Spanish Case Study

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1. Introduction

This section aims to give an overview on the state of the art of underground storage in the Spanish territory, which serves as preface of the business case study foreseen within the HyStories project.

In Europe, there is a significant underground storage capacity of approximately 113 billion cubic meters, primarily utilizing depleted wells. This underground storage infrastructure plays a crucial role in enhancing energy security, particularly in a region heavily dependent on imported fossil fuels. By utilizing underground storage, Europe can mitigate the impact of seasonal energy variations and regulate market prices effectively. This contributes to overall energy independence and helps achieve net-zero emissions targets [1].

Given the current energy supply landscape in Europe, it is imperative to develop robust strategies that address net-zero emissions goals while ensuring security of energy supply and maintaining installed energy capacity. Underground storage facilities provide a viable solution to these challenges, offering flexibility, stability, and control over energy resources. By leveraging underground storage, countries like Italy and Spain can enhance their energy systems' resilience and contribute to the overall sustainability objectives of the European Union.

1.1. Storage market in Spain: an overview

This section provides a review of the current state of the underground storage market on the Spanish territory. A general overview on the existing natural gas storage capacities and the main players involved in the storage market is given.

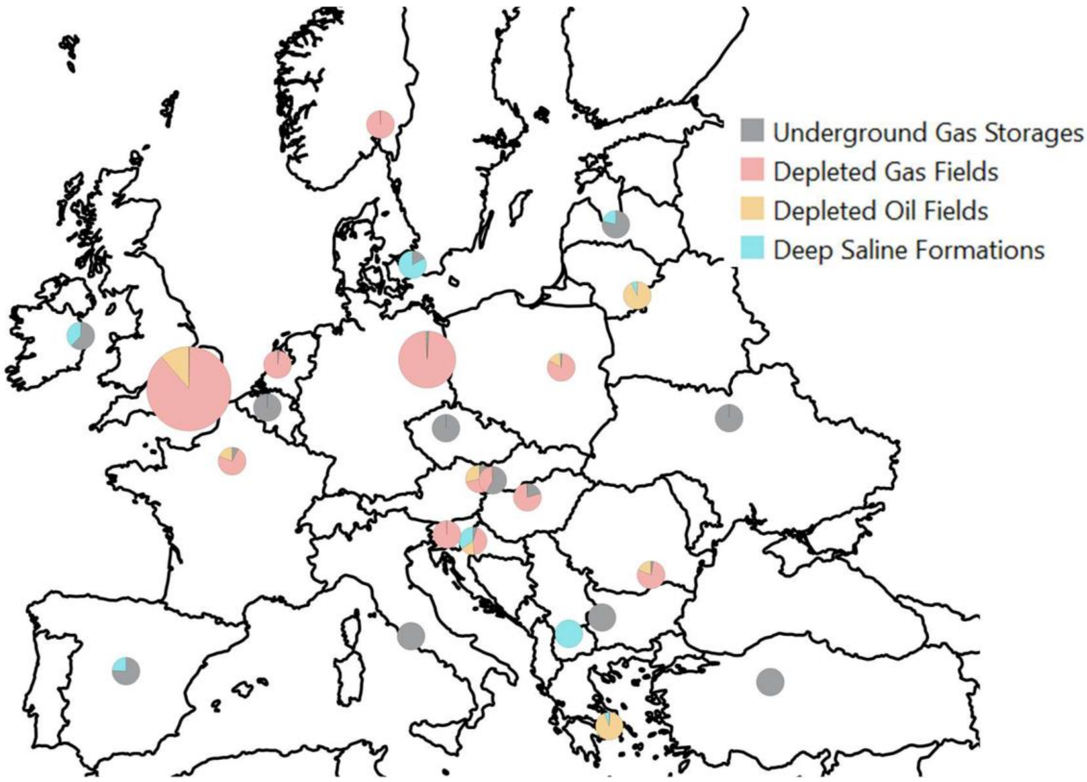

Figure 1 – Storage capacities per country (onshore and offshore). The size of the pie chart is proportional to the country capacity and represents the different categories of porous media storages. Source: D2.2-1

As can be seen in the map shown in Figure 1, obtained from the deliverable "*D2.2-1 - 3D multi-realization simulations for fluid flow and mixing issues at European scale*", storage capacities across Europe are different depending on the region. In detail, underground capacities on the Spanish territory are concentrated in deep saline formations (Figure 1).

Assuming a complete conversion of all underground natural gas storage in Europe for hydrogen storage, Spain's storage capacities would indeed be substantial. With an estimated capacity of around 17 TWh (see Figure 2) of H_2 storage —which would correspond to approximately 7% of the overall electric energy consumption on the national territory during 2022 [2]— Spain would have a significant infrastructure for storing and managing hydrogen. Expanding the storage capacity further is also feasible by creating new wells in saline or porous media. These additional storage facilities would allow for increased flexibility and scalability, accommodating the growing demand for hydrogen storage as it becomes a more prominent energy carrier.

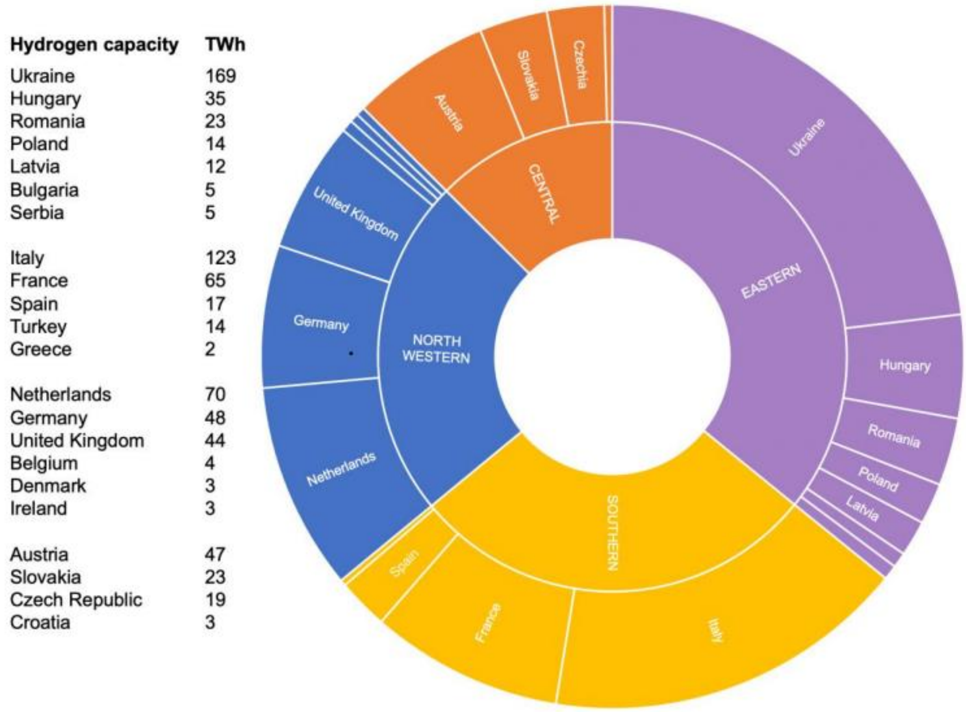

Figure 2 – European hydrogen storage capacity in porous reservoirs for existing natural gas storage by region and country. Source: HyUSPRe

In Spain, the need for large-scale energy storage is necessary, since the institutions are greatly fostering a rapid transition to an energy community based on renewable energies in the country.

The renewable hydrogen roadmap [3] developed by the Ministry for Ecological Transition and the Demographic Challenge envisages the intention to use geological storages such as salt caverns, aquifers and depleted Natural Gas/Oil wells to achieve these long-term storages and large quantities of hydrogen.

Figure 3 – Locations of existing underground storage facilities in Spain. Source: modified by [Enagas]

In Spain, the existing underground storage facilities currently in operation are the following [4, 5]:

- **Yela underground storage** – This is an onshore saline aquifer located 2300 metres below the surface. It has a useful volume of 1050 Mm^3.
- **Serrablo underground storage** – This is an onshore depleted gas well reused as underground storage. It has 680 Mm^3 of useful gas volume.
- **Gaviota underground storage** – Offshore storage in the Cantabrian Sea. This is a depleted field reused for Natural Gas storage. It has a useful gas capacity of 979 Mm^3.
- **Marismas underground storage** – Includes two depleted gas fields in the Guadalquivir basin reused as underground storage sites since 2012. It has 147 Mm^3 of total useful gas volume.

Creating underground storage facilities in salt caverns is indeed a promising approach to increase storage capacities in Spain for hydrogen. The map (see Figure 4) depicting regions with viable geological characteristics for underground hydrogen storage highlights the potential availability of suitable sites across the country. Salt caverns offer several advantages for storage purposes, including their high storage capacity, geological stability, and the ability to quickly inject and withdraw hydrogen. Leveraging these regions with suitable soils and geological formations can facilitate the development of new underground storage facilities dedicated to hydrogen. While establishing new storage facilities from scratch entails significant initial investment costs, they play a critical role in ensuring a reliable energy supply of hydrogen and supporting the energy transition goals set by the Spanish Government. The upfront investment is a necessary step to build the infrastructure required for long-term hydrogen storage and enable the integration of renewable energy sources into the energy system. By strategically developing underground storage facilities in salt caverns, Spain can enhance its energy security, support the growth of the hydrogen sector, and contribute to the decarbonization and energy transition objectives. These investments will lay the foundation for a sustainable and resilient energy system that relies on hydrogen as a clean and versatile energy carrier.

