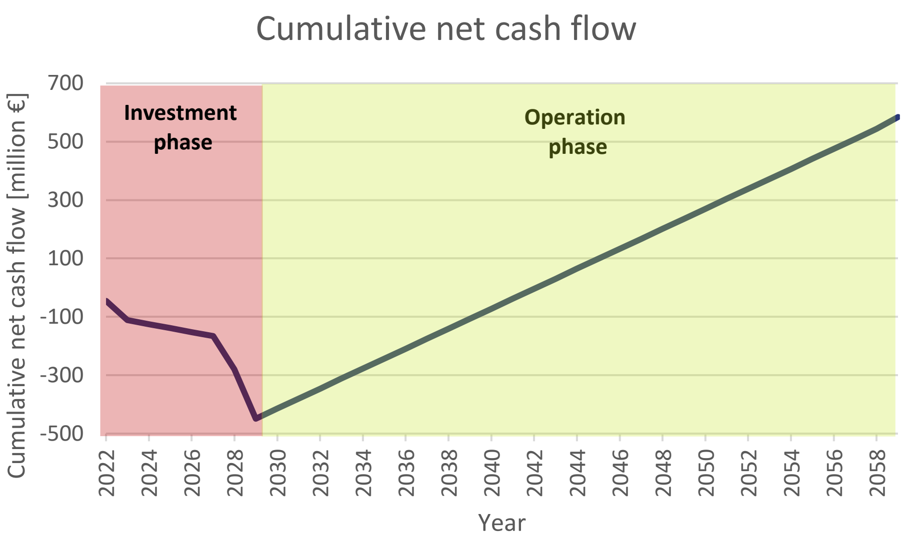

Figure 11: Cumulative net cash flow over the project lifetime

Depending on the assumed hydrogen production cost, hydrogen selling prices at the end consumer range between 5.06 €/kg (H_2 production costs of 2 €/kg) and 17.02 €/kg (production costs of 10 €/kg) (see Table 17 and Figure 12). Especially at low hydrogen production costs of 2 €/kg, hydrogen storage cost (LCOS) and the assumed service margin ("Storage service margin profit") can account for a significant share (up to 37%) of the overall end user's hydrogen price. It should however be noted that, as described in D5.5-2, the overall annual storage throughout in UHS in EU27+UK accounts for only a share of 12.5 to 22.5% of the overall hydrogen demand. Accordingly, only distributing the storage service costs over all hydrogen end consumers will significantly reduce the contribution of hydrogen storage cost to overall hydrogen end users' price.

Table 17: Hydrogen selling prices for different hydrogen production costs assumed

Parameter	Unit	(1) Hydrogen production cost [€/kg] 2.00	4.00	6.00	8.00	10.00
(2) Other costs (30%)	€/kg	0.60	1.20	1.80	2.40	3.00
(3) Storage cost (LOCS)	€/kg	1.71	1.71	1.71	1.71	1.71
(4) Storage service margin profit (5.75%)	€/kg	0.10	0.10	0.10	0.10	0.10
(5) Margin profit (15%)	€/kg	0.66	1.05	1.44	1.83	2.22
(6) Hydrogen selling price (Total)	€/kg	5.06	8.05	11.04	14.03	17.02
Price spread ***Calculation: ((6) - (1)) / (1)***	%	60.5	50.3	45.7	43.0	41.3

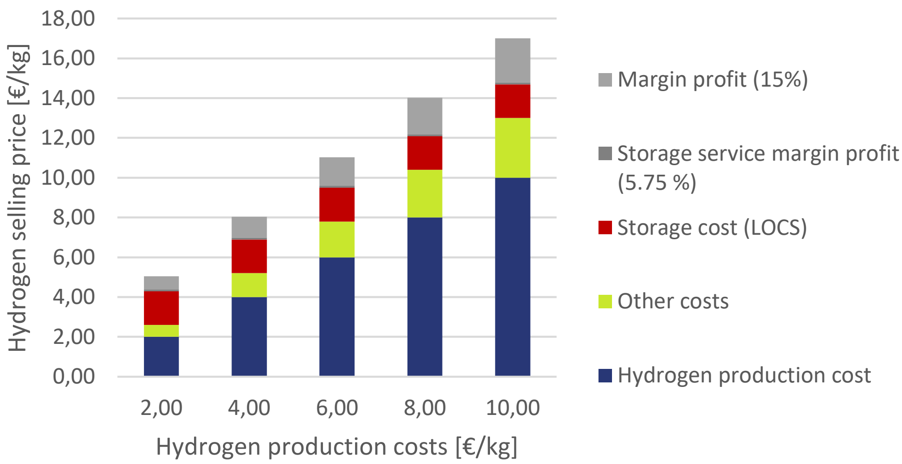

Figure 12: Hydrogen selling price for different hydrogen production costs assumed

4.2.3. Variation in storage service margin profit (SSMP)

For the reference case, the storage service price is calculated based on LCOS and taking an additional storage service margin profit of 5.75% into account. Hence, revenues of 1.81 €/kg are assumed.

By variations in storage service margin profit (and hence the overall storage service price) it is possible to analyse the impact of revenues the storage operator can achieve per kg hydrogen stored on the overall business case. It is an important lever to improve the UHS project's NPV. Table 18 lists key model output parameters for a variation of the respective margins, listed as storage service margin profit (in % of LCOS) and as storage service price (in €/kg).

The results show that the only factors impacted by variations in the potential revenues per kg hydrogen stored are NPV and IRR of the project. Decreasing the storage margin from 5.75% (reference case) to 0%, meaning that only LCOS are achieved as revenue, results in a worsening of the NPV from -19.2 million € to -39.1 million €. At the same time, IRR lowers from 5.31% to 4.83%. On the other side, **an increase in the profit margin by factor 2 (to 11.50%) enable the business case to break even, with an NPV of 0.7 million € at an IRR of 5.77%.** An overall increase to 14.375% (factor 2.5 compared to reference case) improves NPV further to 10.6 million € at an IRR of 5.99%.

Table 18: Results of sensitivity analysis: storage service margin profit

		Storage service margin profit (% of LCOS)						
		0.00%	2.875%	5.75%	8.625%	11.31%	11.50%	14.375%
		0%	50%	100%	150%	197%	200%	250%
CAPEX/OPEX	**Unit**							
CAPEX - subsurface	million €	268.9	268.9	268.9	268.9	268.9	268.9	268.9
CAPEX - surface	million €	199.6	199.6	199.6	199.6	199.6	199.6	199.6
OPEX	million € / year	12.4	12.4	12.4	12.4	12.4	12.4	12.4
ABEX	million €	86.6	86.6	86.6	86.6	86.6	86.6	86.6
Business Case KPIs	**Unit**							
Yearly stored hydrogen	kt/year	29.9	29.9	29.9	29.9	29.9	29.9	29.9
Net Present Value (NPV)	million €	-39.1	-29.1	-19.2	-9.3	0.0	0.7	10.6
IRR	%	4.83%	5.07%	5.31%	5.54%	5.75%	5.77%	5.99%
Net Present Cost (NPC)	million €	460.6	460.6	460.6	460.6	460.6	460.6	460.6
LCOS	€/kg	1.71	1.71	1.71	1.71	1.71	1.71	1.71
Hydrogen storage service price	**Unit**							
Storage cost (=LCOS)	€/kg	1.71	1.71	1.71	1.71	1.71	1.71	1.71
Storage service margin profit	€/kg	0.000	0.049	0.098	0.147	0.193	0.196	0.245
Storage service margin profit	%	0.00%	2.88%	5.75%	8.63%	11.31%	11.50%	14.38%
Storage service price	€/kg	1.71	1.76	1.80	1.85	1.90	1.90	1.95

One key assumption taken to maximize comparability of the results regarding key economic KPIs (i.e. LCOS) is to set a fix storage service profit margin (in €/kg) for all further sensitivity analyses (=basic case). To do so, the marginal value is used at which the business case becomes economically feasible under the assumptions taken. As shown in Table 18, this is the case for a storage service margin profit of 11.31% of LCOS (here: 1.71 €/kg), which is equivalent to 0.193 €/kg. Taking this profit margin for the storage operator into account, the resulting overall storage service price is 1.90 €/kg.

Applying the same absolute storage service margin profit of 0.193 €/kg for all cases guarantees that storage operator's revenues are not impacted by changes in LCOS itself. Instead, for each case the storage service margin profit values (in %) can be identified, which would be required for the business case to break even.

4.3. Business case optimization (sensitivity analysis)

Results for the reference case in chapter 4.2 showed that the business case analysed in this case study does not result in an economic viable business case. With the assumptions taken here, a NPV of -19.2 million € and an IRR of 5.31% is obtained. By applying a higher storage service margin profit of 11.31% instead of 5.75%, the business case, however, turns positive.

The sensitivity analyses performed in this chapter shall serve as the basis i) to check robustness of modelling results regarding variation in key input parameters and ii) to analyse how the business case can be optimized.

To do so, the following input parameters were varied:

A) Economic parameters

- corporate tax
- Cost of Electricity (CoE)
- rate of return (=discount rate).
- subsidies
- financing funds

B) Site-specific parameters

- number of caverns
- number of cycles
- variation in injection rate (= withdrawal to injection ratio)

4.3.1. Corporate tax

Table 19 shows the results in case of variation of corporate tax. In Germany, corporate income tax (CIT) consists of two parts [PWC 2022]:

- corporate income tax (15.825%) and
- trade tax (varies between 8.75% to 20.3%, depending on location of the business establishment).

For this sensitivity analysis, corporate tax values were varied between 15% and 35% (reference case: 25%). In addition, one case with no corporate tax was assumed.

As shown in Table 19, variations in corporate tax only impact NPV and IRR of the UHS project. **A reduction in corporate tax to 15% (-40% compared to reference case) already significantly improves NPV (28.7 million €) at an IRR of 6.38%.** On the other side, an increase of corporate tax to 35%, which is also a possible value under German corporate tax system, decreases NPV to -28.7 million €.

In all cases, there is no change in marginal profits for the storage operator as LCOS remains constant.

Table 19: Results of sensitivity analysis: corporate tax

		Corporate tax [%]					
		0	15	20	25	30	35
Variation in input parameter		0%	60%	80%	100%	120%	140%
CAPEX/OPEX	**Unit**						
CAPEX - subsurface	million €	268.9	268.9	268.9	268.9	268.9	268.9
CAPEX - surface	million €	199.6	199.6	199.6	199.6	199.6	199.6
OPEX	million € / year	12.4	12.4	12.4	12.4	12.4	12.4
ABEX	million €	86.6	86.6	86.6	86.6	86.6	86.6
Business Case KPIs	**Unit**						
Yearly stored hydrogen	kt/year	29.9	29.9	29.9	29.9	29.9	29.9
Net Present Value (NPV)	million €	71.9	28.8	14.4	0.0	-14.4	-28.7
IRR	%	7.27%	6.38%	6.07%	5.75%	5.42%	5.08%
Net Present Cost (NPC)	million €	460.6	460.6	460.6	460.6	460.6	460.6
LCOS	€/kg	1.71	1.71	1.71	1.71	1.71	1.71
Hydrogen storage service price	**Unit**						
Storage cost (=LCOS)	€/kg	1.71	1.71	1.71	1.71	1.71	1.71
Storage service margin profit	€/kg	0.193	0.193	0.193	0.193	0.193	0.193
Storage service margin profit	%	11.31%	11.31%	11.31%	11.31%	11.31%	11.31%
Storage service price	€/kg	1.90	1.90	1.90	1.90	1.90	1.90

4.3.2. Cost of Electricity (CoE)

Variation in cost of electricity only impacts OPEX and consequently key cash flow parameters of the storage. As described in chapter 4.1, CoE only impacts variable OPEX (surface), which are the key element of overall OPEX of the project. Accordingly, the variation of CoE from 50 to 150 €/MWh results in annual OPEX of 10.9 to 13.9 million €/year, respectively (see Table 20). In case, no CoE are assumed, OPEX further reduce to 9.4 million €/year.

