Case Study Poland

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Revision History

Revision	Revision date	Summary of changes
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1. Introduction

The last few years have brought many changes to the global energy market, both planned and forced, in response to socio-political events. One of the aspirations that began to emerge during these changes is an apparent increase in interest in energy independence, energy supply security, and electricity consumption optimization. All these aspects contributed to increasing the awareness of the role of energy storage in the energy market. It also applies to the Polish energy market.

Moreover, because of the increasing contribution of renewable energy to electricity production in Poland, the issue of underground hydrogen storage has become more and more actual. The results showed by Tarkowski (Tarkowski, 2017) confirm that there are favorable conditions in Poland, and the geological structure shows that many areas are suitable for locating practically any type of hydrogen underground storage facility. Good storage conditions for UHS could be found in bedded rock salt deposits, salt domes, deep aquifers, and depleted oil and natural gas fields.

Poland is one of the largest energy consumers in Europe after Germany, France, Italy, the UK, and Spain. This "big six" account for almost 70% of the European power and hydrogen demand (Michalski et al., 2021).

The document published by the Ministry of Climate and Environment (Ministry of Climate and Environment, 2021) indicates that the current demand for electricity in Poland is about 176 TWh, and the maximum power is 25.5 GW. As part of the same document, it was estimated that in 2030 the electricity demand will amount to 201.2 TWh, and the power demand will increase to 30.2 GW. More than 55% of electricity in 2030 will still come from coal-fired power plants and combined heat and power plants, about 10% from gas units, and about 32% from renewable energy sources (RES).

Poland's convenient location in the center of Europe can be very attractive economically due to the resulting benefits, which can be derived, for example, from transport between Eastern, North-Eastern, and Western Europe. Regarding H_2 gas flows, major infrastructure hubs are located in Poland to connect Baltic countries with Central Europe and Slovakia and Austria to allow for flows from Ukraine to other countries in the west (Michalski and Kutz, 2022) (Figure 1).

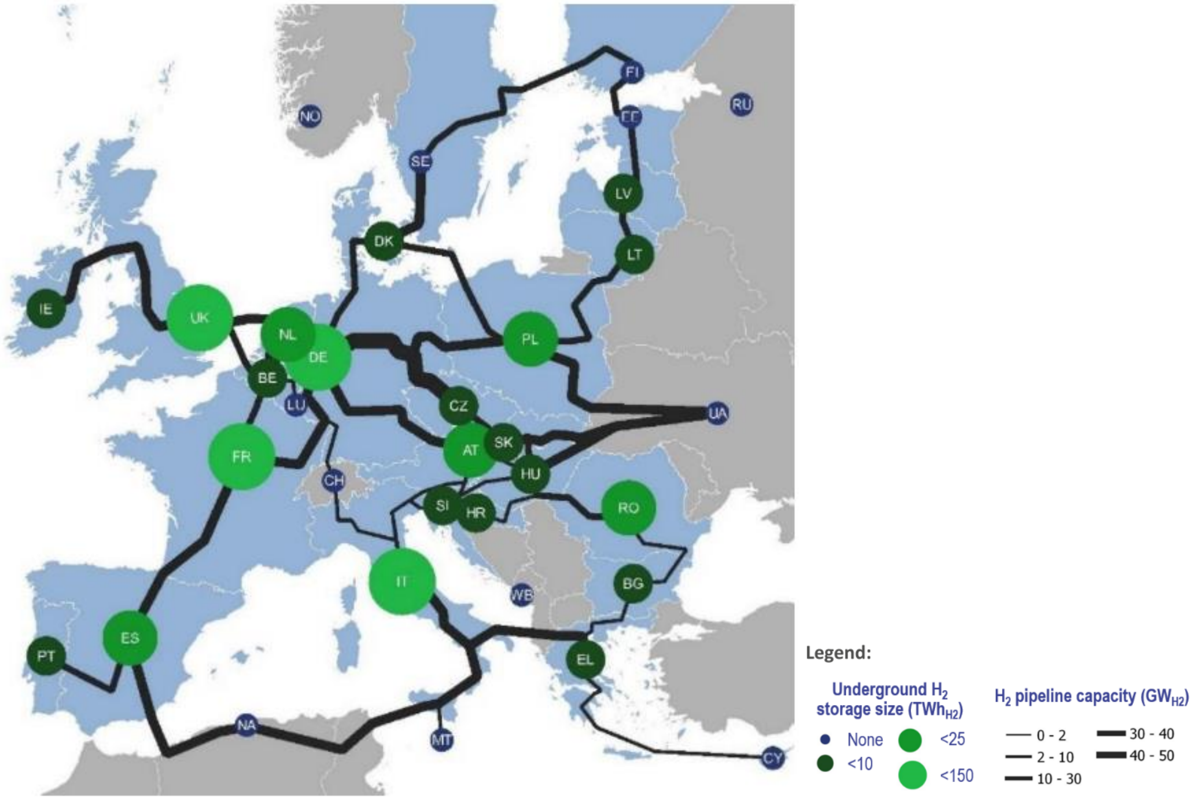

Figure 1: Development of hydrogen transport infrastructure and spatial distribution of underground H_2 storage volume capacity in Europe by 2050 (Scenario D in (Michalski and Kutz, (2022))

1.1. Storage market in Poland: an overview

As in many other EU jurisdictions, the exponentially growing number of RES investments is disrupting the power grid in Poland. One solution to this problem is the large-scale development of energy storage facilities. As experts point out, RES production variability must be balanced by energy storage facilities capable of quickly changing their mode of operation. The development of energy storage facilities will undoubtedly increase the share of renewable energy sources in the Polish energy mix while maintaining the stability and reliability of power system operation ('Energy storage trends - Spotlight on Poland', 2022).

The energy storage projects we encounter on the Polish market are of great diversity, ranging from battery storage facilities with relatively small total installed capacities, through contracts focusing on the joint development of specific technologies (hydrogen, ammonia) for commercial use, to large energy storage facilities within pumped storage power plants, which represent highly complex energy infrastructure ('Energy storage trends - Spotlight on Poland', 2022). There are seven natural gas storage facilities in Poland located throughout the country (Figure 2). Most are found in depleted hydrocarbon deposits, two in salt caverns leached in salt domes (Mogilno) and in a bedded salt deposit (Kosakowo). In addition, two UGS, Daszewo and Bonikowo, are used to stabilize the production of nitrogen-rich natural gas. At present, the working capacity of natural gas storage facilities is 3 327.72 million Nm^3 (PGNiG, 2023).

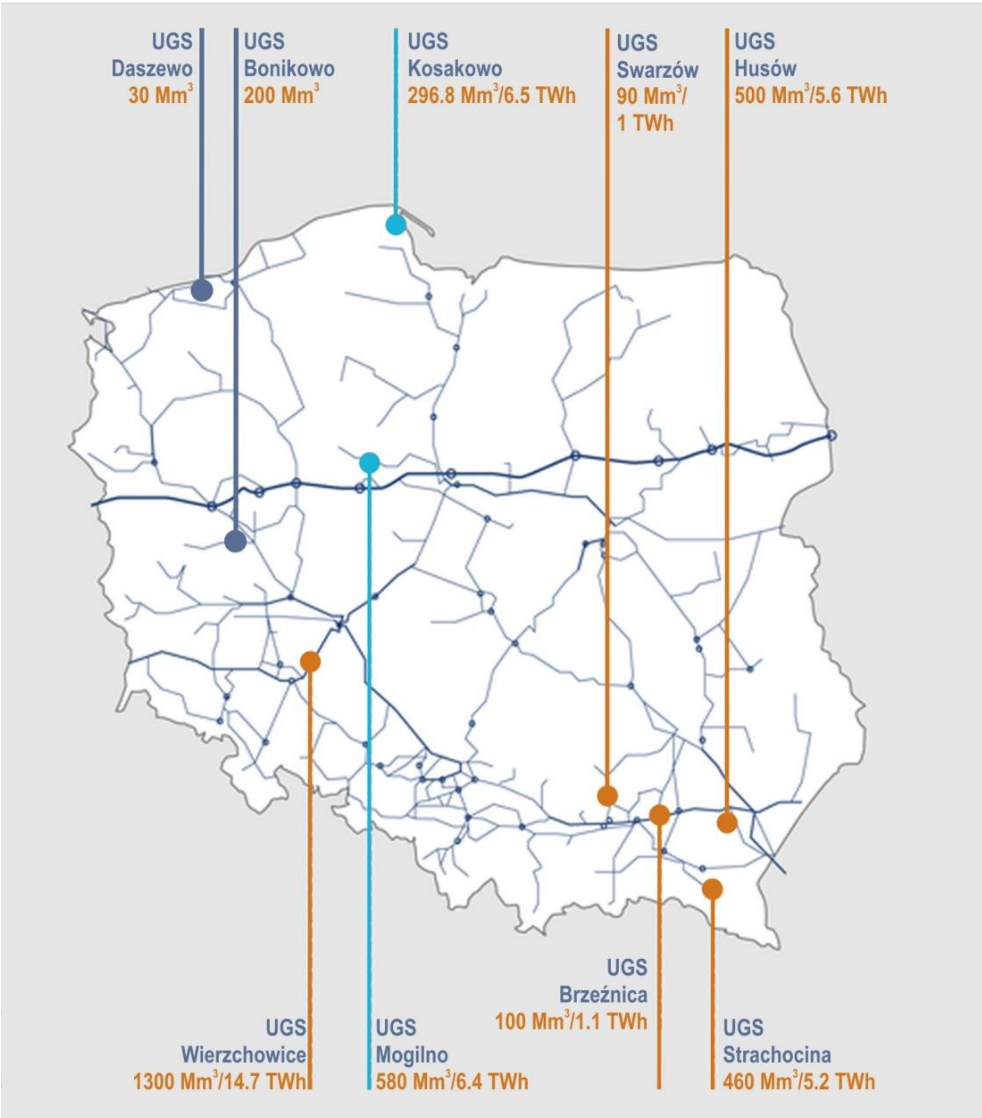

Figure 2. Underground high-methane natural gas storage facilities (UGS) in operation in Poland, connected to the natural gas pipeline network

Underground gas storages operate in two Groups of Storage Facilities (GSF), i.e.:

- GSF Sanok, including Husów, Swarzów, