CASE STUDY FRANCE

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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 Deliverable D8.1, 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. Selected case studies of five hydrogen storage sites in different countries are then performed by different partners: 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
3. Site-specific profitability analysis / business model valuation considering site-specific costs (standard case)
4. Sensitivity analyses

In D8.7, a comparison of the different national case studies will be done.

This document contains the analysis of the French case study. Chapter 2 gives an overview of the existing underground gas storage market in France, 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 the French case study is laid out in Chapter 3, covering common (i.e. valid for all case studies) as well as site-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. H_2 Storage market in France: an overview

2.1. Brief overview of existing gas storage market in France

2.1.1. Transportation and storage infrastructures

In France, in 2021, Natural gas represented 15 % of the total primary energy source consumption, according to Chiffres clés de l'énergie 2022 (Statistiques Publiques, 2022), so 415 TWh.

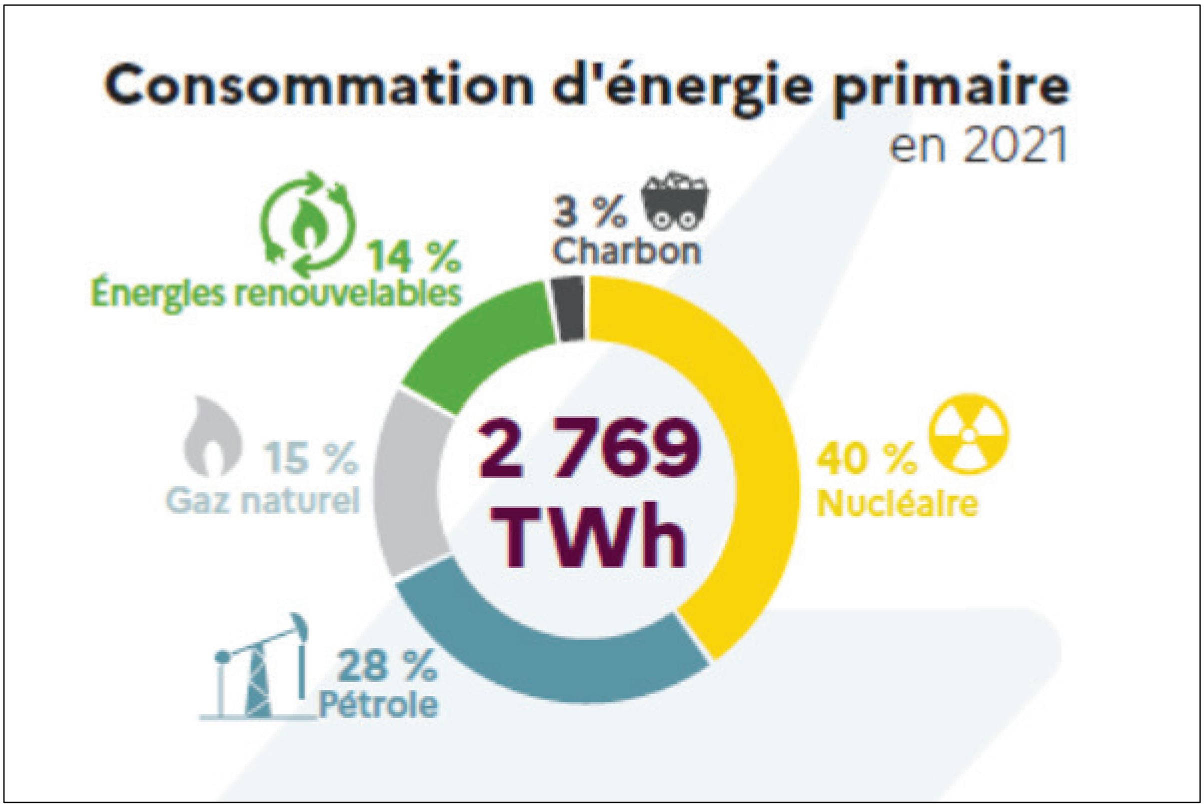

Figure 1: Primary energy mix in France in 2021, from Statistiques Publiques, 2022

The French gas transmission network is operated by two separate operators, GRTgaz and Terēga. As described in CRE, 2023, it consists in:

- a **main network**, which connects the interconnection points with neighbouring countries , LNG terminals, underground storages, the largest industrial consumers and the regional network;
- a **regional network**, which allows gas to be transported from the main network to consumers, industries and distribution networks.

The main network is connected to **11[2] natural gas storage sites** (8 aquifers and 3 salt caverns sites) operated by Storengy, Terēga and Géométhane. Altogether the natural gas storage capacity approximately equates to 130 TWh, which corresponds to 31 % of the annual gas consumption in the country, and a withdrawal capacity of 2.200 GWh/d.

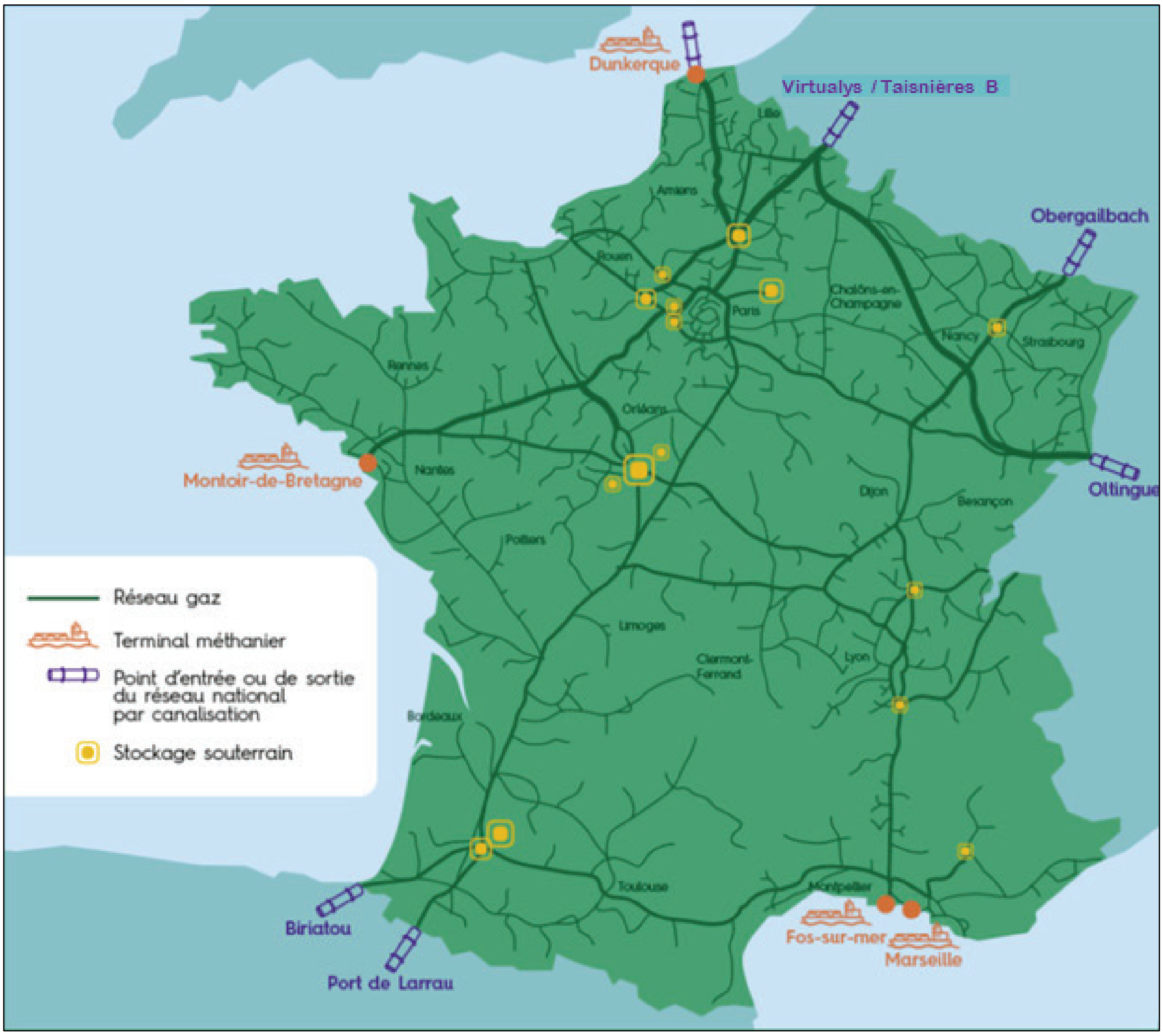

Figure 2: France natural gas grid, and location of underground storages (yellow dots) from CRE, 2023

2 Possibly 12, with the Trois Fontaines depleted gas field storage planned to have restarted at the end of 2022: https://www.storengy.fr/en/our-sites/trois-fontaines-labbaye . Visited on 23/04/2023

2.1.2. Storage roles

According to CRE, 2023, these sites have different performances due to their geological nature:

- 12 TWh of salt cavern storage capacity offering very high deliverability, enabling the volume of gas to be withdrawn in a short time frame;
- 58 TWh of storage capacity in “rapid” aquifers which offer a high deliverability. This enables to address seasonal modulation and provide shorter-term flexibility with withdrawals that may vary during the winter;
- 60 TWh of storage capacity in “slow” aquifers which offer a large storage volume to ensure the seasonal modulation, but which require continuous, limited flow rate, withdrawal throughout the winter.

A large proportion of natural gas is used for heating, which implies large variations in consumption between summer and winter. Storage therefore strongly contributes to the adjustment between supply and demand. The withdrawal from storage represents approximately 1/3 of winter consumption (approximately 90 TWh out of the 300 TWh consumed per winter). On certain days, storage can cover more than half of the needs. The storages are filled during the gas summer from April 1 to October 31, then emptied during the winter.

According to CRE, 2023, the current situation is the result of a long development history, during which the transportation network was designed to integrate the contributions from the storage facilities. By “smoothing out" supply needs upstream, the storage facilities have made it possible to optimize the size of the infrastructures used to transport gas to the market. The underground storage technologies used, with a predominance of aquifer storage, result from the French geological settings; there is only a single storage (Trois Fontaines, assuming it has restarted end of 2022) in a depleted gas field whereas it is the preferred technique overall in Europe.

2.1.3. Storage regulation

Since 2018, the storage is a regulated activity. The following revenue frame is set by law[3]:

- the storage capacities that guarantee the security of supply are planned in a multiannual energy plan. These infrastructures are kept in operation by the storage operators;
- the income of storage operators is determined by CRE, "Commission de Régulation de l'Énergie";
- storage capacities are marketed at auction according to the procedures defined by CRE;
- the difference, positive or negative, between revenue mainly from auctions and the regulated income of storage operators is offset by a tariff term determined by CRE within the tariff for use of the natural gas transmission network.