The analyses show that an increase in CoE by 50% (to 150 €/MWh) results in an overall increase in LCOS of 3%, while a decrease by 50% (to 50 €/MWh) also decreases LCOS by 3%.

As for these sensitivities, storage service margin profit is kept constant at 0.193 €/kg in addition to LCOS, there is no change in NPV or IRR. NPC range from 433.1 million € (for CoE of 0 €/MWh) to 474.3 million € (for CoE of 150 €/MWh). The resulting additional revenues required for the storage operator to break even are between 12.03% of LCOS (for former case) and 10.99% of LCOS (for latter case).

Table 20: Results of sensitivity analysis: Cost of Electricity

		Cost of Electricity [€/MWh]					
		0	50	75	100	125	150
Variation in input parameter		0%	50%	75%	100%	125%	150%
CAPEX/OPEX	**Unit**						
CAPEX - subsurface	million €	268.9	268.9	268.9	268.9	268.9	268.9
CAPEX - surface	million €	199.6	199.6	199.6	199.6	199.6	199.6
OPEX	million € / year	9.4	10.9	11.7	12.4	13.2	13.9
ABEX	million €	86.6	86.6	86.6	86.6	86.6	86.6
Business Case KPIs	**Unit**						
Yearly stored hydrogen	kt/year	29.9	29.9	29.9	29.9	29.9	29.9
Net Present Value (NPV)	million €	0.0	0.0	0.0	0.0	0.0	0.0
IRR	%	5.75%	5.75%	5.75%	5.75%	5.75%	5.75%
Net Present Cost (NPC)	million €	433.1	446.9	453.7	460.6	467.5	474.3
LCOS	€/kg	1.60	1.66	1.68	1.71	1.73	1.76
Hydrogen storage service price	**Unit**						
Storage cost (=LCOS)	€/kg	1.60	1.66	1.68	1.71	1.73	1.76
Storage service margin profit	€/kg	0.193	0.193	0.193	0.193	0.193	0.193
Storage service margin profit	%	12.03%	11.66%	11.48%	11.31%	11.15%	10.99%
Storage service price	€/kg	1.80	1.85	1.87	1.90	1.92	1.95

4.3.3. Rate of return (Discount rate)

Variations in the assumed discount rate have significant impacts on Business Case KPIs (i.e. NPV, NPC and LCOS). Table 21 summarized the results of the sensitivity analysis.

While actual costs remain constant over all cases, an increase in the assumed rate of return / discount factor (r) results in a situation where the present value of costs or (cash) flows in the future is considered lower. For the investigated cases, NPC is between 599.2 million € (r = 2.875%) and 372.9 million € (r = 8.600%). Since also present value of hydrogen throughput changes with r, despite higher NPC, the LCOS are reduced to 1.26 €/kg in case of a low rate of return of 2.875%.

At the same time, NPV ranges from 39.6 million € (r = 2.875%) to -16.7 million € (r = 8.600%). While revenues stay the same for all cases, NPV increases for low discount rates as LCOS decrease.

Table 21: Results of sensitivity analysis: rate of return

		Rate of return (Discount rate)				
		2.875%	4.313%	5.750%	7.188%	8.600%
Variation in input parameter		50%	75%	100%	125%	150%
CAPEX/OPEX	**Unit**					
CAPEX - subsurface	million €	268.9	268.9	268.9	268.9	268.9
CAPEX - surface	million €	199.6	199.6	199.6	199.6	199.6
OPEX	million € / year	12.4	12.4	12.4	12.4	12.4
ABEX	million €	86.6	86.6	86.6	86.6	86.6
Business Case KPIs	**Unit**					
Yearly stored hydrogen	kt/year	29.9	29.9	29.9	29.9	29.9
Net Present Value (NPV)	million €	39.6	15.7	0.0	-10.1	-16.7
IRR	%	3.52%	4.61%	5.75%	6.92%	8.12%
Net Present Cost (NPC)	million €	599.2	521.2	460.6	412.2	372.9
LCOS	€/kg	1.26	1.47	1.71	1.98	2.28
Hydrogen storage service price	**Unit**					
Storage cost (=LCOS)	€/kg	1.26	1.47	1.71	1.98	2.28
Storage service margin profit	€/kg	0.193	0.193	0.193	0.193	0.193
Storage service margin profit	%	15.27%	13.14%	11.31%	9.77%	8.47%
Storage service price	€/kg	1.46	1.66	1.90	2.17	2.47

4.3.4. Subsidies

The reference case assumes a subsidy by the government of 20 million €.

Subsidies are considered as interest free payment, which does not have to be repaid by the UHS storage project. Table 22 compares different subsidies, ranging from zero to 40 million €. **Based on the assumptions of the reference case with an assumed storage service margin profit of 0.193 €/kg, a subsidy of around 40 million € would result in a NPV of 18.9 million €.** With no subsidies assumed, NPV of the overall project is -18.9 million € at an IRR of 5.35%.

No further economic KPIs are impacted by subsidies.

Table 22: Results of sensitivity analysis: subsidy

		Subsidies [million €]				
		0	10	20	30	40
Variation in input parameter		0%	50%	100%	150%	200%
CAPEX/OPEX	**Unit**					
CAPEX - subsurface	million €	268.9	268.9	268.9	268.9	268.9
CAPEX - surface	million €	199.6	199.6	199.6	199.6	199.6
OPEX	million € / year	12.4	12.4	12.4	12.4	12.4
ABEX	million €	86.6	86.6	86.6	86.6	86.6
Business Case KPIs	**Unit**					
Yearly stored hydrogen	kt/year	29.9	29.9	29.9	29.9	29.9
Net Present Value (NPV)	million €	-18.9	-9.4	0.0	9.5	18.9
IRR	%	5.35%	5.54%	5.75%	5.97%	6.20%
Net Present Cost (NPC)	million €	460.6	460.6	460.6	460.6	460.6
LCOS	€/kg	1.71	1.71	1.71	1.71	1.71
Hydrogen storage service price	**Unit**					
Storage cost (=LCOS)	€/kg	1.71	1.71	1.71	1.71	1.71
Storage service margin profit	€/kg	0.193	0.193	0.193	0.193	0.193
Storage service margin profit	%	11.31%	11.31%	11.31%	11.31%	11.31%
Storage service price	€/kg	1.90	1.90	1.90	1.90	1.90

4.3.5. Financing funds

The reference case also assumes no external financing for the UHS project. In the following, the impact of a financial loan on NPV is analysed. Key assumptions are that the loan is received during the beginning of the financing period (2022), with an interest rate of 5% and a financing duration of 30 years, starting with the operation of the storage in 2030.

Impact of these changes are shown in Table 23. High loans increase NPV due to two reasons:

- interest for the investment period between 2022 and 2030 was neglected and
- lower interest rate (i = 5.0%) compared to rate of return (r = 5.75%) were assumed.

In summary, these results show that, due to discounting effects, also external financing can have a significant impact on the business cases, depending on financing conditions. However, it can be expected that external financing will rather worsen the business case due to less favourable financing conditions.

Accordingly, this parameter is not considered further in this analysis.

Table 23: Results of sensitivity analysis: financing funds

		Financing funds [million €]					
		0	25	50	75	100	150
Variation in input parameter							
CAPEX/OPEX	**Unit**						
CAPEX - subsurface	million €	268.9	268.9	268.9	268.9	268.9	268.9
CAPEX - surface	million €	199.6	199.6	199.6	199.6	199.6	199.6
OPEX	million € / year	12.4	12.4	12.4	12.4	12.4	12.4
ABEX	million €	86.6	86.6	86.6	86.6	86.6	86.6
Business Case KPIs	**Unit**						
Yearly stored hydrogen	kt/year	29.9	29.9	29.9	29.9	29.9	29.9
Net Present Value (NPV)	million €	0.0	11.2	22.4	33.6	44.8	67.1
IRR	%	5.75%	6.03%	6.36%	6.77%	7.31%	9.15%
Net Present Cost (NPC)	million €	460.6	460.6	460.6	460.6	460.6	460.6
LCOS	€/kg	1.71	1.71	1.71	1.71	1.71	1.71
Hydrogen storage service price	**Unit**						
Storage cost (=LCOS)	€/kg	1.71	1.71	1.71	1.71	1.71	1.71
Storage service margin profit	€/kg	0.193	0.193	0.193	0.193	0.193	0.193
Storage service margin profit	%	11.31%	11.31%	11.31%	11.31%	11.31%	11.31%
Storage service price	€/kg	1.90	1.90	1.90	1.90	1.90	1.90

4.3.6. Number of caverns

While chapters 4.3.1 to 4.3.5 focus on changes in economic parameters, in the following the impact of an adapted UHS design on LCOS shall be analysed. To do so, several cases with different numbers of caverns are compared. For comparison reasons, all caverns possess the same cavern geometry and injection & withdrawal capacities. By increasing the number of caverns, the overall project size increases accordingly.

While the annual volume of stored hydrogen linearly scales with increasing number of caverns (7.5 kt/year per cavern), the resulting scaling effects in CAPEX and OPEX lead to a decrease in the specific storage costs and, hence, LCOS. In a case of one cavern, LCOS of 3.70 €/kg are achieved, while they are reduced in a case of eight caverns to 1.44 €/kg (see Table 24). An increase in project size, however, has no impact on NPV of the business case, as long as LCOS are covered, and additional revenue streams are kept constant for all cases. Deviations from the reference case are caused by rounding errors and are minor compared to overall NPCs of up to 1.1 billion €.

Storage service margins range from 5.22% in case of one cavern with high LCOS (3.70 €) to 14.03% in case of twelve caverns with low LCOS (1.38 €/kg).

Table 24: Results of sensitivity analysis: number of caverns

		Number of caverns					
		1	2	4	6	8	12
Variation in input parameter		25%	50%	100%	150%	200%	300%
CAPEX/OPEX	**Unit**						
CAPEX - subsurface	million €	167.8	200.5	268.9	372.1	440.7	613.3
CAPEX - surface	million €	84.2	123.0	199.6	278.8	362.0	543.1
OPEX	million € / year	5.8	8.0	12.4	16.9	21.5	31.2
ABEX	million €	48.6	61.2	86.6	119.5	146.3	210.0
Business Case KPIs	**Unit**						
Yearly stored hydrogen	kt/year	7.5	14.9	29.9	44.8	59.7	89.6
Net Present Value (NPV)	million €	-5.1	-3.4	0.0	-1.4	1.3	0.5
IRR	%	5.54%	5.64%	5.75%	5.73%	5.77%	5.75%
Net Present Cost (NPC)	million €	249.5	319.6	460.6	630.4	778.0	1,113.9
LCOS	€/kg	3.70	2.37	1.71	1.56	1.44	1.38
Hydrogen storage service price	**Unit**						
Storage cost (=LCOS)	€/kg	3.70	2.37	1.71	1.56	1.44	1.38
Storage service margin profit	€/kg	0.193	0.193	0.193	0.193	0.193	0.193
Storage service margin profit	%	5.22%	8.15%	11.31%	12.40%	13.40%	14.03%
Storage service price	€/kg	3.89	2.56	1.90	1.75	1.63	1.57

4.3.7. Number of cycles

Finally, also the number of cycles assumed for operation of the salt cavern shall be changed. For the reference case, 1.6 cycles per year were assumed, as this was the long-term cycle value determined for Germany in Hystories D5.5 [LBST 2022]. The number of cycles of a storage are defined as annual storage throughput divided by storage capacity. Accordingly, a higher cycle number goes in line with a higher utilization rate of the storage and hence, should improve the overall business case.

For the sake of this business case, no variation in number of cycles was assumed within the project lifetime. In reality, the expansion of renewable energy capacity over time may increase the storage need and hence increase number of cycles as hydrogen market matures. At the same time, additional storage sites will go into operation resulting in a decrease of number of cycles per cavern (as a consequence of lower utilization rate).

Results for this sensitivity analysis are shown in Table 25. Improving the utilization rate by assuming higher numbers of cycles leads, on the one side, to higher OPEX (and hence NPC), as additional hydrogen is stored in the same facility. On the other side, this also increases the overall volume of stored hydrogen per year, having a positive impact on the specific costs of hydrogen storage (LCOS). LOCS range from 3.31 €/kg (for 0.8 cycles per year) to 1.17 €/kg (for 2.4 cycles per year. Assuming constant revenues of 0.193 €/kg, NPV are between -19.5 million € for low 0.8 cylces per year and 19.6 million € for 2.4 cycles per year.

Table 25: Results of sensitivity analysis: number of cycles

		Number of cycles				
		0.8	1.2	1.6	2	2.4
Variation in input parameter		50%	75%	100%	125%	150%
CAPEX/OPEX	**Unit**					
CAPEX - subsurface	million €	268.9	268.9	268.9	268.9	268.9
CAPEX - surface	million €	199.6	199.6	199.6	199.6	199.6
OPEX	million € / year	10.9	11.7	12.4	13.2	13.9
ABEX	million €	86.6	86.6	86.6	86.6	86.6
Business Case KPIs	**Unit**					
Yearly stored hydrogen	kt/year	14.9	22.4	29.9	37.3	44.8
Net Present Value (NPV)	million €	-19.5	-9.7	0.0	9.8	19.6
IRR	%	5.30%	5.53%	5.75%	5.97%	6.18%
Net Present Cost (NPC)	million €	446.9	453.7	460.6	467.5	474.3
LCOS	€/kg	3.31	2.24	1.71	1.39	1.17
Hydrogen storage service price	**Unit**					
Storage cost (=LCOS)	€/kg	3.31	2.24	1.71	1.39	1.17
Storage service margin profit	€/kg	0.193	0.193	0.193	0.193	0.193
Storage service margin profit	%	5.83%	8.61%	11.31%	13.93%	16.48%
Storage service price	€/kg	3.50	2.43	1.90	1.58	1.36

4.3.8. Withdrawal to injection capacity ratio rate

The assumed storage has the following design parameters:

- maximum withdrawal flowrate capacity: 10.13 million Sm^3/day
- withdrawal to injection capacity ratio: 2.86

By increasing the injection capacity at constant withdrawal flowrate capacity (hence lowering withdrawal to injection ratio), a higher UHS operation flexibility can be achieved – allowing e.g. higher profits from hydrogen trading at future and spot markets. On the other side, additional injection capacities increase CAPEX, OPEX and ABEX of the UHS.

As shown in Table 26, LCOS ranges between 1.96 €/kg (withdrawal/injection capacity ratio of 1.43 – meaning a doubling in injection capacity) and 1.62 €/kg (withdrawal/injection capacity ratio of 4.29 – meaning a reduction in injection capacity by 33%).

Taking constant revenues in form of a storage service margin profit of 0.193 €/kg into account (see chapter 4.2.3), NPV of the UHS slightly decreases for higher injection capacities (= lower withdrawal to injection ratio). The reason is an overall increase in NPC and, hence, LCOS.

Table 26: Results of sensitivity analysis: withdrawal to injection ratio

		Withdrawal to injection ratio				
		1.43	2.15	2.86	3.58	4.29
Variation in input parameter		50%	75%	100%	125%	150%
CAPEX/OPEX	**Unit**					
CAPEX - subsurface	million €	268.9	268.9	268.9	268.9	268.9
CAPEX - surface	million €	270.0	223.1	199.6	185.5	176.2
OPEX	million € / year	14.8	13.2	12.4	12.0	11.6
ABEX	million €	100.7	91.3	86.6	83.8	81.9
Business Case KPIs	**Unit**					
Yearly stored hydrogen	kt/year	29.9	29.9	29.9	29.9	29.9
Net Present Value (NPV)	million €	-7.3	-2.4	0.0	1.5	2.5
IRR	%	5.60%	5.70%	5.75%	5.78%	5.81%
Net Present Cost (NPC)	million €	528.1	483.1	460.6	447.1	438.1
LCOS	€/kg	1.96	1.79	1.71	1.66	1.62
Hydrogen storage service price	**Unit**					
Storage cost (=LCOS)	€/kg	1.96	1.79	1.71	1.66	1.62
Storage service margin profit	€/kg	0.193	0.193	0.193	0.193	0.193
Storage service margin profit	%	9.87%	10.79%	11.31%	11.65%	11.89%
Storage service price	€/kg	2.15	1.98	1.90	1.85	1.82

4.3.9. Summary sensitivity analysis

The sensitivity analyses performed in this chapter show the impact of different parameters on the project's KPIs. Figure 13 and Figure 15 summarize the effect of a variation of each parameter on LCOS and NPV, respectively. In addition, the respective storage service margin profits (SSMP) in % of LCOS are shown in Figure 14 for each case, as this parameter is a key driver for projects' revenue and, hence, NPV.[10]

Starting point of the analyses is the reference case described in chapter 4.1, with an assumed storage service margin profit of 0.193 €/kg (which is derived by applying a storage profit margin of 11.31% in addition to LCOS of the reference case). This case can be seen as the parameter set, where NPV of the reference case turns positive.

The effect of each parameter on LCOS is shown in Figure 13. Pure economic parameters like corporate tax, subsidies and storage service margin profit do not impact LCOS, as LCOS is only impacted by NPC and present value of storage throughput values.

