Benchmarking of individual case studies and final conclusions

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1. Introduction

Underground hydrogen storage (UHS) refers to the practice of storing hydrogen gas in underground reservoirs or caverns for later use. It is an important component of hydrogen energy systems and will play plays a crucial role in ensuring a reliable and continuous supply of hydrogen [1]. UHS is crucial for ensuring a stable and reliable supply of hydrogen. Its importance lies in:

- Balancing supply and demand by storing excess hydrogen and withdrawing it during peak demand.
- Integration of renewable energy by storing its surplus in the form of hydrogen from intermittent sources.
- Enhancing grid stability and flexibility by providing a buffer for variable energy generation.
- Scalability to accommodate increasing hydrogen demand.
- Safe storage in underground sites, utilizing existing infrastructure for cost-effective and reliable hydrogen supply when possible.

In addition to the aforementioned economic advantages, underground hydrogen storage offers various technical benefits. These systems exhibit a heightened level of security, as the likelihood of hydrogen coming into contact with oxygen is considerably diminished. Consequently, they are impervious to fire hazards, and their subterranean nature renders them immune to potential terrorist attacks or military interventions. Another pivotal advantage is their minimal surface footprint, especially when considering the substantial space requirements that would accompany traditional hydrogen cylinders or spheres if they were to possess the capacity of an underground reservoir. This characteristic facilitates seamless integration within an environment and existing infrastructures. Furthermore, the costs associated with alternative surface technologies of comparable capacity would render them financially infeasible and nonviable. Lastly, it is noteworthy that, for natural gas, the geological availability of these storage sites has expanded over the past century, with the number and capacity surpassing 642 as of 2010 [2].

Europe's interest in UHS stems from its ability to support renewable energy integration and ensure a steady hydrogen supply. Among the existing portfolio of UHS projects across Europe, Hystories [3] –, a project funded by the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) – focused on advancing underground hydrogen storage technologies in porous media (depleted fields and aquifers). The project aims to develop innovative solutions for safe, efficient, and cost-effective hydrogen storage in porous media and salt caverns. By addressing technical, economic, environmental, social and regulatory aspects, Hystories seeks to accelerate the deployment of underground hydrogen storage and contribute to the development of a sustainable hydrogen economy in Europe.

Part of Hystories Work Package 8, the objective of the present work is to consolidate and align the results from the individual case studies carried out in project's Task 8.2 and, where applicable, other work packages into a benchmarking of selected Member States drawing conclusions on the profitability of the technology at single sites / under different national frameworks for large-scale underground hydrogen storage in Europe.

2. Benchmarking of European case studies

In the previous Task 8.2 activities, five business case studies in different European Member States (Spain, Germany, France, Poland and Italy) were identified and analysed, providing insights concerning capital investment, costs of construction, operation and abandonment. Additionally, cash flow analysis for each business case was conducted assuming a common set of initial parameters, with the aim of demonstrating the potential economic viability of the five cases More details about the overall work are given in Deliverables D8.2 – 8.6.

This section gathers the main results coming from Task 8.2, with the objective of developing a business cases benchmarking and drawing final conclusions about the Work Package 8.

2.1. Storage potential

The business cases were respectively located in Spain (D8.2), Germany (D8.3), France (D8.4), Poland (D8.5) and Italy (D8.6). The Hystories Deliverable D2.2 presents estimations about the potential storage capacities of several countries across Europe. The storage potential of the five corresponding EU Member States selected for the business case studies are given in Table 1.