The implementation of the regulation was thus intended to guarantee the filling of the storage necessary for the security of supply, while providing transparency in terms of costs. The regulation of operators' income aims to ensure that the end consumer pays the right price for the storage necessary for security of supply.

The primary objective pursued by CRE when it sets the methods for marketing storage facilities is to maximize capacity subscriptions and thus encourage the filling of storage facilities in order to ensure security of supply.

At the end of the auctions (organized by Storengy and Terēga in 2022), almost all of the French natural gas storage capacities for the winter of 2022-2023 have been booked, despite an unfavourable price context. To supplement the revenues collected directly by the storage operators within the framework of these auctions, **CRE has set the storage price at €261.08 /MWh/d/year** collected by the transmission system operators from 1 April 2022.

Since the entry into force of the regulation, almost all of the capacity marketed has been allocated. This good result guaranteed the security of natural gas supply in France, which was the primary objective pursued by CRE.

To put this in perspectives, on November 1, 2021, the filling rate of French storages stood at 94.5 %, a rate well above the European average of 75 %, at a time when the war unleashed by Russia in Ukraine obviously poses a new risk to French security of supply.

This result suggests the strength of a regulated business model for driving the industry in the direction of the national energy security objectives.

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3 https://www.cre.fr/Actualites/le-stockage-de-gaz-en-france visited on 22/04/2023

2.1.4. Brief overview of the foreseen evolution of current natural gas assets

In April 2023, CRE published a report on the future of natural gas infrastructures in horizon 2030 and 2050, in the net-zero context. The possible conversion of these assets for Hydrogen is considered in this analysis, the main messages of this report regarding it are the following:

- Regarding the main gas transmission network, it is still largely necessary for natural gas, to compensate for the geographical and temporal differences between consumption and production. The convertible assets are concentrated in doubled pipelines on the main transmission network, representing only between 3 and 5 % of the km of transmission pipelines by 2050.
- Regarding storage, a possible conflict of use of the facilities for hydrogen or natural gas is foreseen. We note that the CRE considers that to date, salt caverns are the only storage facilities that can be converted to hydrogen. The choice of the storage facilities to be retained for natural gas cannot be made without a multi-energy reflection, taking into account this conflict of uses. By 2030, all of the current storage facilities for CH4 under all studied scenarios will have to be kept in its entirety for natural gas. In the longer term, the abandonment or conversion of some storage facilities could be considered. Two strategies could then be pursued:
  - the first strategy would be to use the storage facilities enabling highest deliverability for natural gas, i.e. salt caverns and Lussagnet sandstone aquifer storage. Hydrogen would then need to be stored in new salt caverns built on purpose
  - the second strategy would be to use aquifer storage for natural gas, in order to be able to convert a maximum of saline storage to hydrogen: however, this possible conversion should not be considered too early: the Etrez site is important for the natural gas system, given its location on the transportation network and the flows and congestions anticipated by 2050 in certain scenarios.

2.2. Underground storage infrastructures other than natural gas

The conversion of part of the natural gas storage and transportation infrastructures is considered by several studies, including:

- The Hydrogen Backbone Initiative (Guidehouse, 2022)
- When estimating the hydrogen storage capacity in Europe, the HyUSPre project potential UHS atlas[4] or GIE (Guidehouse, 2021) both base their assessment only on the conversion of natural gas assets
- In France, by the regulatory authority CRE as detailed above

[4] https://storymaps.arcgis.com/stories/2349ba3eb36d4473861b7701a08985e1 visited on 23/04/2023

Natural gas transportation and storage assets are likely the most compatible, and benefits from being a physically interconnected industry at European scale. They are also connected at European scale through associations such as Gas Infrastructure Europe (GIE) or initiatives (EHB), enabling a clear European vision from the start.

While natural gas is the only product stored in porous media in Europe, there are other products stored underground in salt and unlined rock caverns in France. Conversion of unlined rock caverns is not considered in Hystories project and is currently at a lower maturity level. Regarding salt caverns, the technical feasibility of the conversion of salt caverns storing products other than natural gas may be more difficult to confirm, but it is worth mentioning that these assets exist. In France, there are notably nation-wide pipeline networks that are connected to salt cavern storage for:

- Liquid hydrocarbon products. The storage, in 30 salt caverns, is owned by Géosel and is located next to the Géométhane gas storage site in Manosque, as presented below.
- There is also an ethylene transportation network (Etel, Transugil, Transalpes and Transéthylène pipelines) crossing most of France, from Tavaux to Lavéra, and connected to salt cavern storage in Viriat (close to Etrez nat. gas storage site) and passing nearby the Géométhane / Géosel sites.

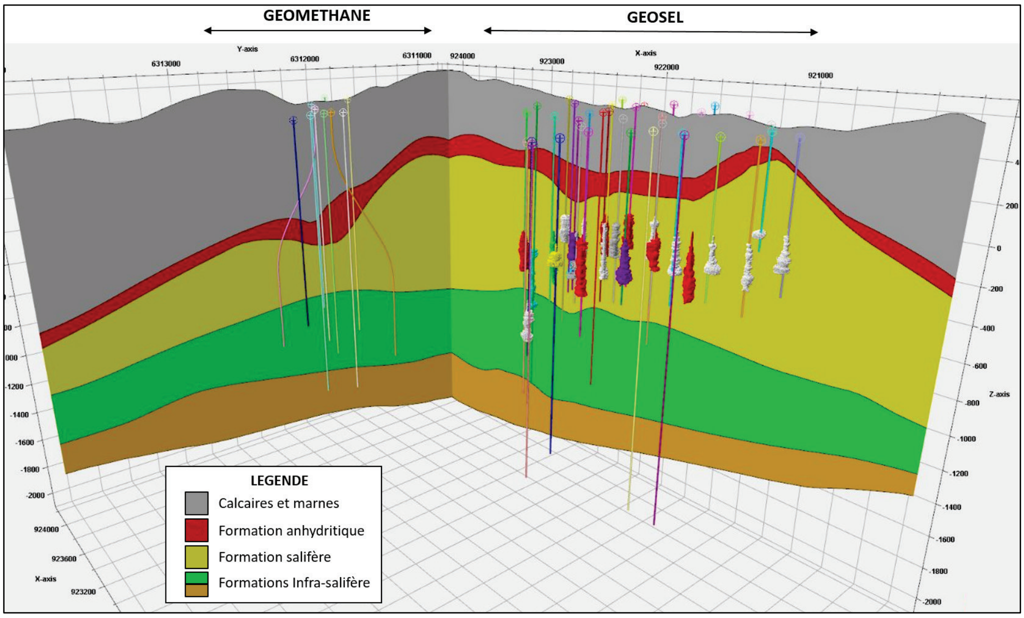

Figure 3: View of the liquid hydrocarbon storage caverns of the Géosel site, and of the Géométhane natural gas storage wells. From https://www.geosel.fr/en/the-storage-site.html visited on 22/04/2023

Natural gas, liquid hydrocarbon, LPG and ethylene are to our knowledge the only products stored in salt caverns in France. There are other pipeline networks, such as the 2700 km of H_2, N_2 and O_2 pipelines of the Northern Europe region operated by Air Liquide in the North of France (and also Belgium and the Netherlands), but these are not connected to underground storages. The European Chemical promotion platform gives an overview of the various industrial gas infrastructures[5]. Although, there is no analysis of the possible opportunity of reuse of such existing transportation or storage assets for hydrogen.

2.3. Underground storage potential in France

2.3.1. Storage potential for France

The above sections briefly presented the existing storage infrastructures, mostly natural gas ones, that could be converted, if technically confirmed by feasibility studies. New infrastructures can also be developed, in salt caverns and porous reservoirs.

Salt caverns could be developed in some of the salt deposits. In a first approach, in those that have already proven they can host storage caverns: near Manosque, Hauterives/Tersanne, and Etrez. Storage caverns also existed in the South-West of France (Carresse), and projects have existed in North-East. These projects could benefit from the active solution mining industry, not necessarily for reusing existing/historical brine caverns might not be likely to meet appropriate stability and tightness requirements, but at least for using the leaching facilities in place.

5 Visited on 23/04/2023: https://chemicalparks.eu/europe/pipeline-networks

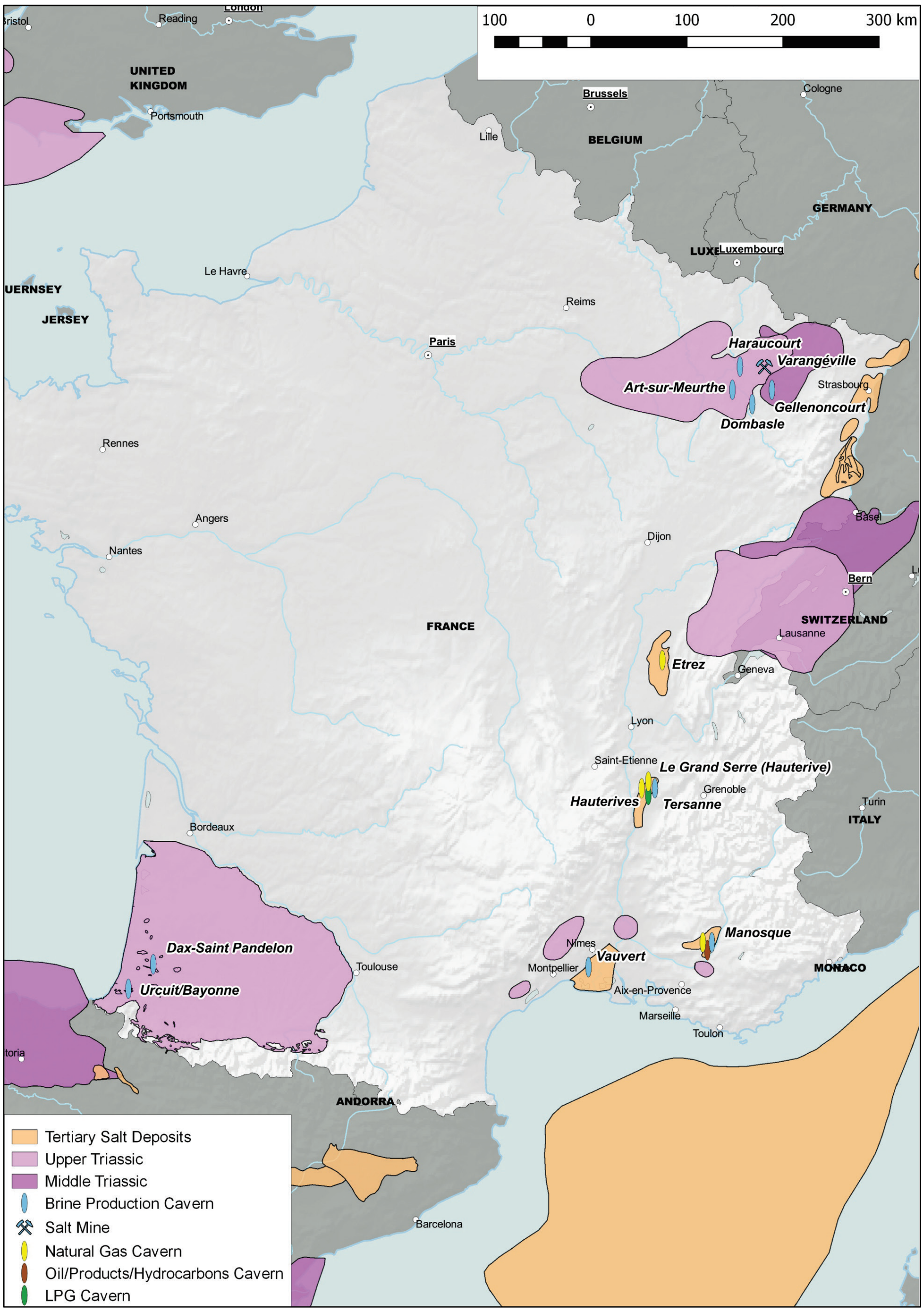

Figure 4: Salt deposits and existing salt caverns in France. From Horváth et al. (2018) SMRI report.