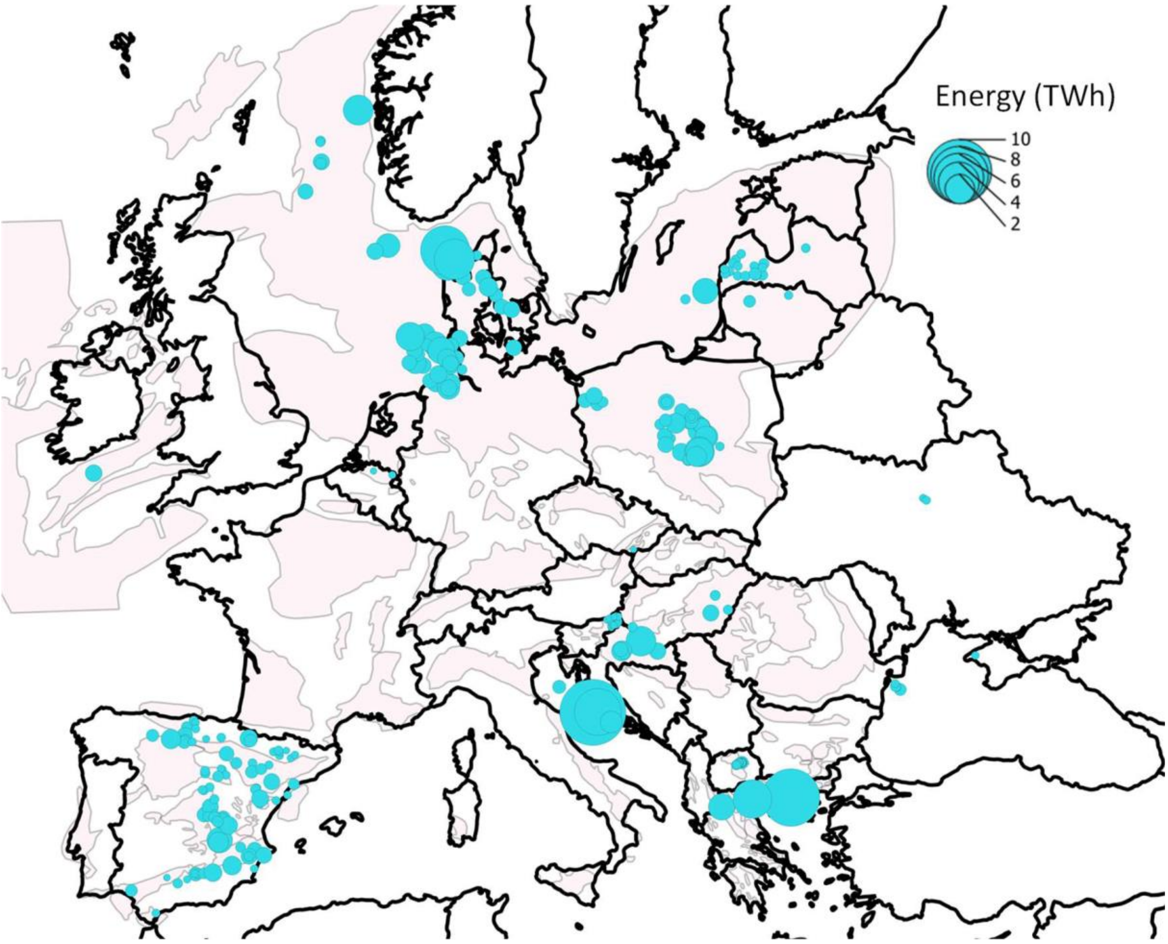

Figure 4 – Storage resource estimates for Deep Saline Formations. Source: D2.2-1ç

1.2. Spanish storage potential

The estimates provided in the report "*D2.2-1 3D multi-realization simulations for fluid flow and mixing issues at European scale*" indicate significant hydrogen storage capacities in porous media for Spain. Based on the current installed underground storage capacity for natural gas, the estimated hydrogen storage capacity is approximately 47 TWh, which might have covered around 19% of the Spanish energy consumption in 2022 (250 TWh [2]).

These estimates highlight the significant potential for hydrogen storage in Spain, both in repurposing existing infrastructure and exploring new storage options. Expanding storage capacities will be crucial for supporting the growing demand for hydrogen as a clean energy carrier and facilitating the integration of renewable energy sources into the energy system.

1.3. Spanish regulatory framework

Taking as a reference the report "*D6.1.1 Assessment of the Regulatory Framework*", in Spain the Hydrogen Route establishes a long-term seasonal approach to underground storage, ensuring the supply of hydrogen to the system and the safety of the population and the environment.

The legislation currently in force is as follows:

- The specific underground natural gas legislation is the Law 34/1998 of 7 October 1998 on the hydrocarbons sector [6], as general frame, and other more specific the Royal Decree *1184/2020,* refer to geological underground storage [7].

The national body that regulates underground natural gas storage permits is the Directorate General for Energy Policy and Mines, part of the Ministry for Ecological Transition and Demographic Challenge, MITECO.

- According to the consulted experts the Directive 2012/18/EU (SEVESO III) should be adapted for underground hydrogen storage, and it is transposed to Spanish regulation by the Royal Decree 840/2015, of 21 September [8].

Spain does not have any legislation in place for underground hydrogen storage, nor has any underground hydrogen storage gone through a legalization process.

2. Input parameters and main assumptions

In this section, the detailed insights on the development and operation of a salt cavern located in Spain are provided as the focus of the present study. The model takes into account the overall assumptions, which are described below.

The sizing of the hypothetical salt cavern was based on the MID case presented in D7.1 and D7.2. This consisted into 8 caverns with a free gas volume and working gas volume per cavern of 0,38 million m^3 and 31 million Sm^3 respectively, giving as a result an overall working gas volume of 250 million Sm^3. The business model developed for this study encompasses an 8-year investment phase (2022-2029) preceding the actual venture period from 2030 to 2059.

To facilitate future benchmarking of the cases in the next Task 8.3 of the project, specific business cases were elaborated for each selected EU Member State (i.e., Spain, France, Germany, Poland and Italy). Common reference baseline parameters were established for all the case studies: the objective was to create a common reference baseline for comparison purposes. The baseline scenario is characterized by a Net Present Value (NPV) of zero (NPV=0), which was achieved by adjusting the storage margin profit (%) applied to the H_2 storage cost, which was initially assumed to be equal to the levelized cost of storage (LCOS). Table 1 and Table 2 present the technical, economic, and financial parameters set for the Italian case. The parameters that are common to the business cases of other Member States are marked in light blue.

Table 1 – Technical parameters for the sizing of underground storage facilities in Spain

Parameters	Description	Units	Value
	Geology and subsurface facilities		
V_{cavern}	Free gas volume per cavern	[millions m^3]	0,38
V_{max}	Working Gas volume per cavern	[millions Sm^3]	31
n_{WH}	Number of caverns (assumption: one well head per cavern)	[nr.]	8
—	H_2 yearly throughput	[kg/yr.]	31.094.672
LCCS	Last cemented casing shoe	[m]	1000
DC_i	Drilling complexity index	[-]	1
L_{fw}	Fresh water pipeline length	[km]	15
L_{bd}	Brine disposal pipeline length	[km]	30
x_{Salt}	Cushion gas / Total gas ratio	[-]	0,43
V_{wg}	Working Gas volume	[millions Sm^3]	250
V_{wg}/Q_w	Storage to withdrawal capacity ratio	[days]	57
$Q_{debrining}$	Debrining flowrate per cavern	[m^3/h]	200
$d_{full\ cycle}$	Duration of one full storage of the cycle	[days]	114
N_{fc}	Number of full cycles per year	[cycle/yr.]	1,4
$N_{fc,\ MAX}$	Maximum number of full cycles per year	[cycle/yr.]	3,2
$d_{T,L}$	Leaching duration	[year]	4,5
$d_{T,C}$	Debrining duration	[year]	1,1
LF	Load Factor	[-]	0,44
	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
τ	Overall compression ratio (ratio of discharging pressure over suction pressure)	[-]	3,23
n	Number of required compression stages	[nr.]	2
WTIR	Withdrawal to injection capacity ratio	[-]	1
netOP	Minimum suction pressure of compression stream (pipeline operating pressure)	[barg]	55
MOP	Maximum storage operating pressure	[barg]	180
minOP	Minimum storage operating pressure	[barg]	70
L_{fl}	Field lines size	[km]	2
K_{purif}	Purification coefficient (Only for porous media)	[-]	0
COE	Cost of Electricity [€/MWh]	[€/MWh]	40

Table 2 – Economic and financial parameters adopted for the business case

Parameters	Units	Value
H_2 production cost	[€/kg]	6,29 [9]
H_2 cushion gas	[€/kg]	6,29 (same as H_2 prod. cost by assumption)
Other costs	[€/kg]	1,89 (30% of hydrogen prod. cost by assumption)
Subsidy	[€]	20.000.000,00
Venture period	[years]	30
Residual value	[%]	20
Storage cost	[€/kg]	2,13
Corporate tax	[%]	25
Financing fund	[€]	0
Interests	[%]	5
Financing duration	[years]	30
Rate of return (Discount rate)	[%]	5,75
Storage service margin profit	[%]	13,49

Additionally, Table 3 presents the parameters of the underground storage sizing model that have been identified as sensitive in the analysis. These parameters have undergone a detailed examination of their impact on the economic aspects of the case scenario. This was accomplished by a thorough sensitivity analysis.

Table 3 – Sensitive parameters considered for the business case analysis.

Sensitive parameters	
A	Cost of Electricity
B	Storage Service Margin Profit
C	Number of Cycles
D	Corporate Tax
E	Number of Depleted Wells
F	Discount Rate

Finally, the energy model utilized for the Spanish case is described as scenario "D" in the report "*D5.1 -Scenario definition for modelling of the European energy system*":

- **Scenario D** is characterized by considering all underground storage methodologies (salt caverns, depleted wells, aquifers, and widely installed surface storage facilities in Europe). It also considers a higher amount of hydrogen imports and a lower amount of hydrogen production than the other estimated cases.

The main criteria considered to design these scenarios were the different hydrogen production routes, available hydrogen storage technologies and geographical locations across Europe. Figure 6 shows a summary of the different cases considered in a summarized and comparative way.

	Scenario A	Scenario B	Scenario C	Scenario D
General assumptions				
GHG emission reduction targets (for EU-27 from 1990 levels)	(2025: -37.5%) | 2030: -55% | 2040: -78.5% | 2050: -100%			
Hydrogen demand	**Identical for all scenarios** to ensure comparability			
Scenario differentiation				
Hydrogen production pathways: Domestic vs. imports from non-EU v	**Mainly domestic,** limited imports	**Mainly domestic,** limited imports	Moderate domestic, **larger imports**	Moderate domestic **larger imports**
Hydrogen storage technologies: Salt caverns, porous media and aboveground technologies	**Salt caverns,** aboveground technologies	**Salt caverns, porous media,** aboveground technologies	**Salt caverns,** aboveground technologies	**Salt caverns, porous media,** aboveground technologies
Spatial distribution across Europe: Centralized/distributed H_2 production and storage	**Centralized storage** (where possible), distributed H_2 production	**Distributed** H_2 production and storage	**Centralized storage** (hubs in central Europe), distributed H_2 production	**Distributed** H_2 production and storage

Figure 6 - Selected scenarios for modelling od the European energy system.

3. Results

Within this section, a comprehensive business case for a salt cavern in Spain is provided. It includes a detailed description of the site costs breakdown and a sensitivity analysis, all with the objective of optimizing the economic feasibility of the business venture.

3.1. Site costs breakdown

Table 4 provides a detailed breakdown of all the expenditures associated with subsurface operations. Among these, the cost for cushion gas was found to be the most significant, amounting to 100.994.447 €. It was followed by EPC costs for leaching facilities (97.600.000 €), leaching operation and maintenance costs (85.758.000 €), contingencies (72.974.523 €), development drilling and leaching completion costs (44.712.000 €) and salt cavern debrining and conversion costs (35.808.169 €) in descending order. The total CAPEX for subsurface operations, obtained by summing up the specific costs mentioned above, amounted to 437.847.140 €.

Figure 7 illustrates the economic relevance of each specific cost related to the subsurface, expressed as a percentage of the overall subsurface CAPEX. As per the distribution of costs, cushion gas represented the highest share at 23%, followed by leaching facilities cost at 22%, and leaching operation and maintenance costs at 20%.

Table 4 - Overall CAPEX breakdown for subsurface operations

CAPEX – subsurface		
Costs breakdown	Description	Value
EPC_1	EPC cost main parameters and cost breakdown for Leaching facilities	97.600.000 €
EPC_2	Leaching operation and maintenance costs	85.758.000 €
EPC_3	Salt cavern debrining and conversion costs	35.808.169 €
EPC_4	Development Drilling and leaching completion costs	44.712.000 €
CG	Cushion gas for salt caverns	100.994.447 €
$CONT_{subsurface}$	Contingencies related to subsurface	72.974.523 €
Total		**437.847.140 €**

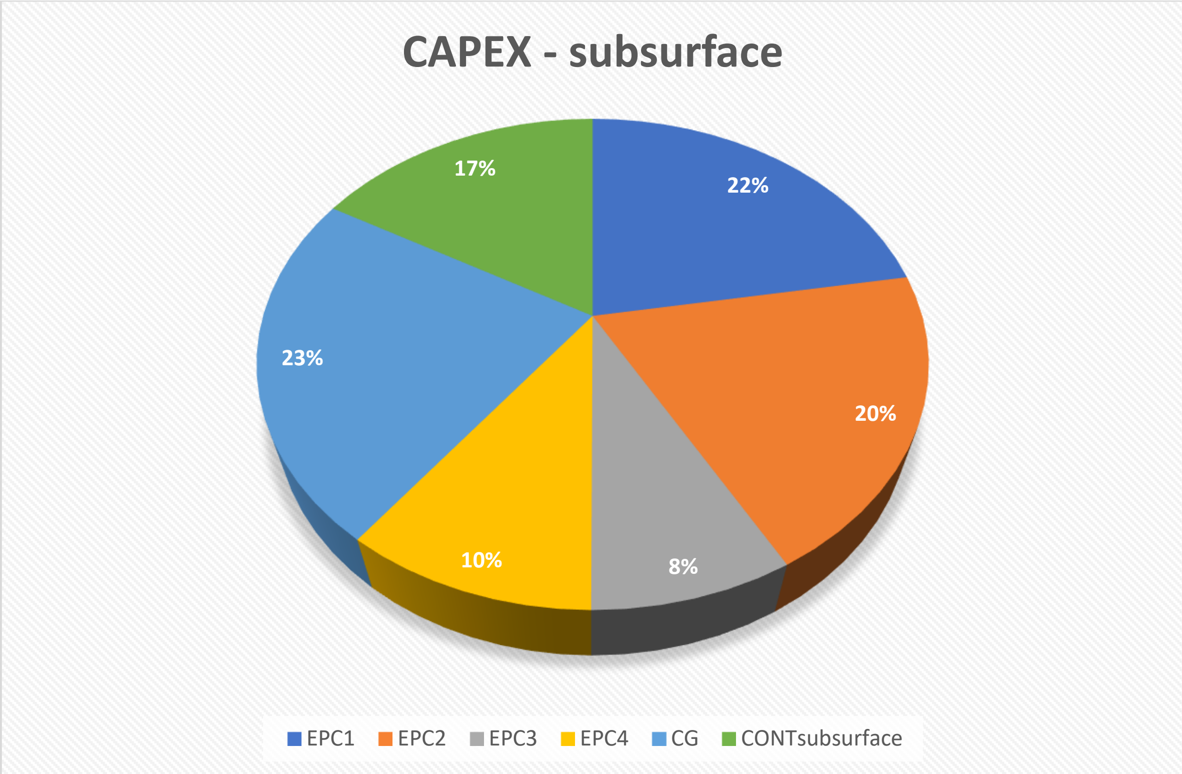

Figure 7 - Percent distribution of CAPEX – subsurface costs.

Table 5 presents the breakdown of CAPEX for surface facilities and operations. Among these costs, filtering, drying, compression and metering units stood out as the largest expenditures, amounting to 136.869.008 € out of a total of 224.270.132 €. This corresponded to the highest share among all the surface-specific costs analysed, accounting for 61% (see Figure 8).

The second most expensive expenditure was for contingencies, totalling 37.378.355 €. This was followed by the costs of wellhead-gas plant interconnections (28.121.848 €), balance of plant costs (16.518.656 €), and additional cost per kilometre between the reservoir wellhead and the gas plant (5.382.263 €).

Table 5 - Overall CAPEX breakdown for surface facilities and operations.