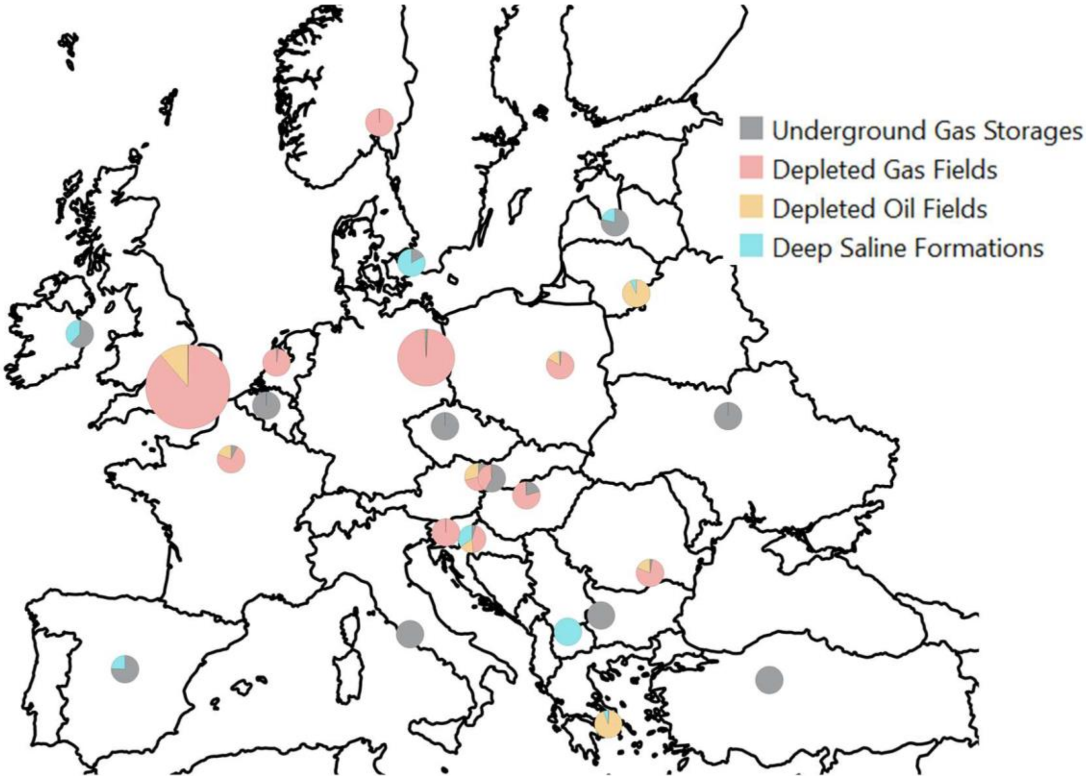

Figure 1 – Storage capacities per country (onshore and offshore). The size of the pie chart is proportional to the country capacity and represents the different categories of porous media storages. Source: D2.2-1

Table 1– Type of reservoir and potential storage capacity, on- and offshore, in each Member State, as reported in D2.2.-1.

	Spain	Germany	France	Poland	Italy
Type of reservoir considered in the case study	Porous media	Porous media	Porous media	Porous media	Porous media
Storage capacity	47 TWh	4,675 TWh	590 TWh	1,050 TWh	71 TWh

2.1.1. Spain

Based on the current installed underground storage capacity for natural gas, the estimated hydrogen storage capacity is approximately 47 TWh, which could have potentially covered the 19% of the Spanish energy consumption in 2022 (250 TWh, [4]). This highlights the importance of expanding and optimizing the existing infrastructure to accommodate higher volumes of hydrogen, remarking the significant potential for hydrogen storage in Spain, both in repurposing existing infrastructure and exploring new storage options.

2.1.2. Germany

To summarize the storage potential based on these analyses for hydrogen storage sites in Germany, an available study conducted by DBI et al. [5] examined possible transformation pathways of existing natural gas underground storage sites towards hydrogen. The study projects that the rededication of all 31 existing salt caverns in Germany would result in a storage capacity of 30.7 TWh_{LHV} (working gas). Additionally, four existing underground hydrogen storages (UHS) in porous reservoirs were deemed suitable for future hydrogen storage, providing an additional capacity of 1.7 TWh_{LHV}. Thus, the overall storage capacity of existing underground natural gas storage sites in Germany sums up to 32.4 TWh_{LHV}. On the other hand, the estimations in Hystories D2.2 indicate that the theoretical potential for hydrogen in porous media alone in Germany is around 4,675 TWh, with almost the entire potential located onshore, considering existing natural gas storages as well as new developments.

2.1.3. France

The estimations in Hystories D2.2 indicate that the theoretical potential for UHS in porous media in France is around 590 TWh, taking into account both offshore and onshore solutions. Underground storage in aquifer is predominant over depleted fields in the country, unlike the overall European picture, due to the French geological settings, with only one storage (Trois Fontaines, assuming it has restarted by the end of 2022) in a depleted gas field.