Depleted fields and aquifer data have been collated by BRGM in Hystories WP1 (D1.2, D1.4), and the data has been used in WP2 (D2.2) for drawing hydrogen storage capacity estimation for each of these traps. These opportunities are presented the figure below:

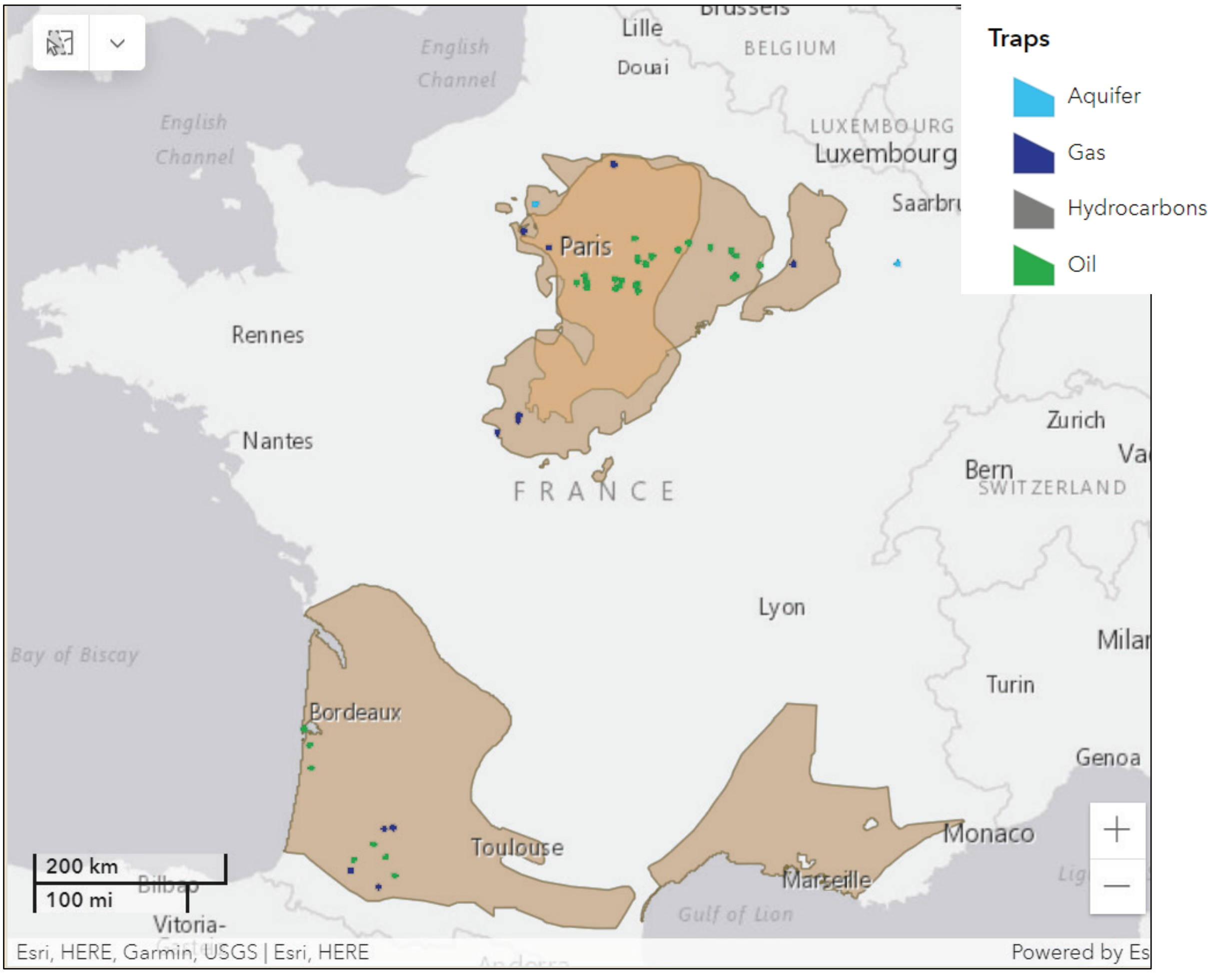

Figure 5: Map of the formations (polygons) and traps (aquifer, depleted gas and oil field. Represented by dots in France since there was no polygon available) developed in WP1. From www.hystories.eu

For the identified technical possibilities in salt deposits or porous traps, the cost of developing underground storage potential in France, and all other EU-27 countries, was analysed in WP7.

This was done for a seasonal “Operation Cycle 1” and a fast “Operation cycle 2”. These 2 cycles resulted for the D5.5-2 energy modelling European-scale results, to enable comparisons of development costs between sites of various countries.

2.3.2. Hydrogen storage demand for France

However, D5.5-2 also enables to draw country-specific cycles, and Hystories WP8 also intends to account for the specific national context. The focus is made on salt caverns for this case study, according to the position expressed for instance by the French regulatory authority in CRE, 2023: “to date, salt caverns are the only storage facilities that can be converted to hydrogen”, but it does not mean that porous storage cannot be a viable option.

While both WP5 scenarios B and D consider salt and porous storage, the reason for choosing scenario D is the publication by the European Commission of the REPowerEU Plan to strengthen Europe’s energy security in “response to the hardships and global energy market disruption caused by Russia's invasion of Ukraine”. It notably sets “a target of 10 million tonnes of domestic renewable hydrogen production and 10 million tonnes of imports by 2030, to replace natural gas, coal and oil in hard-to-decarbonise industries and transport sectors.”[6]. This objective is closer to the import hypotheses of Scenario D.

This leads to the selection of the following storage scenario, based on WP5 results.

Table 1:: Cycle defined from D5.5-2 report for France, scenario D, salt caverns. Reference cycles used in D7.3 are also recalled

		Full cycle equivalent per year	Load factor	Withdrawal to Injection Ratio	Storage/withdrawal capacity ratio (days)	Storage/injection capacity ratio (days)
France, sc. D, salt caverns	2030	3,2	41 %	1,0	31	**31**
	2040	1,6	20 %	1,0	52	52
	2050	1,5	19 %	3,0	**16**	48
(For the reference) D7.3-1 cycles	Seasonal “OC1”	1,1	68 %	1,0	115	115
	Fast “OC2”	1,9	29 %	2,2	18	40

In this project-based approach, the storage is built for 2030 and the facility then does not change, only the number of full cycles per year can. We therefore need to design the injection according to the maximum needed over the site lifetime:

- an injection capacity that enables totally filling in the empty storage in 31 days when working at its maximal injection capacity
- a withdrawal capacity that enables totally emptying the full storage in 16 days, when working at its maximal withdrawal capacity

6 https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131

In terms of inputs to the cost model, it translates into a storage to withdrawal capacity ratio of 16 days and a Withdrawal to injection ratio of 1.9.

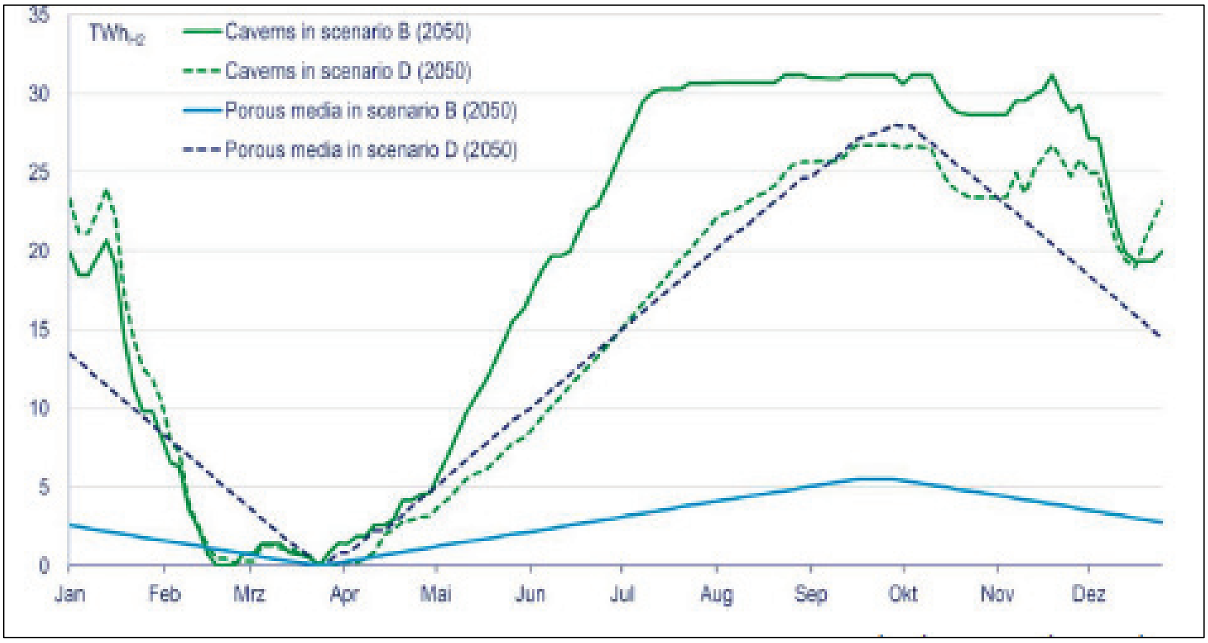

Figure 6: Optimal cycles in 2050 as found by the energy modelling work of WP5, for scenarios B (mainly domestic Hydrogen production) and D (with a larger share of imports) for France. The dotted green line is the storage scenario we apply for 2050. From Hystories D5.5-2.

2.4. Regulatory framework

Hystories deliverables D6.1-1 gives a detailed description of the permitting process a hydrogen storage in France would have to go through. In this deliverable, a table lists the applicable regulations and their requirements. This is not recalled in the present report.

It was notably based on Terēga and Geostock inputs, and on the study carried out by Ineris in Gombert et al. (2021) that discusses in detail the legislative process that underground hydrogen storage would have to go through in France. The flowchart from this report describing the permitting process in France (in French) is recalled below:

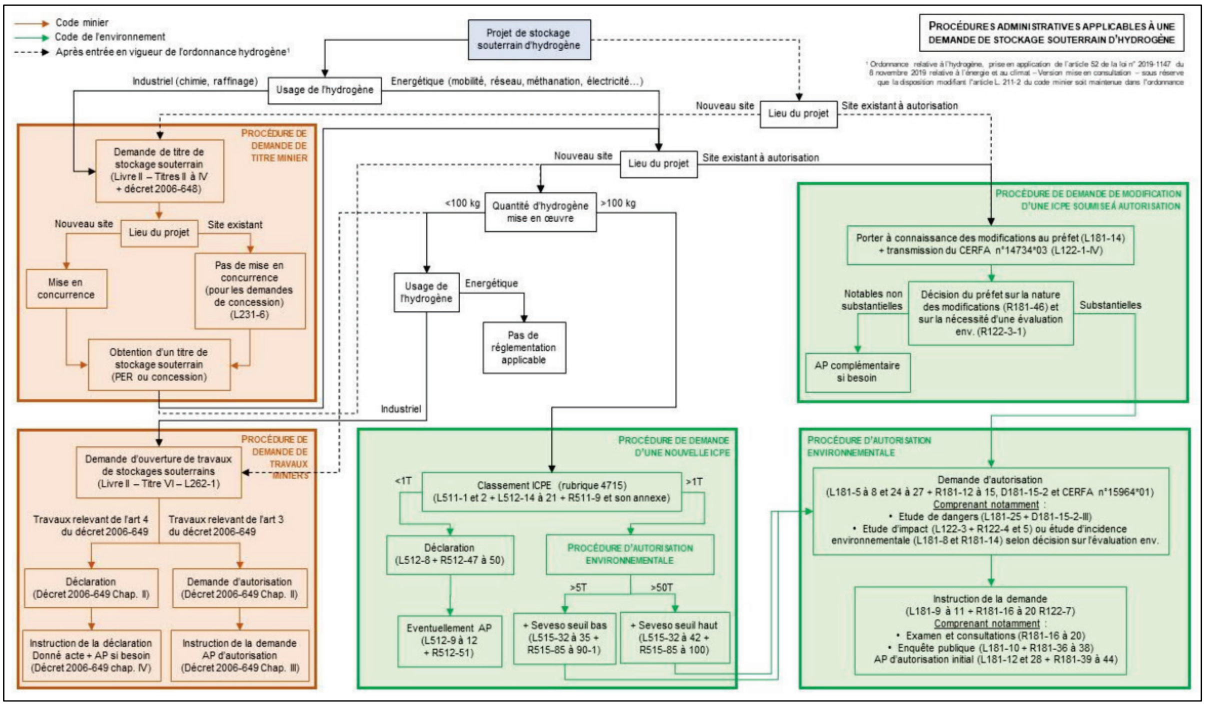

Figure 7:. Administrative procedure applicable to an application for an underground hydrogen storage permit in France. From Gombert et al. (2021)

3. Input parameters and main assumptions

3.1. Case study France - Scenario definition

The case study focuses on the development and operation of a new 8 salt cavern storage site, enabling the storage of 250 MM Sm^3, with cavern characteristics corresponding to the MID case of deliverables D7.1-1 and D7.2-1. This choice of considering the same subsurface design as in D7.1-1, D7.2-1 and D7.3-1 intends to limit the sensibility, compared to D7.3-1 cost results, to the storage cycle that is considered and its resulting impacts:

- on the design of surface facilities
- on the throughput per year.

The parameters are listed below.

Table 2: Key parameters for the France site case study

Parameter	Value	Comment
Total cavern volume in gas	8 * 380,000 m^3	Same as D7.1/D7.2/D7.3 MID case
Cavern status	Cavern construction start in 2022; start of operation in 2030 until 2059	Construction duration according to D7.1/D7.2, also applied in D7.3
Cavern pressure	70 – 180 bar	Same as D7.1/D7.2, also applied in D7.3 when the last cemented casing shoe was at 1000 m.
H_2 storage capacity	Working gas 250 MM Sm^3 (0.7 TWh)	Same as D7.1/D7.2/D7.3 MID case
H_2 withdrawal rate (max)	15.65 MM Sm^3/d	In order to have a storage capacity to withdrawal ratio of 16 days (cf. § 2.3.2)
H_2 injection rate (max)	8.2 MM Sm^3/d	In order to have a withdrawal to injection ratio of 1.9, i.e. a storage capacity to injection ratio of 31 days (cf. § 2.3.2)

3.2. Model input parameters and assumptions for France Case Study

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 3: General parameters – Case Study France

Parameter	D7.1/7.2/7.3	D8.4	Comment
Cost of Electricity (CoE) [€/MWh]	60	60	France was the base case for WP7 cost estimations, including for the cost of electricity
Hydrogen production costs [€/kg]	N/A	6.29	Common assumption for all WP8 Case Studies
Cost for H_2 cushion gas in salt caverns [€/kg]	2.0	6.29	6.29 €/kg in D8.4 is a Common assumption for all WP8 Case Studies, and is the same as Hydrogen production cost 2 €/kg was a low figure, chosen in D7.2 and then reflected in D5.6, D7.3. Reasons were: - The cost was applied to projects developing even in 2050 in WP5 energy model - For cushion gas, using grey or blue hydrogen could be done by some projects
Other costs [€/kg]	N/A	1.89	Common assumption for all Case Studies (30 % of Hydrogen production costs)
Storage service margin profit (%)	N/A	13.35	13.35 %: to reach NPV = 0 for France case study. Basis for the sensitivities

Table 4: Financial input parameters – Case Study France

Title	D7.1/7.2/7.3	D8.4	Comment
Subsidy [Mio. €]	0	20	Common assumption for all Case Studies
Venture period [years]	30	30	Operation period 2030-2059 Common assumption for all Case Studies
Residual value [% of CAPEX]	N/A	20	Common assumption for all Case Studies (approximately equal to ABEX/CAPEX ratio)
Corporate tax [%]	N/A	25	Corporate tax, "Impot sur les sociétés », in France
Financing fund [% of CAPEX]	N/A	none	Common assumption for all Case Studies
Interests [%]	N/A	5	Common assumption for all Case Studies. ***Note****: this as no impact since the financing fund is none*
Financing duration [years]	30	30	Set as venture period, common assumption for all Case Studies
Rate of Return [%]	8	5.75	In D7.3, to compute the LCOS, a WACC of 8 % is considered as the discount rate. In D8.4, 5.57 % is a common assumption for all Case Studies in WP8

Technical parameters are the same as those listed in D7.1, D7.2 or D7.3 and are not recalled in the present report. It is coherent with the common assumption for all case studies made in WP8.

4. Results

The following chapters present the results of the French Case Study. The results were received by using 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 in chapter 0. Sensitivity analyses of selected input parameters are used in chapter 0 to check robustness of the model with regard to variations in specific input parameters.

4.1. Reference Case

Based on the assumptions for the French Case Study described in chapter 3, yearly storage throughout of the assumed storage is about 71,000 t/year from 2030 to 2040, 35,500 t/year from 2040 to 2050 and 33,500 t/year from 2050 to 2059. The project benefits from a high throughput over the first 10 years of operation.

To set this into perspective to projections of the overall national hydrogen storage throughput estimated in Hystories D5.5 (scenario D), key storage parameters are compared Table 5.

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

Parameter	2030	2040	2050
French Hydrogen demand [TWh/year] *	25.9	101.6	186.6
French Capacity of storage [TWh] *	3.2	33.5	54.7
French Capacity of storage [t] *	95 000	1 005 000	1 641 000
French hydrogen storage throughput [TWh/year]*	10	39	69
French hydrogen storage throughput [t/year]*	301 000	1 163 000	2 070 000
Storage throughput of this Case Study project (t/year)	71 000	35 500	33 500
Share of this Case Study project in the national throughput	**24 %**	**3 %**	**2 %**
Number of full cycles per year (for salt caverns) *	3.2	1.6	1.5

* Country-specific modelling results for France from Hystories D5.5-2, scenario D

Based on these results, the assumed annual throughput in 2030 would cover a quarter of the overall storage throughput demand for France in 2030. Since hydrogen demand and hence storage capacity demand will significantly increase in France until 2050, the share of this particular storage project decreases rapidly, to about 3 % in 2040 and 2 % in 2050. It should be noted that Hystories WP5 results are driven by assumptions and do not reflect regional distribution of storage demand within a country. Still, these results show that the case study project is a major part of the storage demand when it comes into operation in the early 2030s, but this soon becomes limited as hydrogen market in France becomes more mature.

The application of the D7.2-1 cost model leads to cost structure of Table 6.

Table 6: Key modelling results for CAPEX, OPEX and ABEX of the France Case Study

Parameter	Unit	Value
CAPEX – subsurface	million €	437.8
CAPEX – surface	million €	409.6
Fixed OPEX (maintenance)	million € / year	17.1
Variable OPEX (energy)	million € / year	2030-2039: 5.1 2040-2049: 2.6 2050-2059: 2.4
ABEX	million €	149.3

In order to understand contributions of different parameters of the model, breakdown of CAPEX subsurface and surface are given below according to D7.2.

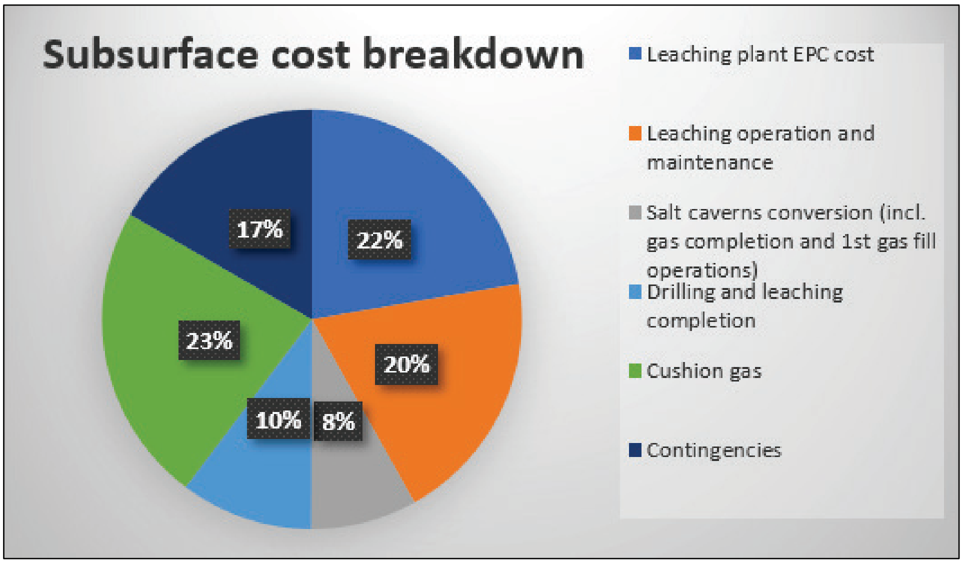

Figure 8: Cost components CAPEX - subsurface

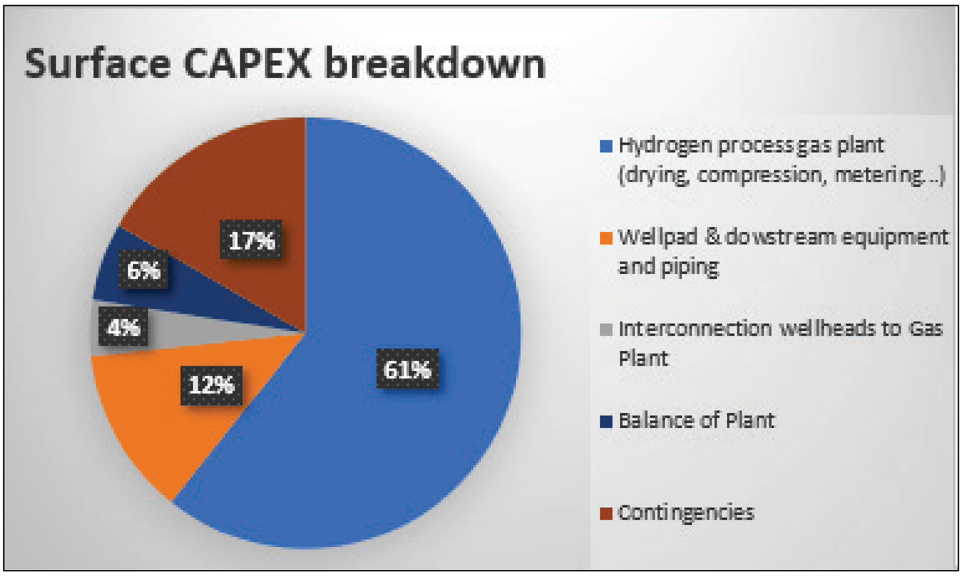

Figure 9: Cost components CAPEX - surface

4.2. Cash flow analysis for the reference case

Key UHS project KPIs include Net Present Value (NPV), Internal Rate of Return (IRR), Net Present Cost (NPC), and Levelized Cost Of Storage (LCOS). Methodology is for instance presented in German Case study D8.8, §4.2.1.

In the reference case, the storage service margin profit is set at 13.35 % in order to have the project break even (NPV = 0).

These data are listed for the reference case in Table 7. For assumption related to financial parameters, please see section 3 above.

Table 7: Key business case results of the France Case Study, base case of the sensitivities analyses

Parameter	Unit	Value
Yearly stored hydrogen	kt/year	2030-2039: 71 2040-2049: 36 2050-2059: 33
Net Present Value (NPV)	million €	0
IRR	%	5.75
Net Present Cost (NPC)	million €	799.1
Levelized Cost Of Storage (LCOS)	€/kg	1.64

The LCOS is about 1.64 €/kg hydrogen stored. It should be noted that this figure does not add to the green hydrogen production cost to make an overall production cost, since it only applies to the part of hydrogen that stored, which is limited to 15 % to 20 % of the total hydrogen consumption in horizon 2050. As discussed in D5.5-2, § 5.1, "The value of the underground storage of renewable hydrogen within the entire value chain can be interpreted as the share of storage cost in overall H2 cost. According to the analysis results it varies between 3 %-15 % or ca. 0.10-0.35 €/kg (3-11 €/MWh)."

Figure 10 shows the cumulative net cash flow (without discounting) over the project lifetime:

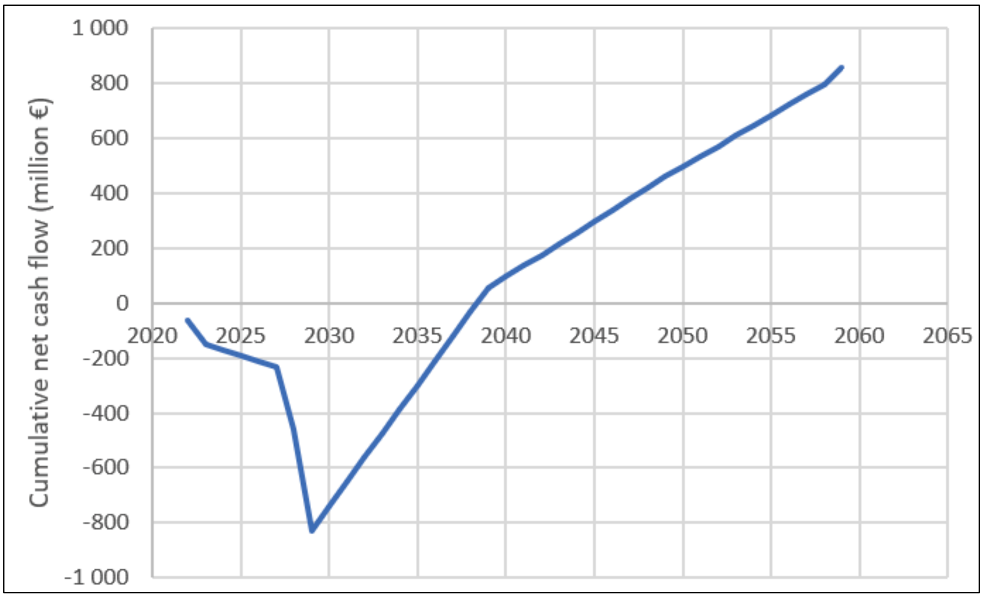

Figure 10: Cumulative net cash flow (without discounting) over the project lifetime. Operation starts in 2030

4.3. Business case optimization (sensitivity analysis)

4.3.1. Base case of the sensitivity analysis

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

- Cost of Electricity (CoE)
- rate of return (=discount rate)
- Subsidies.

B) Site-specific parameters

- Alternative underground storage technologies and project size
- number of caverns.

C) Market conditions parameters

- number of cycles.

4.3.2. Cost of Electricity (CoE)

Variation in cost of electricity only impacts variable OPEX (surface). However most of the OPEX is fixed OPEX (maintenance). Accordingly, the variation of CoE from 30 to 90 €/MWh results in annual OPEX of 19.6 24.7 million €/year (see Table 8) for the first 10 years. In case, no CoE are assumed, OPEX further reduce to 17.1 million €/year.

The analyses show that an increase or decrease in CoE by 50 % (to 90 €/MWh) results in respectively an overall increase or decrease in LCOS of 2.5 %. This shows the limited influence of that parameter.

There is no change in NPV or IRR. NPC range from 764 million € (when electricity is assumed to be free, CoE of 0 €/MWh) to 817 million € (for CoE of 90 €/MWh). As for the other sensitivities, storage service margin profit is kept constant at 0.22 €/kg in addition to LCOS. The resulting additional revenues required for the storage operator to break even are between 14.0 % of LCOS (for former case) and 13.1 % of LCOS (for latter case).

Table 8: Results of sensitivity analysis: Cost of Electricity

		Cost of Electricity [€/MWh]					
		0	30	45	60	75	90
Variation *in input parameter*		0 %	50 %	75 %	100 %	125 %	150 %
CAPEX/OPEX	**Unit**						
CAPEX - subsurface	million €	438	438	438	438	438	438
CAPEX - surface	million €	410	410	410	410	410	410
OPEX 2030-2039 (3.2 cycles/y)	million € / year	17,1	19,6	20,9	22,2	23,5	24,7
OPEX 2040-2049 (1.6 cycles/y)	million € / year	17,1	18,4	19,0	19,6	20,3	20,9
OPEX 2050-2059 (1.5 cycles/y)	million € / year	17,1	18,3	18,9	19,5	20,1	20,7
ABEX	million €	149,3	149,3	149,3	149,3	149,3	149,3
Business Case KPIs	**Unit**						
Yearly stored hydrogen 2030-2039 (3.2 cycles/y)	kt/year	71,1	71,1	71,1	71,1	71,1	71,1
Yearly stored hydrogen 2040-2049 (1.6 cycles/y)	kt/year	35,5	35,5	35,5	35,5	35,5	35,5
Yearly stored hydrogen 2050-2059 (1.5 cycles/y)	kt/year	33,3	33,3	33,3	33,3	33,3	33,3
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 €	764	782	790	799	808	817
LCOS	€/kg	1,57	1,60	1,62	1,64	1,66	1,68
Hydrogen storage service price	**Unit**						
Storage cost (=LCOS)	€/kg	1,57	1,60	1,62	1,64	1,66	1,68
Storage service margin profit	€/kg	0,22	0,22	0,22	0,22	0,22	0,22
Storage service margin profit	%	14,0 %	13,6 %	13,5 %	13,3 %	13,2 %	13,1 %
Storage service price	€/kg	1,79	1,82	1,84	1,86	1,88	1,90

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 9 summarizes the results of the sensitivity analysis.

While CAPEX and OPEX 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 1159.4 million € (r = 1.90 %) and 640.6 million € (r = 8.63 %). Since also present value of hydrogen throughput changes with r, despite higher NPC, the LCOS are reduced to 1.21 €/kg in case of a low rate of return of 1.90 %.

At the same time, NPV ranges from 66.7 million € (r = 1.90 %) to -16.8 million € (r = 8.63 %). While revenues stay the same for all cases, NPV increases for low discount rates as LCOS decrease.

Table 9: Results of sensitivity analysis: Rate of return (Discount rate)

		Rate of return (Discount rate)					
		1,90 %	2,88 %	4,31 %	5,75 %	7,19 %	8,63 %
Variation in input parameter		33 %	50 %	75 %	100 %	125 %	150 %
CAPEX/OPEX	**Unit**						
CAPEX - subsurface	million €	437,8	437,8	437,8	437,8	437,8	437,8
CAPEX - surface	million €	409,6	409,6	409,6	409,6	409,6	409,6
OPEX 2030-2039 (3.2 cycles/y)	million € / year	22,2	22,2	22,2	22,2	22,2	22,2
OPEX 2040-2049 (1.6 cycles/y)	million € / year	19,6	19,6	19,6	19,6	19,6	19,6
OPEX 2050-2059 (1.5 cycles/y)	million € / year	19,5	19,5	19,5	19,5	19,5	19,5
ABEX	million €	149,3	149,3	149,3	149,3	149,3	149,3
Business Case KPIs	**Unit**						
Yearly stored hydrogen 2030-2039 (3.2 cycles/y)	kt/year	71,1	71,1	71,1	71,1	71,1	71,1
Yearly stored hydrogen 2040-2049 (1.6 cycles/y)	kt/year	35,5	35,5	35,5	35,5	35,5	35,5
Yearly stored hydrogen 2050-2059 (1.5 cycles/y)	kt/year	33,3	33,3	33,3	33,3	33,3	33,3
Net Present Value (NPV)	million €	66,7	41,6	16,3	0,0	- 10,3	- 16,8
IRR	%	2,59 %	3,36 %	4,53 %	5,75 %	7,00 %	8,27 %
Net Present Cost (NPC)	million €	1159,4	1043,4	907,2	799,1	712,0	640,6
LCOS	€/kg	1,21	1,31	1,46	1,64	1,83	2,05
Hydrogen storage service price	**Unit**						
Storage cost (=LCOS)	€/kg	1,21	1,31	1,46	1,64	1,83	2,05
Storage service margin profit	€/kg	0,22	0,22	0,22	0,22	0,22	0,22
Storage service margin profit	%	18,1 %	16,7 %	15,0 %	13,3 %	11,9 %	10,7 %
Storage service price	€/kg	1,43	1,53	1,68	1,86	2,05	2,27

4.3.4. Subsidies

The reference case assumes a public subsidy of 20 million €. Subsidies are considered as interest free payment, which does not have to be repaid by the UHS storage project. Table 10 compares different subsidies, ranging from zero to 40 million €.

There is only a very limited impact of such subsidy for all of the KPIs.

Table 10: Results of sensitivity analysis: Subsidies

		Subsidies [million €]				
		0	10	20	30	40
Variation in input parameter		0 %	50 %	100 %	150 %	200 %
CAPEX/OPEX	**Unit**					
CAPEX - subsurface	million €	437,8	437,8	437,8	437,8	437,8
CAPEX - surface	million €	409,6	409,6	409,6	409,6	409,6
OPEX 2030-2039 (3,2 cycles/y)	million € / year	22,2	22,2	22,2	22,2	22,2
OPEX 2040-2049 (1,6 cycles/y)	million € / year	19,6	19,6	19,6	19,6	19,6
OPEX 2050-2059 (1,5 cycles/y)	million € / year	19,5	19,5	19,5	19,5	19,5
ABEX	million €	149,3	149,3	149,3	149,3	149,3
Business Case KPIs	**Unit**					
Yearly stored hydrogen 2030-2039 (3,2 cycles/y)	kt/year	71,1	71,1	71,1	71,1	71,1
Yearly stored hydrogen 2040-2049 (1,6 cycles/y)	kt/year	35,5	35,5	35,5	35,5	35,5
Yearly stored hydrogen 2050-2059 (1,5 cycles/y)	kt/year	33,3	33,3	33,3	33,3	33,3
Net Present Value (NPV)	million €	- 18,9	- 9,5	0,0	9,5	18,9
IRR	%	5,46 %	5,60 %	5,75 %	5,90 %	6,07 %
Net Present Cost (NPC)	million €	799,1	799,1	799,1	799,1	799,1
LCOS	€/kg	1,64	1,64	1,64	1,64	1,64
Hydrogen storage service price	**Unit**					
Storage cost (=LCOS)	€/kg	1,64	1,64	1,64	1,64	1,64
Storage service margin profit	€/kg	0,22	0,22	0,22	0,22	0,22
Storage service margin profit	%	13,3 %	13,3 %	13,3 %	13,3 %	13,3 %
Storage service price	€/kg	1,86	1,86	1,86	1,86	1,86

4.3.5. Smaller/larger project in salt; porous options in France

While above sections focus on changes in economic parameters, in the following the impact of an adapted UHS design on LCOS is analysed.

For the cycle defined in section 2.2 and the Conceptual design case, the Levelized cost of storage is 1.64 €/kg. Should the storage be in salt cavern of lower capacity, or higher capacity, the LCOS would vary according to the solid lines shown below, following the methodology developed in D7.3-1. Should it be in the identified porous traps, notably in converted natural gas porous storage available in France, it could be lower, as presented in the figure below:

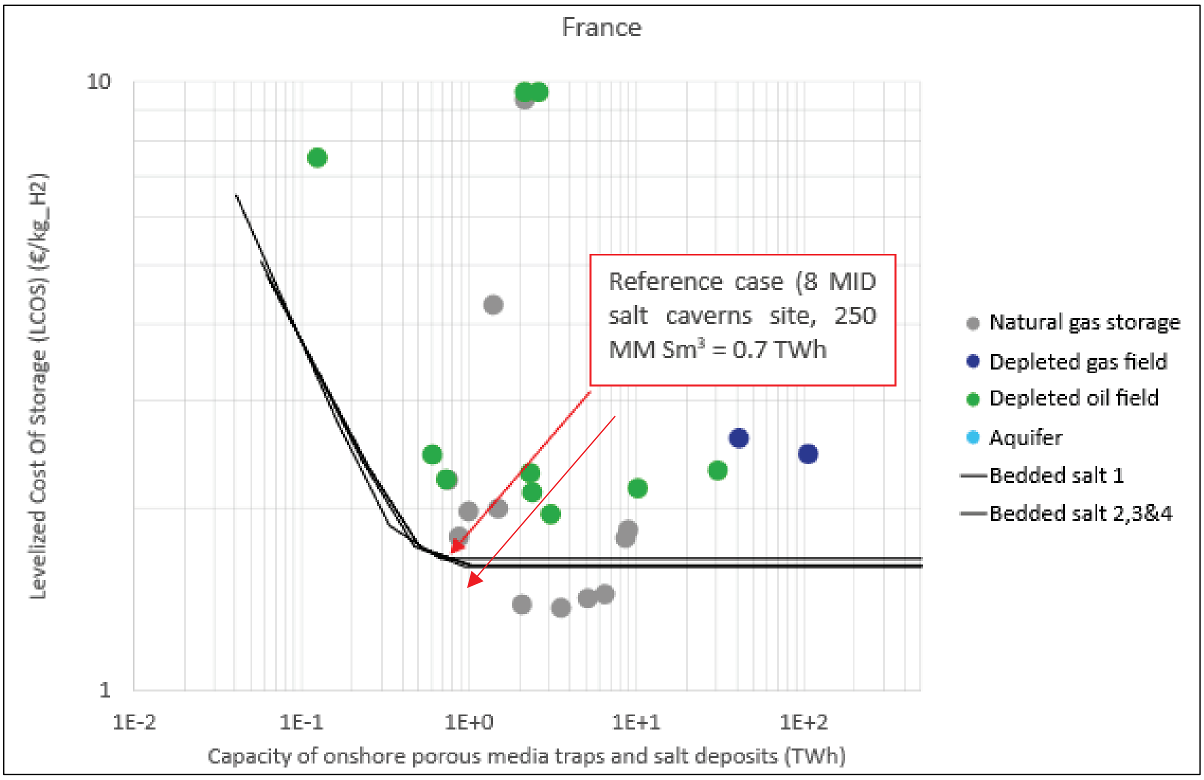

Figure 11: LCOS of storage for various capacities and geological options in France, for the cycle defined in section 2.2.2

4.3.6. Number of caverns

This sensitivity section details the above analysis (of varying the storage size) by giving KPIs when different numbers of caverns are considered. By increasing the number of caverns (all having the same characteristics), the overall project size increases accordingly.

While the annual volume of stored hydrogen linearly scales with increasing number of caverns, the resulting scaling effects in CAPEX and OPEX lead to a decrease in the specific storage costs and, hence, in LCOS. It however is of limited effect after the Conceptual Typical Design size of 8 caverns (250 MM Sm^3 of storage capacity) is reached. As already discussed in Hystories deliverable D7.3-1, the cost model does not lead to significant LCOS decrease when getting bigger than the Conceptual Design, notably because the construction is then not fully optimized. For instance, more rigs would be needed to be considered working in parallel to optimize the construction time, and the leaching plant would need to be larger. This is not captured in current Cost model as described in D7.2-1 report and would require a specific feasibility study analysis.

In a case of two caverns, relatively high LCOS of 2.64 €/kg is achieved, while it is reduced in a case of sixteen caverns to 1.54 €/kg (see Table 11).

Storage service margins range from 8.3 % in case of one cavern with high LCOS (2.64 €/kg) circa. 14.0 % in case of eight to twenty-four caverns, while assuming a constant storage service margin profit of 0.22 €/kg (as for all sensitivities).

Table 11: Results of sensitivity analysis: Number of caverns

		Number of caverns					
		2	4	8	12	16	24
Variation in input parameter		25 %	50 %	100 %	150 %	200 %	300 %
CAPEX/OPEX	**Unit**						
CAPEX - subsurface	million €	195,6	267,6	437,8	608,7	780,2	1124,9
CAPEX - surface	million €	134,1	223,3	409,6	611,9	832,2	1329,9
OPEX 2030-2039 (3.2 cycles/y)	million € / year	8,2	12,8	22,2	32,2	42,7	65,8
OPEX 2040-2049 (1.6 cycle/y)	million € / year	7,5	11,5	19,6	28,3	37,6	58,1
OPEX 2050-2059 (1.5 cycle/y)	million € / year	7,5	11,4	19,5	28,1	37,3	57,6
ABEX	million €	60,9	88,1	149,3	213,8	282,1	430,4
Business Case KPIs	**Unit**						
Yearly stored hydrogen 2030-2039 (3.2 cycles/y)	kt/year	17,8	35,5	71,1	106,6	142,1	213,2
Yearly stored hydrogen 2040-2049 (1.6 cycle/y)	kt/year	8,9	17,8	35,5	53,3	71,1	106,6
Yearly stored hydrogen 2050-2059 (1.5 cycle/y)	kt/year	8,3	16,7	33,3	50,0	66,6	99,9
Net Present Value (NPV)	million €	9,1	6,5	0,0	- 6,7	- 13,5	- 27,8
IRR	%	6,10 %	5,93 %	5,75 %	5,67 %	5,63 %	5,59 %
Net Present Cost (NPC)	million €	320,9	471,1	799,1	1142,8	1504,3	2283,4
LCOS	€/kg	2,64	1,93	1,64	1,56	1,54	1,56
Hydrogen storage service price	**Unit**						
Storage cost (=LCOS)	€/kg	2,64	1,93	1,64	1,56	1,54	1,56
Storage service margin profit	€/kg	0,22	0,22	0,22	0,22	0,22	0,22
Storage service margin profit	%	8,3 %	11,3 %	13,3 %	14,0 %	14,2 %	14,0 %
Storage service price	€/kg	2,85	2,15	1,86	1,78	1,76	1,78

4.3.7. Number of cycles

This sensitivity analysis is made neither on economic parameters nor on technical design ones, but the operating conditions of the storage.

In the reference case, 3.2, 1.6 and then 1.5 cycles per year are assumed successively during each of the 3 decades of the storage operational lifetime. This is a result found by the energy modelling work for France in Hystories as presented in D5.5 [LBST 2022].

To simplify the analysis, only a single figure of cycles per year is assumed for the sensitivity cases over the 30 years.

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.