CAPEX – surface		
Costs breakdown	Description	Value
EPC_1	EPC cost main parameters and breakdown for filtering, drying & compression, and metering units	136.869.008 €
EPC_2	EPC costs for interconnection WH - Gas Plant	28.121.848 €
EPC_3	EPC cost per additional kilometer between Gas Plant and nearest WH	5.382.263 €
EPC_4	EPC cost estimate for hydrogen purification at storage outlet	- €
EPC_5	EPC cost main parameters and cost breakdown for Balance of Plant	16.518.656 €
$CONT_{surface}$	Contingencies related to surface facilities	37.378.355 €
Total		**224.270.132 €**

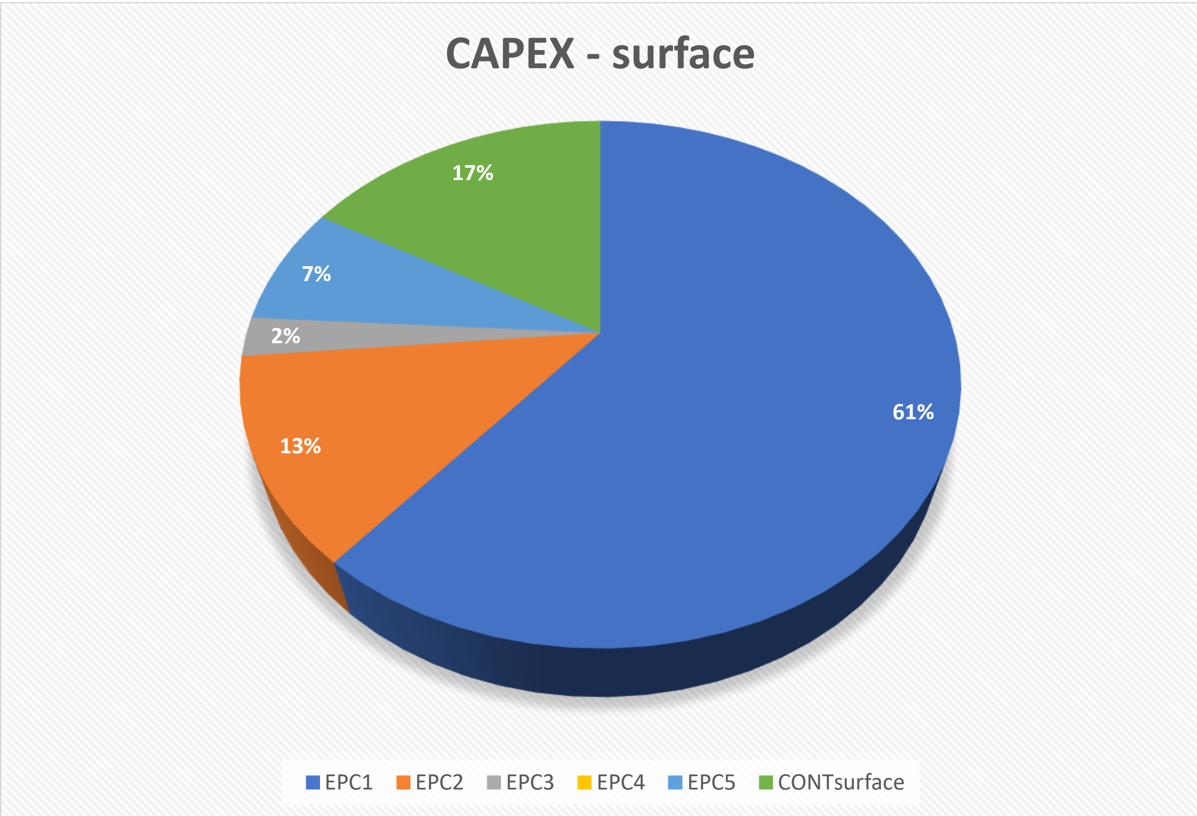

Figure 8 – Percent distribution of CAPEX – surface costs.

Considering the main assumption of a constant yearly OPEX throughout the entire site operation period, the total global expenditure amounted to 12.405.069 €. This includes costs for subsurface operations (1.341.360 €), as well as fixed costs (9.575.671 €) and variable costs

(1.488.038 €) associated with surface operations. The distribution of each individual cost is depicted in Figure 9.

Table 6 – Overall OPEX breakdown for subsurface and surface (fixed and variable) operations.

	OPEX	
Costs breakdown	Description	Value
$OPEX_{fix, UG}$	OPEX - Subsurface	1.341.360 €
$OPEX_{fix, AG}$	Fixed OPEX - Surface	9.575.671 €
$OPEX_{var, AG}$	Variable OPEX - Surface	1.488.038 €
Total		**12.405.069 €**

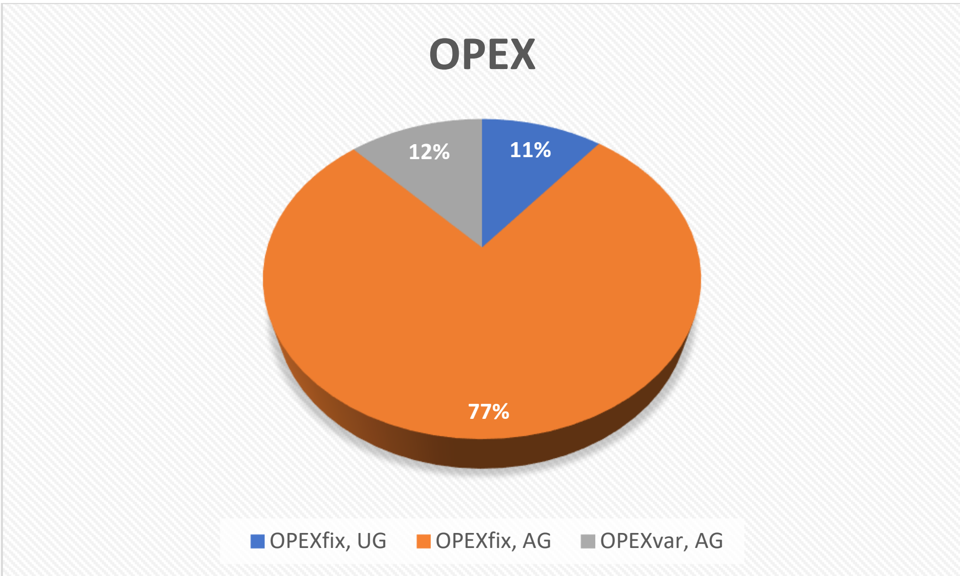

Figure 9 – Percent distribution of OPEX costs.

Finally, the ABEX for facilities and equipment totalled 112.224.565 €, divided between 67.370.538 € for the abandonment expenditure for subsurface (which represents 60% of the overall ABEX, as shown in Figure 10), and 44.854.026 € for the abandonment expenditure for surface facilities (which accounts for 40% of the overall ABEX, as depicted in Figure 10).

Table 7 – Overall ABEX breakdown for subsurface and surface facilities.

	ABEX	
Costs breakdown	Description	Value
$ABEX_{subsurface}$	Abandonment Expenditure for subsurface	67.370.538 €
$ABEX_{surface}$	Abandonment Expenditure for surface facilities	44.854.026 €
Total		**112.224.565 €**

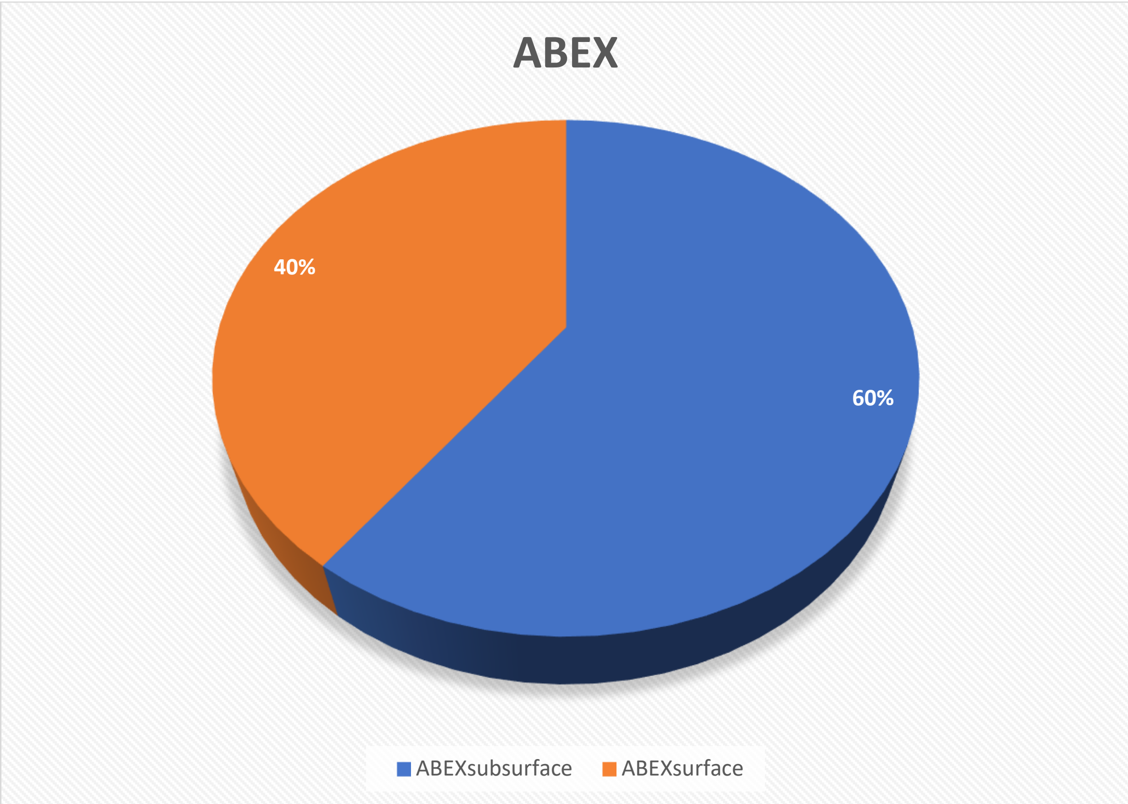

Figure 10 – Percent distribution of ABEX costs.

3.2. Cash flow analysis

To evaluate the economic feasibility of geological storage of H_2 in the salt cavern, several financial Key Performance Indicators (KPIs) were identified and considered, as shown in Table 8. These included Net Present Value (NPV), Internal Rate of Return (IRR), Net Present Cost (NPC), and Levelized Cost of Storage (LCOS), which were defined in D7.3 and D8.1.

It is important to note that the baseline scenario presented in this section establishes the economic break-even conditions for the investigated business case and served as starting point for the planned optimization study.

To achieve a null NPV in the baseline scenario, a storage service margin profit of 13,49% was applied to the LCOS, resulting in a H_2 storage service price of 2,42 €/kgH_2. Considering this, the assumed H_2 production cost of 6,29 €/kgH_2, and other costs of 1,89 €/kgH_2, the minimum selling price of hydrogen would be 12,19 €/kgH_2. The IRR was equal to the chosen discount rate for the case, which is 5.75%, while the NPC amounted to 599.792.798 €. The LCOS results are predicated on a series of assumptions; as such, the LCOS estimates are cycle-specific and may differ in alternative case studies where the number of cycles is optimized. In a broader context, LCOS exhibits a highly case-specific nature, as factors such as asset reutilization and meticulous site selection have the potential to substantially reduce costs, thereby altering the project's economic dynamics.

Table 8 – Financial KPIs of the business case.

	Finance	
Parameter	Description	Value
NPV	Net Present Value	0 €
IRR	Internal Rate of Return	5,75%
NPC	Net Present Cost	599.792.798 €
LCOS	Levelized Cost of Storage	2,13 €/kgH_2
—	Storage service margin profit	13,49%
—	H_2 storage service price	2,42 €/kgH_2

Examining the trend depicted in Figure 11, from 2022 to 2028, the cumulative net cash flow remained consistently negative, ranging from –65.387.200 € to –365.819.066 €. In 2029, it reached a negative peak of –642.117.272 €, assuming no revenues during the investment period. However, starting from 2030 (the beginning of the venture period), the net cash flow became less negative and gradually improved. It continued to increase each year, indicating a positive trend. The values rose from –74.799.143 € in 2040 to 925.312.878 € in 2059.

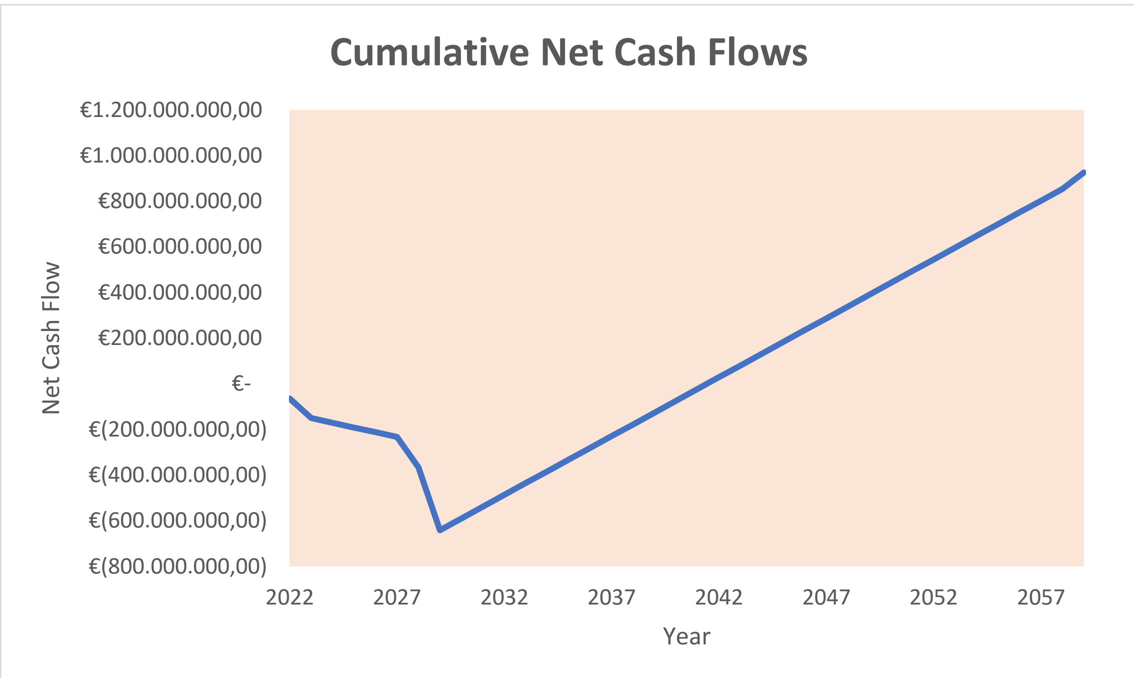

Figure 11. Net Cash Flow trend along the investment years and the venture period.

3.3. Business case optimization

To assess the impact of the sensitive parameters listed in Table 3 (cost of electricity, storage service margin profit, number of cycles, corporate tax, number of wells, discount rate) on the chosen response variables (NPV, IRR, NPC, and LCOS), an unreplicated 2-level full factorial design with a centre point [10] was employed. This design also considered the potential interaction effects among the parameters, if any. Table 9 presents the selected value ranges for the sensitive parameters. Using this design, a comprehensive set of 65 scenarios was generated and thoroughly analysed. The regression model structure utilized during statistical analysis for the response variables, involving normalized values for factors ranging from -1 to 1 with 0 as the centre point of the factorial design, is as follows:

$$\hat{y} = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 D + \beta_5 E + \beta_6 F + \beta_{12} A \cdot B + \beta_{13} A \cdot C + \beta_{14} A \cdot D + \beta_{15} A \cdot E + \beta_{16} A \cdot F + \beta_{23} B \cdot C + \beta_{24} B \cdot D + \beta_{25} B \cdot E + \beta_{26} B \cdot F + \beta_{34} C \cdot D + \beta_{35} C \cdot E + \beta_{36} C \cdot F + \beta_{45} D \cdot E + \beta_{46} D \cdot F + \beta_{56} E \cdot F$$

where A, B, C, D, E and F are the response variables (see Table3), while β_0, β_i and β_{ij} are the intercept, linear, and 2-way interaction coefficients, respectively. All the statistical calculations were conducted using Minitab software (v17). The estimated regression coefficients and the adjusted coefficients of determination (R^2_{adj}) were taken as indicators of the goodness of regression models. This section covers the results obtained from the optimization of the business case studied here. The numerical results of the different scenarios generated are reported in Table 10.

Table 9 – Ranges of values selected for the sensitive parameters.

Parameter	–1	0	1
Cost of Electricity	20 €/MWh	40 €/MWh	60 €/MWh
Storage Service Margin Profit	5,75%	32,87%	60%
Number of Cycles	0,4	1,4	2,4
Corporate Tax	12,5%	25%	37,5%
Number of Caverns	1	8	15
Discount Rate	2,8%	5,75%	8,6%

Table 10 – Case scenarios obtained through the optimization study. The scenarios with a positive NPV are marked in bold.

Electricity	Storage profitability	Number of cycles	Corporate tax	Number of caverns	Discount rate	NPV (€)	IRR (%)	NPC (€)	LCOS (€/kgH_2)	CAPEX - subsurface (€)	CAPEX - surface (€)	OPEX (€)	ABEX (€)
20 €/MWh	**60%**	**0,4**	**12,5%**	**15**	**2,8%**	**543.544.071 €**	**6,31%**	**1.074.469.697 €**	**4,00 €**	**744.920.086 €**	**255.274.470 €**	**13.522.780 €**	**162.165.993 €**
20 €/MWh	**5,75%**	**0,4**	**12,5%**	**15**	**2,8%**	**33.506.736 €**	**3,05%**	**1.074.469.697 €**	**4,00 €**	**744.920.086 €**	**255.274.470 €**	**13.522.780 €**	**162.165.993 €**
20 €/MWh	**5,75%**	**2,4**	**12,5%**	**1**	**8,6%**	**10.279.838 €**	**9,01%**	**279.025.469 €**	**7,61 €**	**160.549.128 €**	**193.265.794 €**	**8.869.295 €**	**68.238.123 €**
20 €/MWh	**60%**	**2,4**	**37,5%**	**15**	**8,6%**	**149.812.363 €**	**10,17%**	**974.434.500 €**	**1,77 €**	**744.920.086 €**	**599.851.607 €**	**27.001.593 €**	**231.081.421 €**
20 €/MWh	5,75%	2,4	37,5%	15	2,8%	-120.071.807 €	2,06%	1.572.017.924 €	0,98 €	744.920.086 €	599.851.607 €	27.001.593 €	231.081.421 €
60 €/MWh	**60%**	**0,4**	**37,5%**	**1**	**8,6%**	**56.130.061 €**	**10,71%**	**278.516.710 €**	**45,57 €**	**160.549.128 €**	**193.168.919 €**	**8.786.350 €**	**68.218.748 €**
20 €/MWh	**60%**	**0,4**	**12,5%**	**1**	**2,8%**	**235.081.029 €**	**7,13%**	**445.291.090 €**	**24,86 €**	**160.549.128 €**	**193.168.919 €**	**8.733.206 €**	**68.218.748 €**
60 €/MWh	**60%**	**2,4**	**12,5%**	**1**	**2,8%**	**238.906.219 €**	**7,19%**	**452.577.167 €**	**4,21 €**	**160.549.128 €**	**193.168.919 €**	**9.184.932 €**	**68.218.748 €**
20 €/MWh	**60%**	**0,4**	**37,5%**	**1**	**2,8%**	**130.215.082 €**	**5,40%**	**445.291.090 €**	**24,86 €**	**160.549.128 €**	**193.168.919 €**	**8.733.206 €**	**68.218.748 €**
60 €/MWh	5,75%	2,4	37,5%	15	2,8%	-117.299.348 €	2,08%	1.649.164.617 €	1,02 €	744.920.086 €	599.851.607 €	31.784.574 €	231.081.421 €
60 €/MWh	**60%**	**2,4**	**12,5%**	**1**	**8,6%**	**143.619.145 €**	**13,50%**	**280.710.525 €**	**7,65 €**	**160.549.128 €**	**193.168.919 €**	**9.184.932 €**	**68.218.748 €**
60 €/MWh	**60%**	**0,4**	**37,5%**	**15**	**8,6%**	**104.657.771 €**	**9,97%**	**718.802.627 €**	**7,84 €**	**744.920.086 €**	**255.163.786 €**	**14.316.254 €**	**162.143.857 €**
20 €/MWh	5,75%	0,4	37,5%	15	2,8%	-88.466.654 €	2,10%	1.074.320.203 €	4,00 €	744.920.086 €	255.163.786 €	13.519.091 €	162.143.857 €
20 €/MWh	**60%**	**0,4**	**12,5%**	**1**	**8,6%**	**142.313.825 €**	**13,47%**	**278.224.202 €**	**45,52 €**	**160.549.128 €**	**193.168.919 €**	**8.733.206 €**	**68.218.748 €**
60 €/MWh	5,75%	2,4	37,5%	1	2,8%	-20.504.584 €	2,32%	452.577.167 €	4,21 €	160.549.128 €	193.168.919 €	9.184.932 €	68.218.748 €
20 €/MWh	5,75%	2,4	37,5%	1	2,8%	-20.689.415 €	2,32%	447.434.054 €	4,16 €	160.549.128 €	193.168.919 €	8.866.066 €	68.218.748 €
20 €/MWh	**60%**	**2,4**	**12,5%**	**15**	**2,8%**	**788.265.133 €**	**6,72%**	**1.572.017.924 €**	**0,98 €**	**744.920.086 €**	**599.851.607 €**	**27.001.593 €**	**231.081.421 €**
20 €/MWh	**60%**	**2,4**	**12,5%**	**1**	**2,8%**	**236.206.085 €**	**7,15%**	**447.434.054 €**	**4,16 €**	**160.549.128 €**	**193.168.919 €**	**8.866.066 €**	**68.218.748 €**
20 €/MWh	**60%**	**2,4**	**37,5%**	**1**	**2,8%**	**131.018.693 €**	**5,41%**	**447.434.054 €**	**4,16 €**	**160.549.128 €**	**193.168.919 €**	**8.866.066 €**	**68.218.748 €**
60 €/MWh	**60%**	**0,4**	**37,5%**	**15**	**2,8%**	**280.616.707 €**	**4,75%**	**1.087.177.985 €**	**4,05 €**	**744.920.086 €**	**255.163.786 €**	**14.316.254 €**	**162.143.857 €**
20 €/MWh	5,75%	0,4	37,5%	1	2,8%	-20.766.428 €	2,32%	445.291.090 €	24,86 €	160.549.128 €	193.168.919 €	8.733.206 €	68.218.748 €
60 €/MWh	**5,75%**	**0,4**	**12,5%**	**15**	**2,8%**	**34.151.419 €**	**3,06%**	**1.087.177.985 €**	**4,05 €**	**744.920.086 €**	**255.163.786 €**	**14.316.254 €**	**162.143.857 €**
20 €/MWh	5,75%	0,4	37,5%	1	8,6%	-38.315.022 €	6,95%	278.224.202 €	45,52 €	160.549.128 €	193.168.919 €	8.733.206 €	68.218.748 €

60 €/MWh	5,75%	0,4	37,5%	1	2,8%	-20.735.623 €	2,32%	446.148.275 €	24,91 €	160.549.128 €	193.168.919 €	8.786.350 €	68.218.748 €
60 €/MWh	5,75%	0,4	12,5%	1	2,8%	23.750.041 €	3,32%	446.148.275 €	24,91 €	160.549.128 €	193.168.919 €	8.786.350 €	68.218.748 €
60 €/MWh	5,75%	2,4	12,5%	15	2,8%	45.929.317 €	3,07%	1.649.164.617 €	1,02 €	744.920.086 €	599.851.607 €	31.784.574 €	231.081.421 €
60 €/MWh	60%	2,4	12,5%	15	2,8%	828.767.146 €	6,89%	1.649.164.617 €	1,02 €	744.920.086 €	599.851.607 €	31.784.574 €	231.081.421 €
20 €/MWh	5,75%	2,4	37,5%	15	8,6%	-180.581.834 €	6,46%	974.434.500 €	1,77 €	744.920.086 €	599.851.607 €	27.001.593 €	231.081.421 €
60 €/MWh	60%	2,4	12,5%	15	8,6%	466.908.016 €	13,09%	1.000.760.279 €	1,82 €	744.920.086 €	599.851.607 €	31.784.574 €	231.081.421 €
20 €/MWh	60%	0,4	37,5%	15	2,8%	275.795.039 €	4,72%	1.074.320.203 €	4,00 €	744.920.086 €	255.163.786 €	13.519.091 €	162.143.857 €
60 €/MWh	60%	0,4	37,5%	1	2,8%	130.536.526 €	5,40%	446.148.275 €	24,91 €	160.549.128 €	193.168.919 €	8.786.350 €	68.218.748 €
60 €/MWh	60%	0,4	12,5%	1	8,6%	142.467.392 €	13,47%	278.516.710 €	45,57 €	160.549.128 €	193.168.919 €	8.786.350 €	68.218.748 €
20 €/MWh	60%	0,4	37,5%	15	8,6%	103.012.410 €	9,95%	714.414.997 €	7,79 €	744.920.086 €	255.163.786 €	13.519.091 €	162.143.857 €
60 €/MWh	5,75%	2,4	12,5%	1	8,6%	10.369.368 €	9,01%	280.710.525 €	7,65 €	160.549.128 €	193.168.919 €	9.184.932 €	68.218.748 €
60 €/MWh	5,75%	0,4	37,5%	15	8,6%	-139.061.244 €	6,54%	718.802.627 €	7,84 €	744.920.086 €	255.163.786 €	14.316.254 €	162.143.857 €
60 €/MWh	60%	2,4	37,5%	15	2,8%	441.870.530 €	5,15%	1.649.164.617 €	1,02 €	744.920.086 €	599.851.607 €	31.784.574 €	231.081.421 €
20 €/MWh	5,75%	0,4	37,5%	15	8,6%	-139.218.924 €	6,54%	714.414.997 €	7,79 €	744.920.086 €	255.163.786 €	13.519.091 €	162.143.857 €
20 €/MWh	5,75%	0,4	12,5%	1	8,6%	10.244.274 €	9,01%	278.224.202 €	45,52 €	160.549.128 €	193.168.919 €	8.733.206 €	68.218.748 €
60 €/MWh	60%	0,4	12,5%	1	2,8%	235.531.051 €	7,14%	446.148.275 €	24,91 €	160.549.128 €	193.168.919 €	8.786.350 €	68.218.748 €
60 €/MWh	60%	2,4	37,5%	1	2,8%	132.947.360 €	5,45%	452.577.167 €	4,21 €	160.549.128 €	193.168.919 €	9.184.932 €	68.218.748 €
20 €/MWh	60%	0,4	12,5%	15	8,6%	333.479.197 €	12,59%	714.414.997 €	7,79 €	744.920.086 €	255.163.786 €	13.519.091 €	162.143.857 €
60 €/MWh	60%	0,4	12,5%	15	8,6%	335.782.702 €	12,62%	718.802.627 €	7,84 €	744.920.086 €	255.163.786 €	14.316.254 €	162.143.857 €
20 €/MWh	5,75%	2,4	12,5%	15	8,6%	-9.464.894 €	8,50%	974.434.500 €	1,77 €	744.920.086 €	599.851.607 €	27.001.593 €	231.081.421 €
60 €/MWh	5,75%	2,4	37,5%	15	8,6%	-179.635.752 €	6,47%	1.000.760.279 €	1,82 €	744.920.086 €	599.851.607 €	31.784.574 €	231.081.421 €
20 €/MWh	5,75%	2,4	12,5%	1	2,8%	23.814.732 €	3,33%	447.434.054 €	4,16 €	160.549.128 €	193.168.919 €	8.866.066 €	68.218.748 €
20 €/MWh	5,75%	0,4	12,5%	15	8,6%	-5.644.671 €	8,52%	714.414.997 €	7,79 €	744.920.086 €	255.163.786 €	13.519.091 €	162.143.857 €
60 €/MWh	60%	0,4	12,5%	15	2,8%	562.475.085 €	6,14%	1.106.327.642 €	3,95 €	744.920.086 €	255.163.786 €	14.316.254 €	162.143.857 €
60 €/MWh	5,75%	0,4	37,5%	1	8,6%	-38.304.510 €	6,95%	278.516.710, €	45,57 €	160.549.128 €	193.168.919 €	8.786.350 €	68.218.748 €
20 €/MWh	5,75%	0,4	12,5%	1	2,8%	23.706.914 €	3,32%	445.291.090 €	24,86 €	160.549.128 €	193.168.919 €	8.733.206 €	68.218.748 €
20 €/MWh	60%	2,4	37,5%	15	2,8%	412.940.520 €	5,01%	1.572.017.924 €	0,98 €	744.920.086 €	599.851.607 €	27.001.593 €	231.081.421 €
60 €/MWh	60%	2,4	37,5%	15	8,6%	159.684.530 €	10,27%	1.000.760.279 €	1,82 €	744.920.086 €	599.851.607 €	31.784.574 €	231.081.421 €