2.1.4. Poland

Poland holds substantial potential for underground hydrogen storage. The expertise gained in identifying geological structures for carbon dioxide underground storage has proven to be valuable in evaluating the feasibility of geological hydrogen storage in underground formations. The favourable geological structure of Poland enables the establishment of storage sites in numerous areas throughout the country, accommodating various types of storage. In the context of WP1, it was established a comprehensive database comprising data on 38 deep aquifer structures (traps) in Poland suitable for underground hydrogen storage in porous media, representing a combined total capacity of approximately 1,050 TWh.

2.1.5. Italy

Finally, the existing installed capacities for underground gas storage (UGS) — and potentially to be readapted for hydrogen — in Italy are roughly estimated to be around 71 TWh, distributed between depleted oil and gas fields located across the national territory.

2.2. Regulatory framework

In this section, a visual and straightforward overview on the regulatory framework for underground hydrogen storage (UHS) in Spain, Germany, France, Poland, and Italy is provided. While in Spain, Poland and Italy there is no UHS legislation under development, in Germany, the regulatory framework encompasses the storage of both chemical products and natural gas. Notably, an industrial helium storage facility was successfully established in a salt cavern in 2016. Consequently, the existing legislation governing underground natural gas storage in Germany is also applicable to future hydrogen storage initiatives. Conversely, in France, comprehensive legislation specifically addressing Underground Hydrogen Storage (UHS) is currently in the developmental stage. The Mining Code presently permits UHS for industrial purposes, with anticipated near-term modifications to extend its applicability to energy-related uses.

Table 2 shows the status of UHS legislation gathered from D6.1-1 for each Member State, as of 2021, while more comprehensive details on the legislation in force for each country are given in the before-mentioned Deliverable.

Table 2– Current status of UHS legislation in Spain, Germany, France, Poland and Italy as of 2021. From D6.1-1.

	Spain	Germany	France	Poland	Italy
UHS legislation in force		X			
Absence of UHS legislation (under development)			X		
Absence of UHS legislation and lack of its development	X			X	X

2.3. Cost analysis

The business cases in the five selected EU Member States were extensively examined using the joint methodology outlined in D8.1. This approach involved the utilization of a toolbox to assess the profitability of various large-scale hydrogen storage options and business models for underground hydrogen reservoirs, specifically from the perspective of individual operators. The methodology served as the foundation for analysing specific European case studies. The economic evaluation of the business model was primarily based on the outcomes of D7.2-1 [3], encompassing the development costs or capital expenditure (CAPEX) associated with engineering, procurement, construction, commissioning, and project start-up. Additionally, it incorporated cost estimates for operating costs (OPEX) throughout the hydrogen storage facility's life cycle, along with abandonment expenditures (ABEX). The business model incorporates multiple initial assumptions, with some of them standardized across all case studies to establish a reference baseline for comparison purposes. The techno-economic parameters, as presented in Table 3, are applied to all five business cases, with those common to other Member States' business cases marked in light blue.

Table 3 – Set of techno-economic parameters of each business case. The parameters taken as common reference for all Member States are marked in light blue.

Parameters	Description	Units	Spain	Germany	France	Poland	Italy
	Type of reservoir		Salt cavern	Salt cavern	Salt cavern	Salt cavern	Porous media
Geology and subsurface facilities							
$\mathbf{V_{cavern}}$	Geometrical volume per cavern	[millions m^3]	0.38	0.56	0.38	0.38	—
$\mathbf{V_{max}}$	Working Gas volume per cavern	[millions Sm^3]	31	52	31	31	22 (entire site)
$\mathbf{n_{WH}}$	Number of caverns (assumption: one well head per cavern)	[nr.]	8	4	8	8	—
$\mathbf{n_{WH,prod}}$	Number of storage wells (for porous storage)	[nr.]	—	—	—	—	25
$\mathbf{n_{WH,obs}}$	Number of observation wells	[nr.]	—	—	—	—	6

Parameters	Description	Units	Spain	Germany	France	Poland	Italy
—	H_2 yearly throughput	[t/yr]	31,095	29,860	71,000	46,642	48,785
LCCS	Last cemented casing shoe	[m]	1000	850	1000	1000	1200
DC_i	Drilling complexity index	[-]	1	1	1	1	1
L_{fw}	Fresh water pipeline length	[km]	15				—
L_{bd}	Brine disposal pipeline length	[km]	30				—
$x_{Salt/porous}$	Cushion gas / Total gas ratio	[-]	0.43	0.24	0.43	0.43	0.5
V_{wg}	Working Gas volume	[millions Sm^3]	250	210	250	250	550
V_{wg}/Q_w	Storage to withdrawal capacity ratio	[days]	57	21	16	15	110
$Q_{debrining}$	Debrining flowrate per cavern	[m^3/h]	200				—
$d_{full\ cycle}$	Duration of one full storage cycle	[days]	114	80	46	58	231
N_{fc}	Number of full cycles per year	[cycle/yr.]	1.4	1.6	3.2/1.6/1.5	2.1	1
$N_{fc,\ MAX}$	Maximum number of full cycles per year	[cycle/yr.]	3.2	4.6	7.9	6.3	1.58
LF	Load Factor	[-]	0.44	0.35	0.41	0.33	0.63
Operating costs and surface facilities							
MCF_i	Material cost factor for injection (compression) stream	[-]	1				
MCF_w	Material cost factor for withdrawal stream	[-]	1				
Q_w	Total storage maximum withdrawal flowrate capacity	[millions Sm^3/day]	4.39	10.13	15.65	16.50	5
τ	Overall compression ratio (ratio of discharging pressure over	[-]	3.23	2.52	3.23	3.23	2.34

Parameters	Description	Units	Spain	Germany	France	Poland	Italy
	suction pressure)						
n	Number of required compression stages	[nr.]	2				
WTIR	Withdrawal to injection capacity ratio	[-]	1	2.86	1.9	2.8	1.1
netOP	Minimum suction pressure of compression stream (pipeline operating pressure)	[barg]	55				
MOP	Maximum storage operating pressure	[barg]	180	140	180	180	130
minOP	Minimum storage operating pressure	[barg]	70	60	70	70	60
L_{fl}	Field lines size	[km]	2				
K_{purif}	Purification coefficient (Only for porous media)	[-]	0	0	0	0	1.5
COE	Cost of Electricity [€/MWh]	[€/MWh]	40	100	60	100	66

The comprehensive analysis of CAPEX (subsurface operation and surface facilities), OPEX, and ABEX for the business cases derived from D8.2 – 6 is depicted in Figure 2. The CAPEX - subsurface costs were notably similar for Spain, France, and Poland, amounting to approximately 438 M€, while the German case displayed a visibly lower value of 269 M€. The overall annual OPEX for Spain and Germany was approximately 12 M€ each, while for France and Poland, it was 22 M€ and 21 M€, respectively. In contrast, the Italian case, representing a porous media, exhibited the highest CAPEX (both subsurface and surface), surpassing a global total of 1.000 M€. Additionally, it demonstrated the highest OPEX and ABEX, amounting to 30 M€ and 151 M€, respectively. Nonetheless, it is crucial to bear in mind that these outcomes result directly from the site-specific assumptions incorporated into the cost model, thus suggesting the possibility of cost reduction by considering alternative scenarios with different techno-economic parameters. A detailed cost breakdown of the business cases is provided in Table 4.

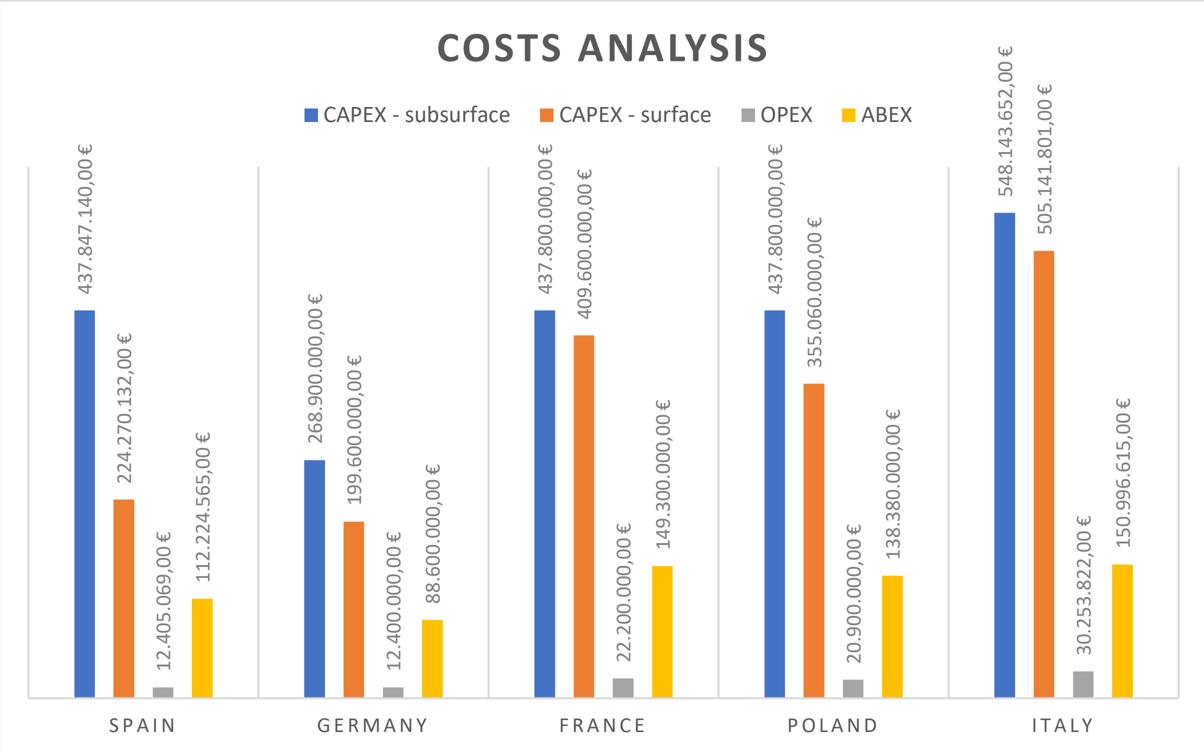

Figure 2 – Cost analysis for each business case.

Table 4 – Costs breakdown for each business case.

CAPEX – subsurface						
Costs breakdown	Description	Spain	Germany	France	Poland	Italy
EPC1	EPC cost main parameters and cost breakdown for Leaching facilities	97.6 M€	88.2 M€	96.3 M€	97.6 M€	–
EPC2	Leaching operation and maintenance costs	85.8 M€	57.4 M€	87.6 M€	85.8 M€	–
EPC3	Salt cavern debrining and conversion costs	35.8 M€	21.9 M€	35.0 M€	35.8 M€	–
	First Gas Fill (FGF) costs for porous media	–	–	–	–	4.2 M€
EPC4	Development Drilling and	44.7 M€	21.1 M€	43.8 M€	44.7 M€	158.5 M€

	leaching completion costs					
CG	Cushion gas	101.0 M€	35.5 M€	100.7 M€	101.0 M€	294.1 M€
$CONT_{subsurface}$	Contingencies related to subsurface	73 M€	44.8 M€	74.4 M€	73.0 M€	91.4 M€
Total		**437.8 M€**	**268.9 M€**	**437.8 M€**	**437.8 M€**	**548.1 M€**
			CAPEX – surface			
Costs breakdown	Description	Spain	Germany	France	Poland	Italy
EPC_1	EPC cost main parameters and breakdown for filtering, drying & compression, and metering units	136.9 M€	121.3 M€	249.8 M€	202.7 M€	119.9 M€
EPC_2	EPC costs for interconnection WH - Gas Plant	28.1 M€	19.1 M€	16.4 M€	53.4 M€	86.7 M€
EPC_3	EPC cost per additional kilometer between Gas Plant and nearest WH	5.4 M€	10.4 M€	49.1 M€	18.1 M€	5.2 M€
EPC_4	EPC cost estimate for hydrogen purification at storage outlet	–	–	–	–	181.5 M€
EPC_5	EPC cost main parameters and cost breakdown for Balance of Plant	16.5 M€	15.5 M€	24.6 M€	21.7 M€	27.7 M€
$CONT_{surface}$	Contingencies related to surface facilities	37.4 M€	33.3 M€	69.6 M€	59.2 M€	84.2 M€
Total		**224.3 M€**	**199.6 M€**	**409.6 M€**	**355.1 M€**	**505.1 M€**
			Annual OPEX			
Costs breakdown	Description	Spain	Germany	France	Poland	Italy
$OPEX_{fix, UG}$	OPEX - Subsurface	1.3 M€	0.6 M€	1.3 M€	13.9 M€	4.7 M€
$OPEX_{fix, AG}$	Fixed OPEX - Surface	9.6 M€	8.7 M€	15.7 M€	5.6 M€	18.9 M€
$OPEX_{var, AG}$	Variable OPEX - Surface	1.5 M€	3.0 M€	5.1 M€	1.3 M€	6.6 M€
Total		**12.4 M€**	**12.4 M€**	**22.2 M€**	**20.9 M€**	**30.2 M€**
			ABEX			
Costs breakdown	Description	Spain	Germany	France	Poland	Italy

$ABEX_{subsurface}$	Abandonment Expenditure for subsurface	67.3 M€	46.7 M€	67.4 M€	71.0 M€	50.0 M€
$ABEX_{surface}$	Abandonment Expenditure for surface facilities	44.8 M€	39.9 M€	81.9 M€	67.4 M€	101.0 M€
Total		**112.2 M€**	**86.6 M€**	**149.3 M€**	**138.4 M€**	**151.0 M€**

2.4. Finance

Table 5 gathers the economic and financial assumption adopted for the business cases under analysis. In elaborating the specific business cases for each of the selected EU Member States, several parameters were established as common for all case studies, with the objective to create a common reference baseline, in order to facilitate the business cases benchmarking. The baseline scenario described in this section was built to present the economic break-even conditions for the business case under investigation, and, hence, it is characterized by a null Net Present Value (NPV=0), achieved by properly adjusting the storage margin profit (%) applied to H_2 storage cost, which is equal to the levelized cost of storage (LCOS) by initial assumption. According to the null NPV condition, the IRR results to be equal to the discount rate chosen for all the cases (i.e., 5.75%).

Table 5 – Economic and financial assumptions adopted for each business case. The assumptions taken as common reference for all Member States are marked in light blue.

Parameters	Units	Spain	Germany	France	Poland	Italy
Subsidy	[€]	20,000,000.00				
Venture period	[years]	30				
Residual value	[%]	20				
Corporate tax	[%]	25	25	25	25	25
Financing fund	[€]	0				
Interests	[%]	5				
Financing duration	[years]	30				
Rate of return	[%]	5.75				
Storage service margin profit	[%]	13.49	11.31	13.35	13.00	22.98

In order to assess the economic feasibility of the geological storage of H_2 in the various scenarios, a number of financial KPIs were identified and taken into account: Net Present

Value (NPV), Internal Rate of Return (IRR), Net Present Cost (NPC), Levelized Cost of Storage (LCOS) and H_2 storage service price (i.e., obtained by applying the storage service margin profit to LCOS), all defined as reported in D7.3 as well as in D8.1. Table 6 provides the financial outcomes obtained from the baseline scenario of the business cases, which all comprehend an investment phase of 8 years (2022 – 2029) prior to the actual venture period of the case, starting from 2030 and finalizing in 2059. The baseline scenarios were then used as starting point for a sensitivity analysis, aiming at improving the corresponding cash flows. The optimization study is reported in D8.2 – 6.

Table 6 – Financial KPIs for each business case.

		Finance				
Parameter	Description	Spain	Germany	France	Poland	Italy
NPV	Net Present Value	0 €				
IRR	Internal Rate of Return	5.75%				
NPC	Net Present Cost	599.8 M€	460.6 M€	799.1 M€	762.2 M€	1.660.4 M€
LCOS	Levelized Cost of Storage	2.13 €/kgH_2	1.71 €/kgH_2	1.64 €/kgH_2	1.81 €/kgH_2	3.76 €/kgH_2
—	H_2 storage service price	2.42 €/kgH_2	1.90 €/kgH_2	1.86 €/kgH_2	2.04 €/kgH_2	4.63 €/kgH_2