Key lever to decrease LCOS are (in order of decreasing importance):

- increase in number of cycles,
- increase in number of caverns,
- decrease in rate of return (discount rate),
- increase in withdrawal to injection ratio (at constant withdrawal rate), and
- decrease in CoE.

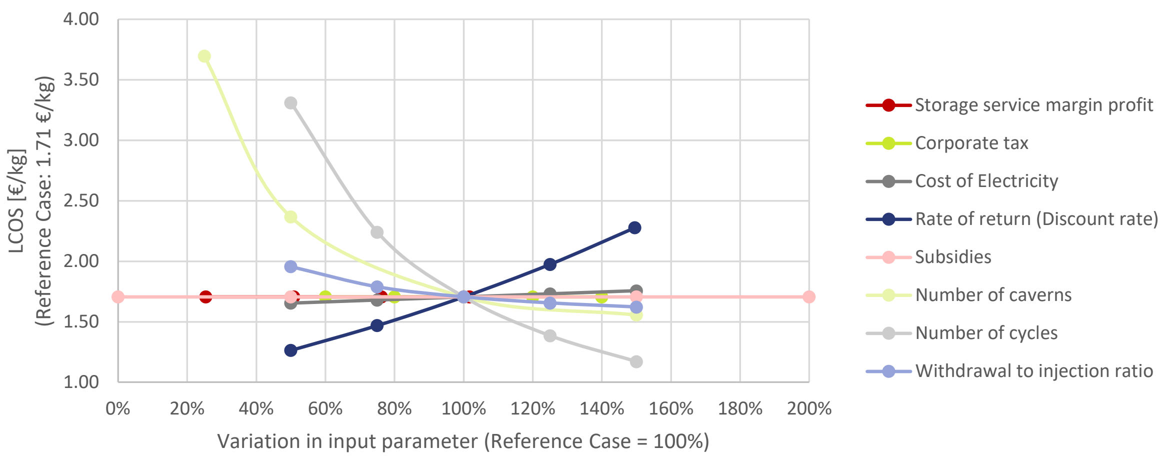

Figure 13: Effect of key parameters on LCOS as result of sensitivity analyses

[10] Please note that for all sensitivities a constant absolute value of storage service margin profit (SSMP) of 0.193 €/kg was assumed, which is equivalent to a SSMP of 11.31% in case of the reference case. This value was selected as it was the value where the NPV is zero.

As the storage service margin profit (in €/kg) was fixed for all cases at 0.193 €/kg, depending on LCOS also their relative value in percentage of LCOS changes. Accordingly, for high LCOS in Figure 13, low SSMPs (in %) are observed and the other way round.

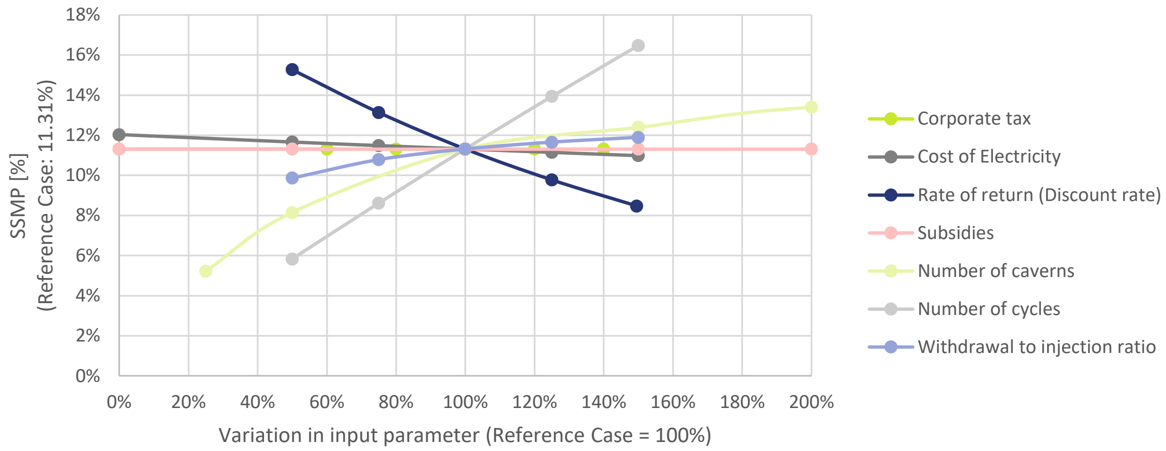

Figure 14: Effect of key parameters on Storage Service Margin Profit (SSMP) as result of sensitivity analyses

Regarding NPV, the following factors help improve the business case (ordered by decreasing effect on NPV per percentage changed):

- decrease in rate of return (discount rate),
- decrease in corporate tax,
- increase in storage service margin profit.
- increase in number of cycles,
- increase in subsidies,
- increase in withdrawal to injection ratio, and
- increase in number of caverns.

In contrast to that, no effect of CoE on NPV is observed. This is because these changes only have an impact on LCOS, which are completely reimbursed under the assumed business case – while the revenues for storage operators in for of storage service margin profit remain constant.

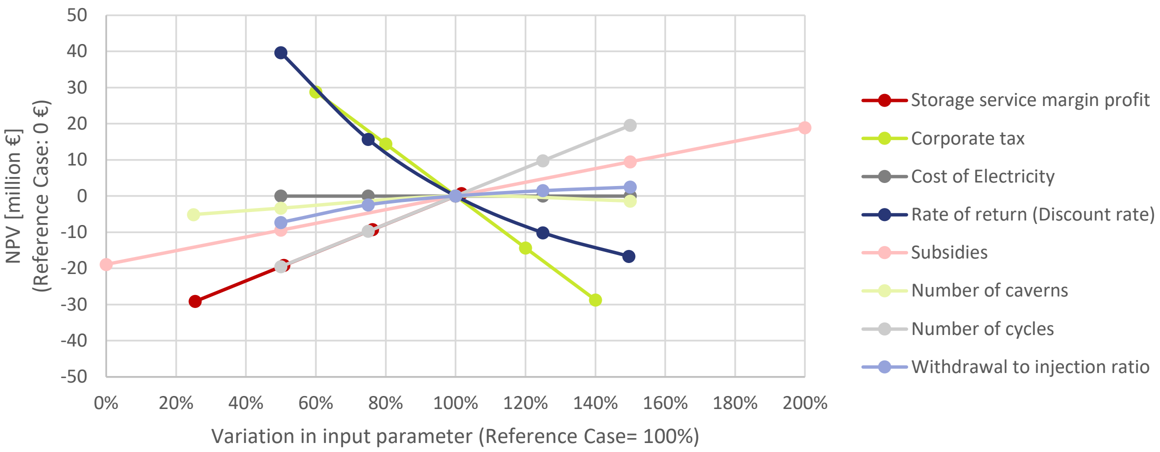

Figure 15: Effect of key parameters on NPV as result of sensitivity analyses

5. Conclusions

This document contains a case study of underground hydrogen storage in a salt cavern in Germany. The technical parameters of the hypothetical cavern project are derived from the parameters of an existing UHS project in Germany, the so-called “Energiepark Bad Lauchstädt”. Business case and cash flow analysis were performed applying a cost tool developed in Hystories WP7 and the business case tool developed in Hystories WP8 task 8.1.

The reference case consisted of an UHS with four caverns, each having a working gas capacity of 52.6 million Sm^3. Assuming a constant number of storage cycles per year of 1.6 over the project lifetime (2030-2059), overall hydrogen storage throughput of 29.9 kt hydrogen per year was obtained. By comparing these volumes with the demand for hydrogen storage in Germany identified in Hystories WP5, this would be equivalent to 99%, 17% and 2% of annual storage throughput demands in 2030, 2040 and 2050, respectively.

According to the costs analysis in chapter 4, the reference case is no viable business case under the assumption of a storage service margin profit of 5.75% with a NPV of -19.2 million € and an IRR of 5.31%. Overall NPC of the project sum up to 468.9 million € over a project lifetime of 38 years (8 years investment period and 30 years operation period). Levelized Cost of Storage (LCOS) of the project is 1.71 €/kg hydrogen. Break-even of the project is achieved by assuming a storage service margin profit of 11.31% in addition to LCOS, which is equivalent to 0.193 €/kg. Sensitivity analyses in chapter 4.2.3 show the impact on project KPIs of different key parameters (storage service margin, corporate tax, Cost of Electricity (CoE), rate of return, subsidies, financing funds, number of caverns, and number of cycles, and withdrawal to injection capacity ratio) under the assumption that this storage service margin profit of 0.193 €/kg is obtained in all cases.

In summary, lower LCOS are achieved by higher hydrogen throughput, by an increased number of cycles and caverns, a decrease in rate of return, an increase in withdrawal to injection ratio (= optimal UHS design) as well as lower cost of electricity. In addition, by assuming constant additional revenues on top of LCOS for all analysed cases, several ways to improve NPV were identified: Key levers are economic parameters like a decrease of the rate of return (discount rate) or corporate tax as well as an increase in storage service margin profit as well as subsidies. From a technical point of view, main impact parameter on the business case is the number of cycles, as a higher utilization of the UHS can significantly improve the NPV of the project.

There are, however, some shortcomings of the analysis in this work package:

1) Financial funds and cost of capital (interest rate) are not included in the business case analysis for the reference case, meaning that the company does not require to take a loan for the investments. The assumed case with interest i = 5%, while rate of return is 5.75%, as well as the implementation that no interest payments are made during the investment period, show an improvement of NPV at higher external financing rates (see chapter 4.3.5). The sensitivity analysis show that these results are highly assumption driven and, accordingly, may strongly differ for other cases.

2) Storage operation optimization based on hydrogen market prices are not considered. Instead, a fixed storage service margin profit of 11.13% of LCOS (in reference case: 1.71 €/kg)

is assumed for the reference case accounting for about 0.193 €/kg. For the sensitivity analysis, this constant absolute value was assumed, to decouple NPV and LCOS calculation. Also, in real storage operation, revenues may not only be based on regulatory specification of admissible margins. Instead, additional revenues can be realized by storage operators by optimized hydrogen trading strategies based on hydrogen market prices at future or spot markets. In any case, hydrogen trading will increase the number of cycles compared to the assumed value of 1.6, which is optimal from energy system perspective. As storage utilization has a high impact on NPV, this should be seen as a key lever for business case optimization.

Finally, the LCOS obtained for the reference case are compared to other storage costs summarized in literature. [ENTSOG 2021] summarize different case studies for hydrogen storage sites. For salt caverns, LCOS of 0.18 €/kg, 0.23 €/kg, 0.35 €/kg and 1.34 €/kg have been described based on different sources, while the project's CAPEX per kg of produced hydrogen were between 25.5 and 29.0 €/kg. These LCOS literature values are significantly lower compared to the reference case with 1.71 €/kg. This value also seems to be high compared to the general green hydrogen production costs which may, in the long term, fall below 2 €/kg. It should, however, be noted that, as described in D5.5-2, the overall annual storage throughout in UHS in EU27+UK accounts for only a share of 12.5 to 22.5% of the overall hydrogen demand. Accordingly, a reallocation of the storage service costs over all hydrogen end consumers will significantly reduce the contribution of hydrogen storage cost to overall hydrogen end users' price. In case of a mature hydrogen market, it seems furthermore realistic that storage operation will not only be driven from an overall energy system perspective but might also take hydrogen price arbitrages into account (as seen for the natural gas market) or other energy system services like security of supply or grid balancing services as additional into account. These could not only serve as additional revenue streams but especially increase the number of storage cycles (= utilization). However, a more detailed analysis of key input parameters may be required to identify main impact factors of these results. Based on analysis in Hystories D7.3-1, LCOS for hydrogen storage in salt caverns in Germany range between around 2 and 2.5 €/kg. Specific CAPEX requirements (= $CAPEX_{subsurface}$ + $CAPEX_{surface}$) of the reference case are 15.69 € per kg of stored hydrogen.

In conclusion, the analysed business cases show that profitability of the storage is achievable under certain circumstances. While in the reference case with a storage service margin profit of 5.75% of LCOS, a NPV of -19.2 million € is achieved, break-even is possible by applying a higher profit margin of 11.31% of LCOS. Optimal storage utilization might be a key lever to drive the business case. In addition, also financial support (especially during early market phase) is a key parameter to improve the business case.

6. References

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7. List of Acronyms

CAPEX	Capital Expenditure
CH_4	Methane
CO_2	Carbon dioxide
EPC	Engineering, Construction & Procurement
H_2	Hydrogen
KPIs	Key Performance Indicators
LCOS	Levelized Cost of Storage
LHV	Lower Heating Value
minOP	Minimum Operating Pressure of the storage
MOP	Maximum Operating Pressure of the storage
NPC	Net Present Value
NPV	Net Present Cost
OPEX	Operational Expenditure
SSMP	Storage Service Margin Profit
UHS	Underground Hydrogen Storage
WG	Working Gas
WTIR	WTIR
WP	Work Package

8. Annex

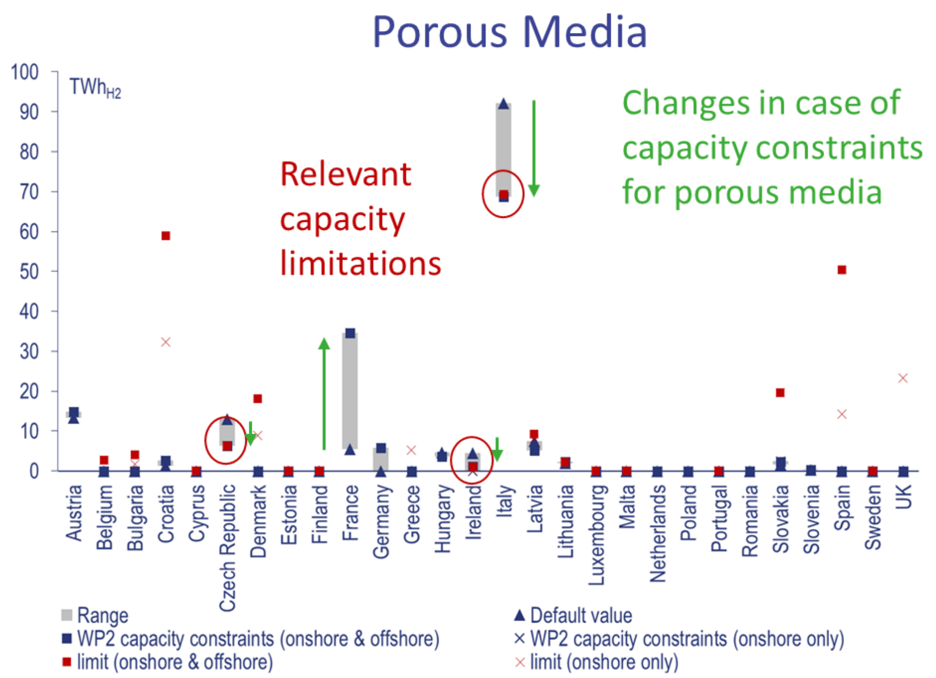

Figure 16: Impact of capacity constraints in the case of porous media storage capacity on optimal storage distribution (porous media storages) between MS.

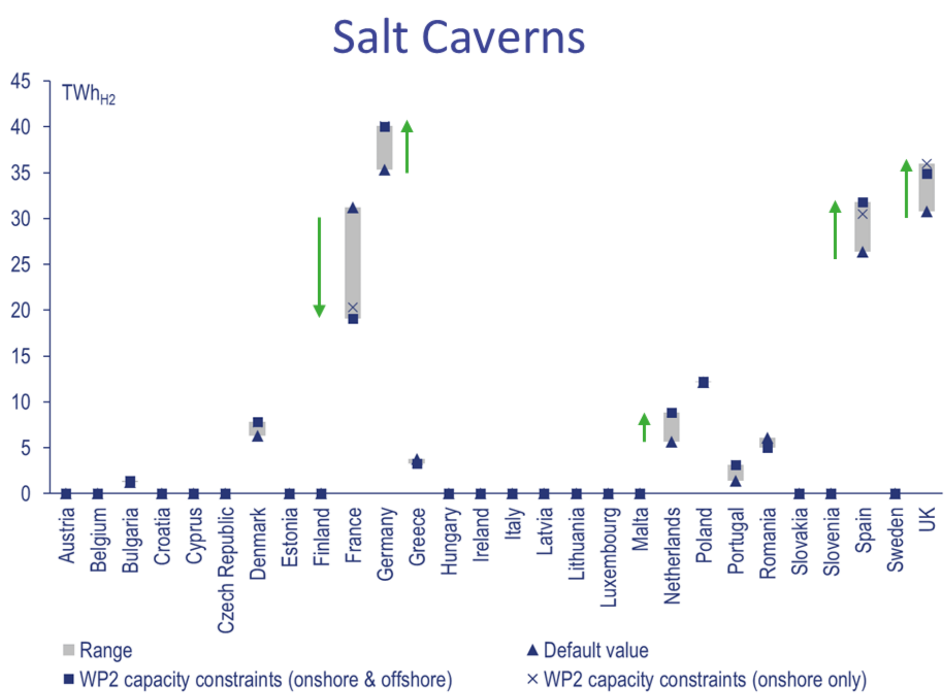

Figure 17: Impact of capacity constraints in the case of porous media storage capacity on optimal storage capacity distribution (salt caverns) between MS.

Hystories project consortium

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