20 €/MWh	60%	2,4	37,5%	1	8,6%	56.294.597 €	10,71%	278.955.473,63 €	7,61 €	160.549.128 €	193.168.919 €	8.866.066 €	68.218.748 €
60 €/MWh	5,75%	2,4	37,5%	1	8,6%	-38.225.670 €	6,96%	280.710.525,55 €	7,65 €	160.549.128 €	193.168.919 €	9.184.932 €	68.218.748 €
60 €/MWh	5,75%	0,4	12,5%	1	8,6%	10.258.991 €	9,01%	278.516.710,65 €	45,57 €	160.549.128 €	193.168.919 €	8.786.350 €	68.218.748 €
60 €/MWh	5,75%	2,4	12,5%	1	2,8%	24.073.495 €	3,33%	452.577.167,01 €	4,21 €	160.549.128 €	193.168.919 €	9.184.932 €	68.218.748 €
60 €/MWh	5,75%	0,4	37,5%	15	2,8%	-88.004.578 €	2,10%	1.087.177.985,54 €	4,05 €	744.920.086 €	255.163.786 €	14.316.254 €	162.143.857 €
20 €/MWh	60%	2,4	12,5%	1	8,6%	142.697.743 €	13,48%	278.955.473,63 €	7,61 €	160.549.128 €	193.168.919 €	8.866.066 €	68.218.748 €
20 €/MWh	5,75%	2,4	37,5%	1	8,6%	-38.288.742 €	6,96%	278.955.473,63 €	7,61 €	160.549.128 €	193.168.919 €	8.866.066 €	68.218.748 €
20 €/MWh	5,75%	2,4	12,5%	15	2,8%	42.047.874 €	3,05%	1.572.017.924,91 €	0,98 €	744.920.086 €	599.851.607 €	27.001.593 €	231.081.421 €
40 €/MWh	32,87%	1,4	25%	8	5,75%	87.200.570 €	7,07%	599.693.259,34 €	2,13 €	437.847.140 €	224.166.353 €	12.401.610 €	112.203.809 €
60 €/MWh	60%	2,4	37,5%	1	8,6%	56.952.742 €	10,74%	280.710.525,55 €	7,65 €	160.549.128 €	193.168.919 €	9.184.932 €	68.218.748 €
60 €/MWh	5,75%	0,4	12,5%	15	8,6%	-5.423.919 €	8,53%	718.802.627,11 €	7,84 €	744.920.086 €	255.163.786 €	14.316.254 €	162.143.857 €
20 €/MWh	60%	2,4	12,5%	15	8,6%	453.086.983 €	12,97%	974.434.500,95 €	1,77 €	744.920.086 €	599.851.607 €	27.001.593 €	231.081.421 €
20 €/MWh	60%	0,4	37,5%	1	8,6%	56.020.371 €	10,70%	278.224.202,00 €	45,52 €	160.549.128 €	193.168.919 €	8.733.206 €	68.218.748 €
60 €/MWh	5,75%	2,4	12,5%	15	8,6%	466.908.016 €	13,09%	1.000.760.279,74 €	1,82 €	744.920.086 €	599.851.607 €	31.784.574 €	231.081.421 €
R^2_{adj}						*88,83%*	*97,43%*	*99,16%*	*97,73%*	–	–	–	–

Figure 12 illustrates the impact of the sensitive parameters on the NPV of the business case. The normal plot of standardized effects revealed that the storage service margin profit had the most significant influence on the NPV. It ranged from a minimum of –180.581.834 € to a maximum of 828.767.146 € across the various scenarios. Another noteworthy finding was the positive interaction between the storage margin profit and the number of caverns, which led to a higher NPV. This can be attributed to increased revenues resulting from a greater amount of stored H_2 in the geological site. Conversely, the NPV significantly decreased with an increase in the corporate tax. Additionally, higher discount rates had a negative impact on the NPV, aligning with the financial model adopted. As the discount rate increased, the economic feasibility of the business case became progressively more challenging. Overall, among the sensitive parameters considered, determining an appropriate margin profit for the storage service proved crucial in achieving a positive NPV for the business case.

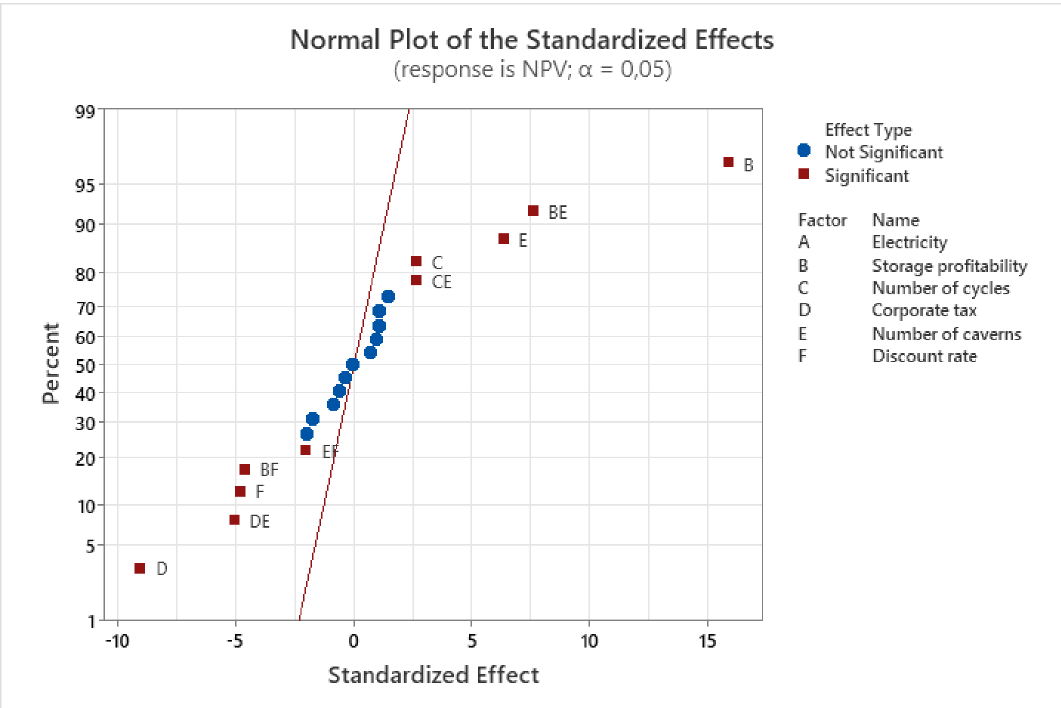

Figure 12 – Normal plot of standardized effects for NPV (square, significant effect; circle, non-significant effect).

As expected, the discount rate had a significant impact on the IRR, as increasing the discount rate resulted in higher values of the IRR. Additionally, both the storage service margin profit and corporate tax had noteworthy effects on the IRR. In detail, the storage service margin profit positively influenced the final IRR, while the corporate tax had a negative impact on it. Overall, the range of IRR values spanned from 2,06% to 13,48%.

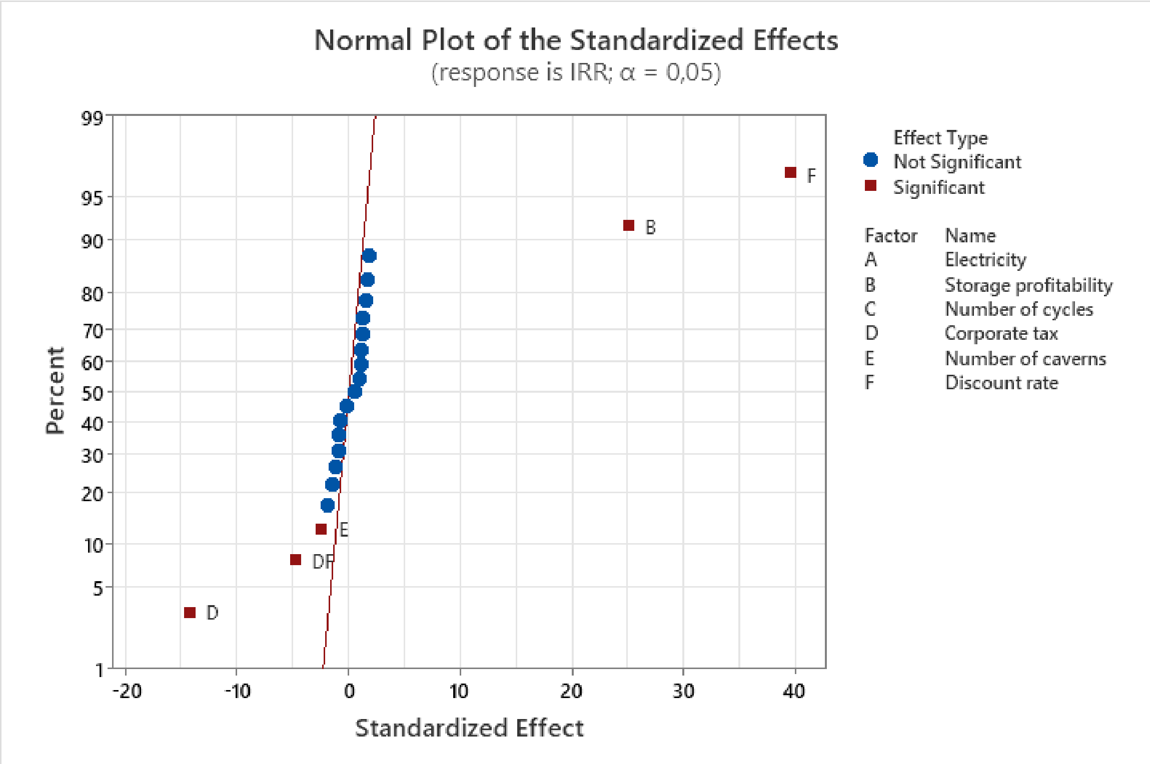

Figure 13 – Normal plot of standardized effects for IRR (square, significant effect; circle, non-significant effect).