Upon reviewing the outcomes for the respective cases (as shown in Table 6 and Figure 3), the hypothetical construction, operation, and maintenance of the salt cavern facility in Spain entails a total expenditure of 599.8 M€, yielding an appealing LCOS at 2.13 €/kgH_2. This corresponds to a final hydrogen storage service price of 2.42 €/kgH_2, incorporating a margin profit of 13.49%. In contrast, the German case exhibits lower NPC and LCOS values, amounting to 460.6 M€ and 1.71 €/kgH_2, respectively. Notably, it possesses the lowest margin profit among all the examined business cases, contributing to its economic break-even performance. Despite registering the highest NPC (799.1 M€) among the scrutinized salt cavern options due to its significant hydrogen storage throughput, the French case boasts the most favourable LCOS (1.64 €/kgH_2). Moreover, despite having a margin profit (13.35%) roughly on par with Spain and Poland, it boasts the most competitive hydrogen storage service price at 1.86 €/kgH2. The Polish salt cavern NPC is marginally lower than the French case, standing at 762.2 M€. In terms of LCOS and hydrogen storage service price, it ranks as the third-best scenario after France and Germany, yielding values of 1.81 €/kgH_2 and 2.04 €/kgH_2, respectively. Conversely, the Italian porous media case necessitates a substantial storage service margin profit of 22.98% applied to the LCOS (3.76 €/kgH_2) to achieve a null NPV, thereby resulting in a higher hydrogen storage service price of 4.63 €/kgH_2. The NPC for this case stands at 1,660.4 M€. As discussed in the preceding section, these economic findings are contingent on a set of assumptions that are site-specific, potentially differing in alternative case studies optimized for distinct boundary conditions. Specifically, LCOS exhibits a high degree of case-specific nature, with factors like asset reutilization and meticulous site selection having the potential to significantly mitigate costs, thereby altering the economic dynamics of the project.