Results for this sensitivity analysis are shown in Table 12. Improving the utilization rate by assuming higher numbers of cycles leads to higher variable OPEX (and hence NPC). However, this is largely compensated by the increase in the overall volume of stored hydrogen per year, having a very strong positive impact on the specific costs of hydrogen storage (LCOS). LCOS ranges from 3.88 €/kg (for 1 cycle per year, in which case the storage facility, designed for fast cycling, can be seen as oversized) to 0.55 €/kg (for 7.9 cycles per year, which is a physical maximum for this facility: it corresponds to load factor of 100 %, i.e. operation at full injection or withdrawal capacity and no stand-by in between). Assuming constant storage service margin profit of 0.22 €/kg (as for all sensitivities), NPV are between -2.1 million € for low 1 cycle per year and 7.9 million € for the maximum cycling capacity of 7.9 cycles per year.

Table 12: Results of sensitivity analysis: number of cycles

		Number of cycles per year						
		1 (2030-2059)	1.5 (2030-2059)	3.2 (2030-2039) 1.6 (2040-2049) 1.5 (2050-2059)	3.2 (2030-2059)	4.2 (2030-2059)	6.3 (2030-2059)	7.9 (2030-2059) (max. feasible @ Load factor = 100 %)
Variation in input parameter		48 %	71 %	100 %	152 %	200 %	300 %	376 %
CAPEX/OPEX	**Unit**							
CAPEX - subsurface	million €	437,8	437,8	437,8	437,8	437,8	437,8	437,8
CAPEX - surface	million €	409,6	409,6	409,6	409,6	409,6	409,6	409,6
OPEX 2030-2039 (3.2 cycles/y)	million € / year	18,7	19,5	22,2	22,2	23,8	27,1	29,7
OPEX 2040-2049 (1.6 cycles/y)	million € / year	18,7	19,5	19,6	22,2	23,8	27,1	29,7
OPEX 2050-2059 (1.5 cycles/y)	million € / year	18,7	19,5	19,5	22,2	23,8	27,1	29,7
ABEX	million €	149,3	149,3	149,3	149,3	149,3	149,3	149,3
Business Case KPIs	**Unit**							
Yearly stored hydrogen 2030-2039 (3.2 cycles/y)	kt/year	22,2	33,3	71,1	71,1	93,3	139,9	175,5
Yearly stored hydrogen 2040-2049 (1.6 cycles/y)	kt/year	22,2	33,3	35,5	71,1	93,3	139,9	175,5
Yearly stored hydrogen 2050-2059 (1.5 cycles/y)	kt/year	22,2	33,3	33,3	71,1	93,3	139,9	175,5
Net Present Value (NPV)	million €	- 2,1	- 1,3	0,0	1,1	2,6	5,6	7,9
IRR	%	5,72 %	5,73 %	5,75 %	5,76 %	5,78 %	5,82 %	5,85 %
Net Present Cost (NPC)	million €	778,5	785,8	799,1	810,3	824,7	854,9	878,0
LCOS	€/kg	3,88	2,61	1,64	1,26	0,98	0,68	0,55
Hydrogen storage service price	**Unit**							
Storage cost (=LCOS)	€/kg	3,88	2,61	1,64	1,26	0,98	0,68	0,55
Storage service margin profit	€/kg	0,22	0,22	0,22	0,22	0,22	0,22	0,22
Storage service margin profit	%	5,6 %	8,4 %	13,3 %	17,4 %	22,4 %	32,4 %	39,6 %
Storage service price	€/kg	4,10	2,83	1,86	1,48	1,20	0,89	0,77

4.3.8. Summary of the sensitivity analysis

The sensitivity analyses performed in this chapter shows the impact of different parameters on the project's KPIs. Figure 12 and Figure 14 summarize the effect of a variation of each parameter on LCOS and NPV, respectively. In addition, the storage service margin profits (SSMP) in % of LCOS are shown in

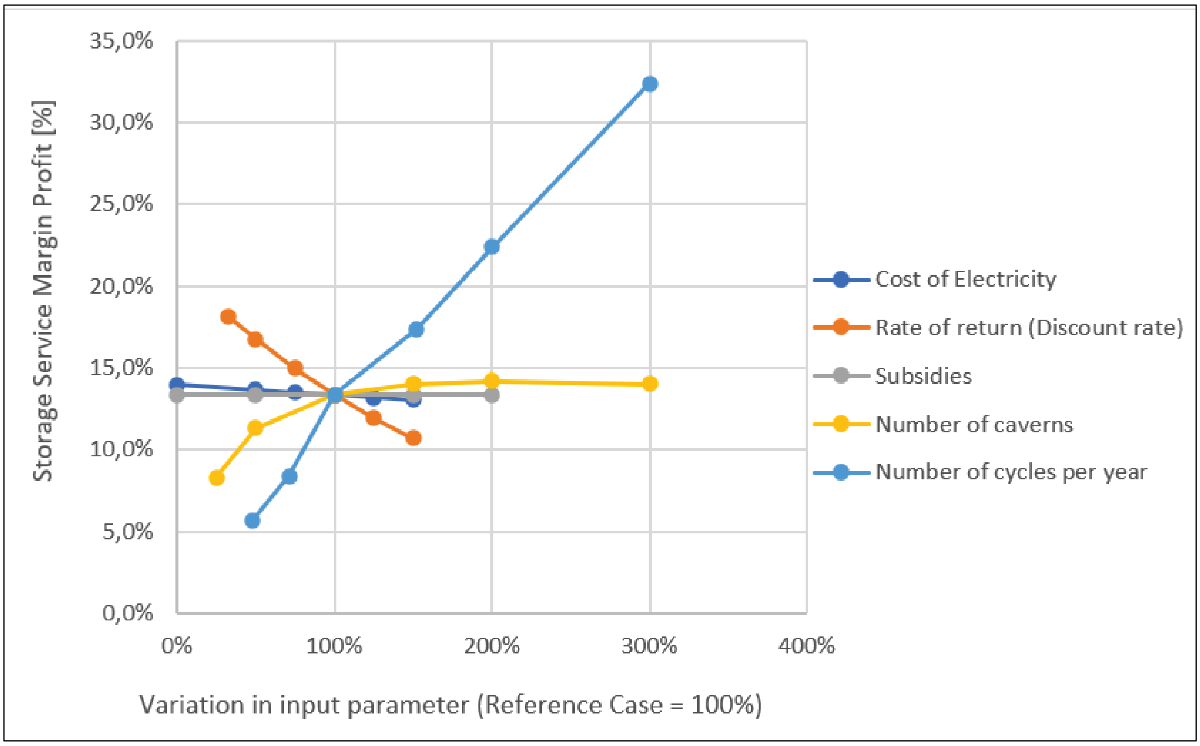

Figure *13* for each case, as this parameter is a key driver for projects' revenue and, hence, NPV.[7]

Starting point of the analyses is the reference case described in chapter 4.1. which corresponds to a project at breakeven point (NPV=0), and an assumed storage service margin profit of 0.22 €/kg).

The effect of each parameter on LCOS is shown in Figure 12. The two key lever to decrease LCOS are:

- increase in number of cycles,
- decrease in rate of return (discount rate),

The increase in number of caverns impacts up to the reference case (corresponding to 8 caverns storing 250 MM Sm^3, which is also D7.1/D7.2 Conceptual design)

The decrease in the cost of electricity only have limited effect. Pure economic parameters like subsidies do not impact LCOS, as LCOS is only impacted by NPC and present value of storage throughput values.

7 Please note that for all sensitivities a constant absolute value of storage service margin profit (SSMP) of 0.22 €/kg was assumed, which is equivalent to a SSMP of 13.3 % in case of the reference case. This value was selected as it was the value where the NPV is zero.

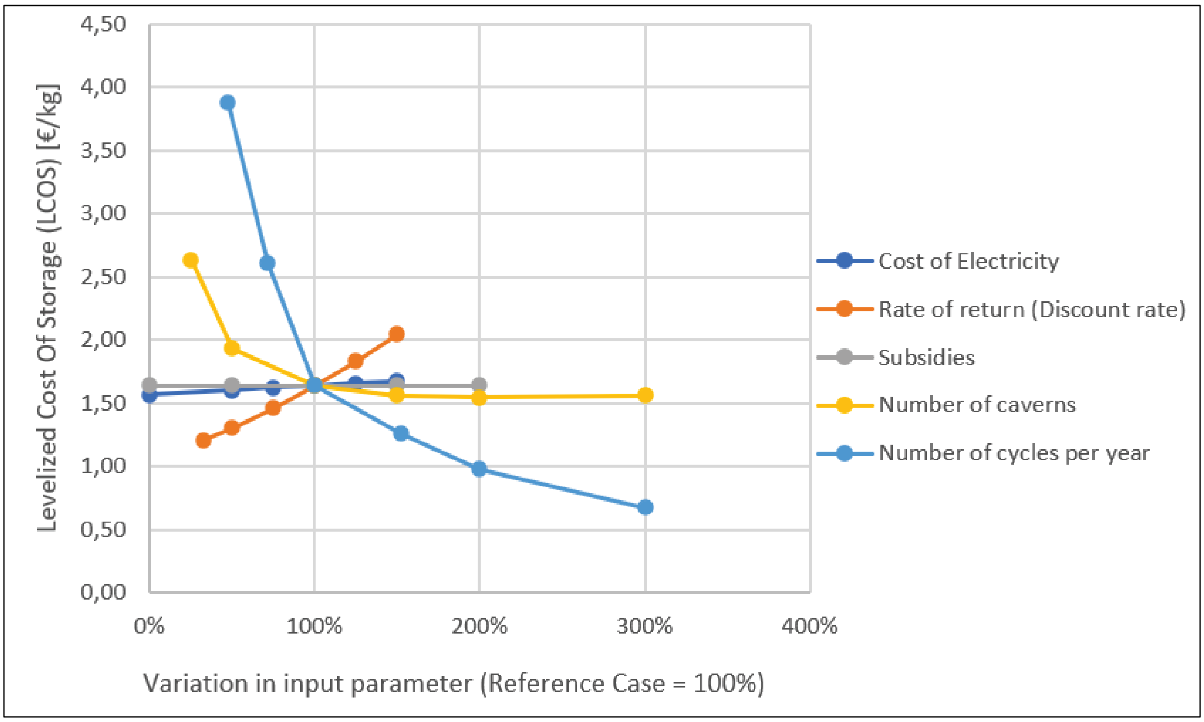

Figure 12: Effect of key parameters on LCOS as result of sensitivity analyses

As the storage service margin profit (in €/kg) was fixed for all cases at 0.22 €/kg, depending on LCOS also their relative value in percentage of LCOS change. Accordingly, for high LCOS in Figure 12, low storage service margin profit (in %) are observed and the other way round.

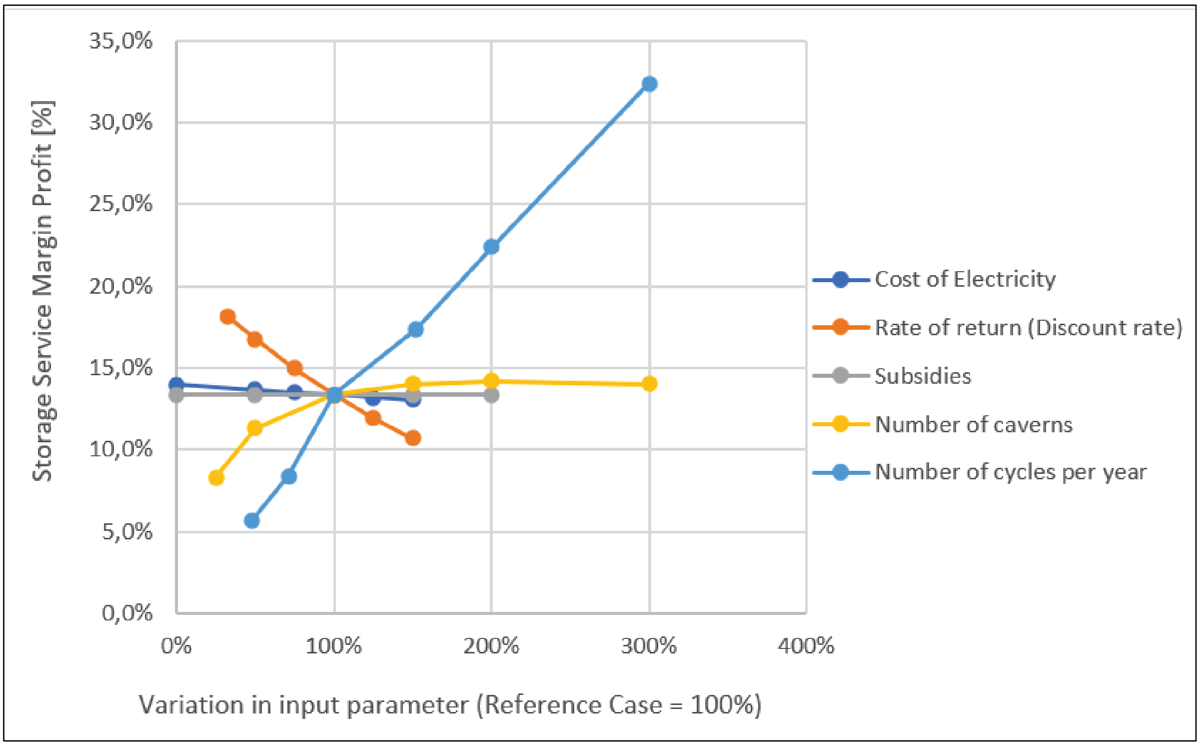

Figure 13: Effect of key parameters on Storage Service Margin Profit (SSMP) as result of sensitivity analyses

Regarding NPV, decrease in rate of return (discount rate) has the strongest effect to help improve the business case. Ordered by decreasing effect on NPV per percentage changed, it is followed by increase in subsidies.

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 form of storage service margin profit remain constant. The number of cycles per year only has a limited effect.

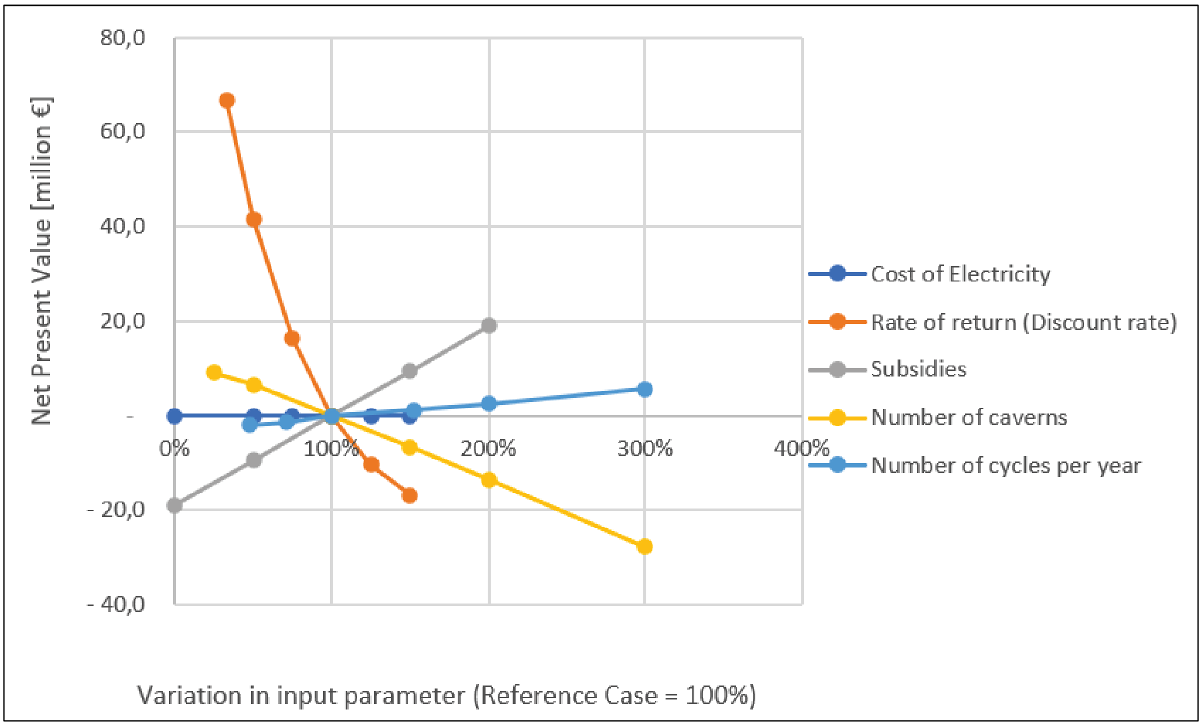

Figure 14: Effect of key parameters on NPV as result of sensitivity analyses

5. Conclusions

This report contains a case study of underground hydrogen storage in a salt cavern in France. The technical parameters of the hypothetical cavern project are derived from the Conceptual Design case presented in Hystories report D7.1-1 and is coherent with salt cavern development at circa. 1000 m depth, which is possible in France and broadly corresponds to sites currently developed for natural gas cavern storage cavern such as Bresse basin or Manosque region.

Business case and cash flow analysis were performed applying a cost tool developed in Hystories WP7, the business case tool developed in Hystories WP8 task 8.1, and the storage cycle found for France by the European energy system cost minimization work developed in WP5.

This reference case consists of an UHS with eight caverns at 1000 m depth, having a total working gas capacity of 250 million Sm^3. The number of storage cycles was found at 3.2 per year (2030-2039), and then 1.6 per year (2040-2049) and 1.5 per year (2050-2059), with a hydrogen throughput of respectively 71 000, 35 500 and 33 500 ton per year over these decades. By comparing these volumes with the demand for hydrogen storage in France identified in Hystories WP5, this would be equivalent to 24 %, 3 % and 2 % of annual storage throughput demands in over these periods, respectively.

According to the costs analysis in chapter 4, overall NPC of the project sum up to 799.1 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 found at 1.64 €/kg hydrogen**. It should be noted that this figure does not add to the cost of green hydrogen production cost to make a green hydrogen available on demand, since it only applies to the circa. 15 % of the hydrogen overall consumption that is stored[8].

The r storage service margin profit was adjusted to 13.3 % in order to break even the project (obtain a null Net Present Value, NPV = 0) and serve as a reference case for sensitivity studies. This 13.3 % storage service margin profit applied to the LCOS is equivalent to 0.22 €/kg. This break-even point is used as a basis for the sensitivity analyses in chapter 0, showing the impact on project KPIs of different key parameters (Cost of Electricity (CoE), rate of return, subsidies, number of caverns, and number of cycles) under the assumption that this storage service margin profit of 0.22 €/kg is obtained in all cases.

8 If green hydrogen production is assumed to be 2 €/kg (as expected in horizon 2050), the cost of green hydrogen available to offtakers when they need would be circa. 2 €+15 %*1.64 € = 0.25 €, less than 11 % of the cost of green hydrogen available on demand. More detailed and precise approach of value of the underground storage of renewable hydrogen within the entire value chain can be found in D5.5-2, § 5.1.

In summary of this sensitivity analysis, **lower LCOS are achieved with an increased number of full cycles equivalent per year, and by the decrease in rate of return (discount rate). Doubling the number of full cycle equivalent per year, to 4.2 cycles/years, for instance brings the storage LCOS to 0.98 €/kg and tripling it (6.3 cycles/year) bring the LCOS down to 0.68 €/kg.** The higher hydrogen throughput enables delivering more storage service while having the same investment costs. The lower discount rate positive impact is related the fact that most costs are invested upfront the operation and service provision in this infrastructure business. The storage size, as seen by the increased number of caverns, also impacts the LCOS but this effect stops at the Conceptual Design level (250 MM Sm^3 capacity) with current cost model, that is not optimized for larger projects, or for projects significantly smaller than the Conceptual Design. Subsidies and cost of electricity only have a minor impact of the LCOS.

This analysis is however highly hypothetical, relying on cost estimation hypotheses (D7.1 and D7.2), cycles hypotheses (from D5.4) and financial parameters hypotheses (from WP8). There are also some shortcomings of the analysis in this work package:

1) Storage operation optimization based on hydrogen market prices are not considered. Instead, a fixed storage service margin profit of 13.3 % of LCOS (in reference case: 1.64 €/kg) is assumed for the reference case accounting for about 0.22 €/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, which is found as optimal from energy system perspective, and can significantly lower the LCOS of a particular project. This should be seen as a key lever for business case optimization.

2) 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 to 1.34 €/kg have been described based on different sources. Public source giving an LCOS of 1.02 €/kg for depleted gas field and 1.07 €/kg for aquifer is also given. These LCOS literature values are significantly lower compared to the reference case with 1.64 €/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.

In conclusion, the analysed business cases show that profitability of the storage is achievable under certain circumstances. **Optimal storage utilization and increase in the number of cycles equivalent per year, might be a key lever to drive the business case.**

6. References

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Hystories D1.2 Geological database report

Hystories D1.4 Report on opportunities for geological storage of hydrogen

Hystories D2.2 3D Multi-realization simulations for fluid flow and mixing issues

Hystories D5.1 Scenario definition for modelling of the European energy system.

Hystories D5.3 European energy system model description.

Hystories D5.4 Assumptions and input parameters for modelling of the European energy system.

Hystories D5.5-2 Major results of techno-economic assessment of future scenarios for deployment of underground renewable hydrogen storages.

Hystories D6.1-1 – Assessment of the regulatory framework

Hystories D7.1-1 – Conceptual design of salt cavern and porous media underground storage site

Hystories D7.2-1 – Life Cycle Cost Assessment of an underground storage site

Hystories D7.3-1 – Ranking and selection of geological stores

Hystories D8.1 – Joint Methodology for individual EU Case Studies

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