The number of caverns had a significant impact on the CAPEX of the geological site, resulting in a higher NPC (as shown in Figure 14). The number of cycles also contributed to an increase in the overall NPC of the facilities, while the discount rate had a reducing effect on the NPC. Specifically, the NPC for the Spanish business case ranged between 278.224.202 € and 1.649.164.617 €.

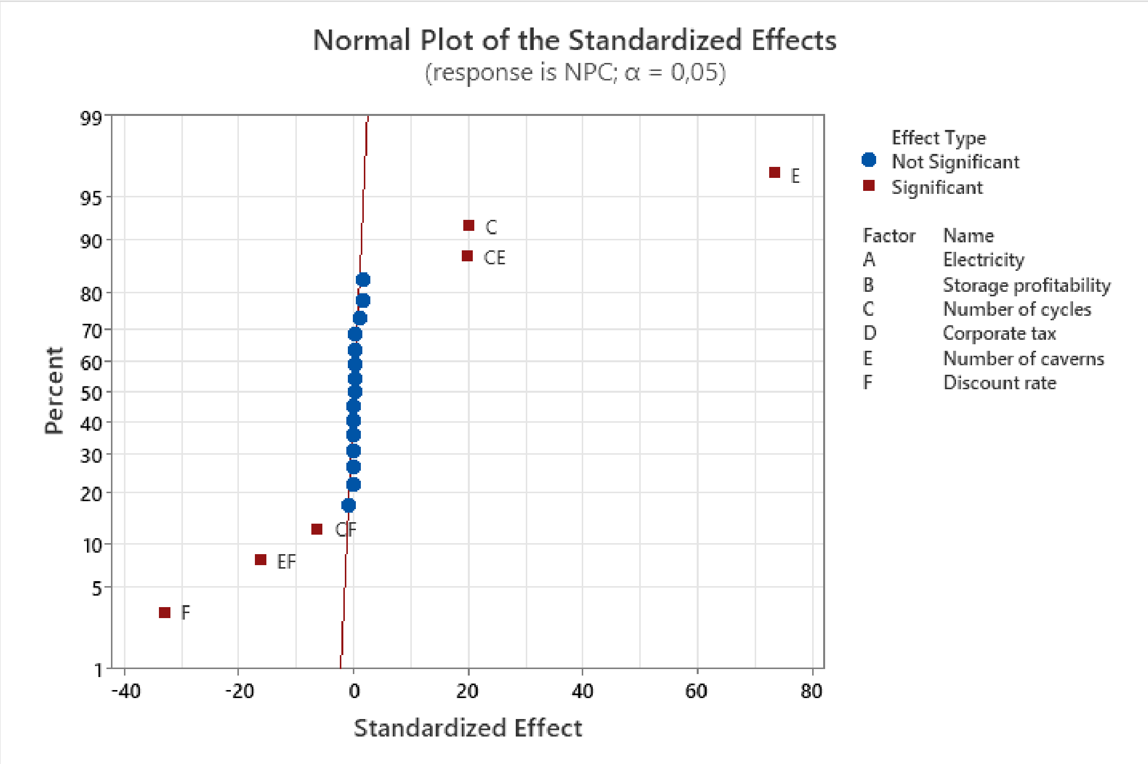

Figure 14 – Normal plot of standardized effects for NPC (square, significant effect; circle, non-significant effect).

Figure 15 displays the normal plot of standardized effects of the sensitive parameters on LCOS. LCOS was calculated as the ratio between NPC and the sum of the H_2 yearly throughputs discounted over the entire business period (investment phase + venture period). Higher discount rates resulted in higher LCOS, indicating increased costs per unit of H_2. Conversely, both the number of cycles and the number of caverns significantly reduced LCOS, as they led to larger H_2 throughputs processed per year, thereby decreasing the LCOS denominator. The optimization study revealed a wide range of LCOS values, ranging from 0,98 €/kgH_2 to 45.58 €/kgH_2. It is important to note that a case scenario with a positive NPV does not necessarily guarantee economic feasibility. Ensuring an appropriate LCOS is crucial for a profitable business case. From Table 10, it is evident that many scenarios had a positive NPV; however, they may not be viable in a real business case due to high LCOS that is incompatible with the upstream H_2 production cost.

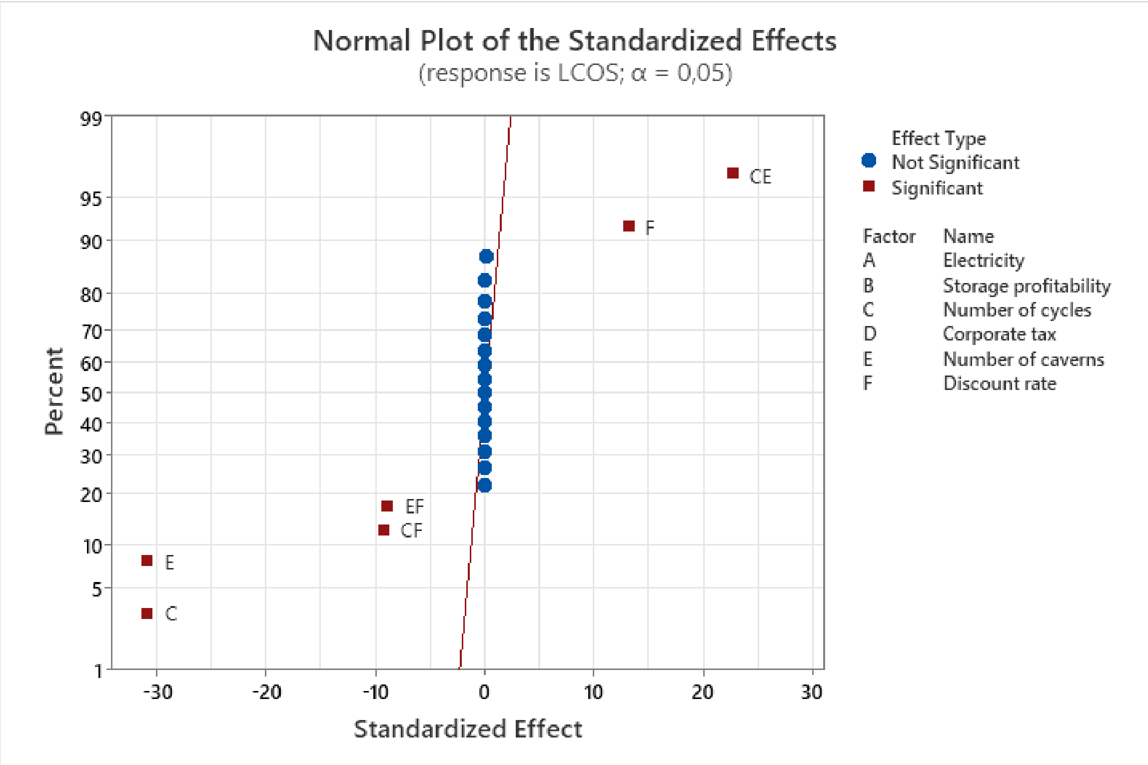

Figure 15 – Normal plot of standardized effects for LCOS (square, significant effect; circle, non-significant effect).

4. Conclusions

Despite the absence of a unique combination of sensitive parameters that renders the business case economically feasible, several insights can be derived from the aforementioned results:

- The Internal Rate of Return (IRR) was strongly impacted by the discount rate and the storage service margin profit, while higher corporate taxes had a negative effect on the IRR.
- A higher number of caverns resulted in an increased Net Present Cost (NPC) across the presented scenarios, peaking at 1.649.164.617 €.
- The Levelized Cost of Storage (LCOS) experienced a noticeable reduction through higher numbers of cycles and caverns, attributable to larger annual H_2 throughputs. Among the scenarios considered in this study, an LCOS of 0,98 €/kgH_2 was achieved, which stands out as remarkably low and highly appealing from an economic perspective.
- Ensuring a positive NPV alongside an appropriate LCOS, which, when combined with the H_2 production cost, yields a reasonable H_2 selling price, is crucial for achieving economic feasibility in a given scenario.

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