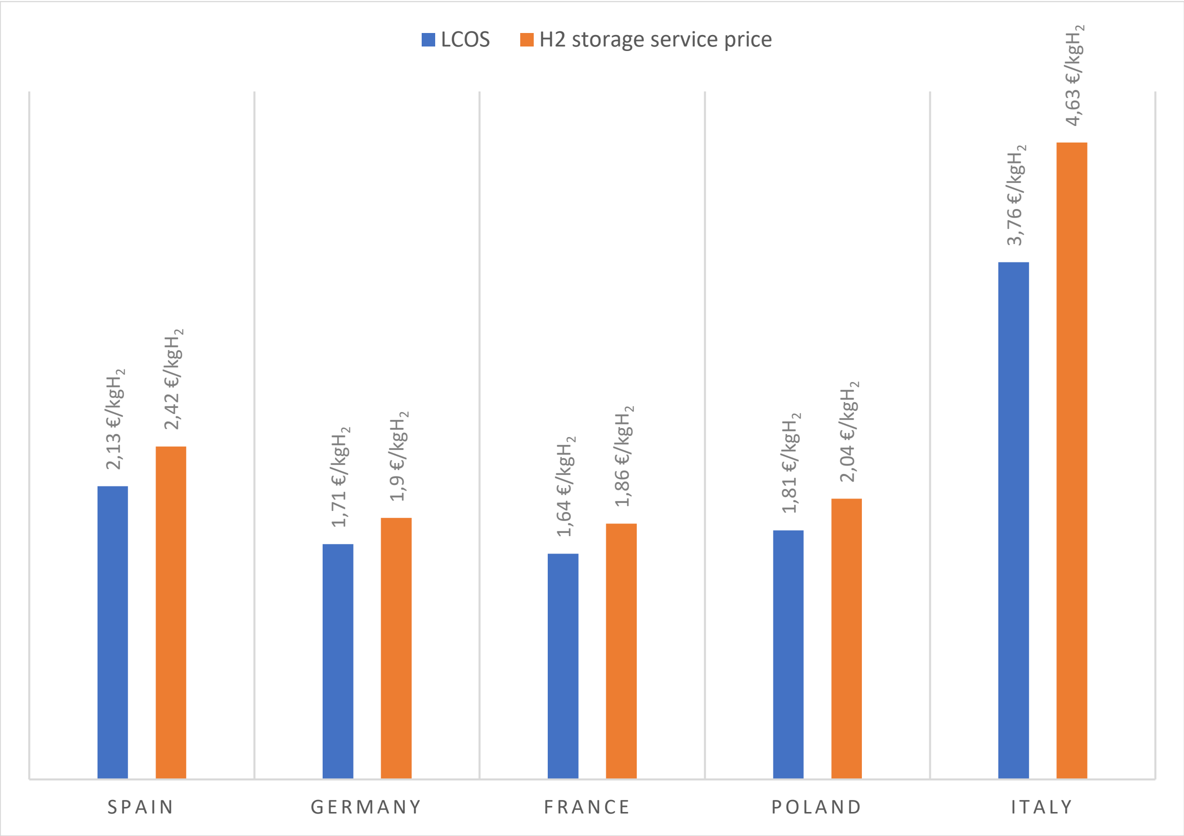

Figure 3 – Levelized Cost of Storage (LCOS) and H_2 storage service price resulting from each business case.

3. Conclusions

3.1. Benchmark conclusion

In culmination of the presented study, five distinct business case analyses were exhaustively conducted utilizing the joint methodology previously established in Task 8.1. This evaluation centred on the economic dimension, drawing upon the findings of D7.2-1, encompassed the full spectrum of development costs (CAPEX), spanning engineering, procurement, construction, commissioning, and project initiation. It is however based on a hypothetical storage site for each of the cases and is not necessarily representative of the diversity of the storage sites that can be done in that country. This assessment also integrated projected operating costs (OPEX) spanning the lifecycle of the hydrogen storage facility, coupled with abandonment expenditures (ABEX). Subsequently, the economic feasibility of each business case was evaluated, accounting for the array of assumptions inherent in the adopted economic model. In addition to the presented analysis, it is recommended for future endeavours to extend the evaluation of economic viability to encompass a broader spectrum of variables. This includes appraising factors not included in the scope of the current study, such as the geological suitability for subsurface reservoir construction, proximity to industrial consumption or diverse demand channels, adjacency to compatible hydrogen transport infrastructures, legal imperatives, and societal acceptance.

3.2. Call for action

Underground hydrogen storage remains an emerging technology, riddled with obstacles and uncertainties that necessitate resolution to facilitate its successful deployment and scalability. While the journey towards mature and commercially viable UHS is lengthy, the demand for storage capacities is on the rise, projected to surge significantly post-2030 [1]. Swift and coordinated efforts from industry players, governmental bodies, and public stakeholders are imperative to bridge knowledge gaps, mitigate risks, establish credibility, and gather experience, thereby securing a full operational license. However, the economic landscape for UHS is nascent, characterized by gaps in understanding certain cost elements, market regulations, and revenue models, rendering it challenging to justify the substantial investments associated with UHS project development. The anticipation of hydrogen storage demand and the economic rationale behind UHS projects rely heavily on fluctuating assumptions, extending to the envisioned services and applications in the evolving energy landscape. Additionally, elusive cost factors linked to UHS creation and operation, such as cushion gas expenses, treatment, maintenance, and well interventions, introduce significant uncertainties that can greatly affect both capital and operational expenditures. The absence of practical experience in real subsurface settings further intensifies uncertainties regarding injection/extraction performance and hydrogen quality and retrievability, amplifying the ambiguity around operational expenditures. Moreover, the ambiguity surrounding future market regulations magnifies the unpredictability of revenue potential from UHS operations, thereby elevating investment risks for major industrial stakeholders. Given these multifaceted considerations, a potential course of action could be formulated with the following key points:

- Explore strategies to decrease and manage the investment risks associated with early-stage underground hydrogen storage (UHS) projects, aiming to enhance knowledge for accurate economic evaluations of these projects.
- Evaluate the significance of UHS in ensuring energy security and balance on both national and global levels, involving a comprehensive analysis of societal costs and benefits within different energy transition scenarios.
- Analyse the necessity for national and international regulatory frameworks for UHS markets, encompassing regulated and third-party access storage facilities.
- Exchange operational insights gained from the scalable growth of UHS in salt caverns, with potential applicability to UHS development in porous rock reservoirs, thereby fostering improvements and learnings.

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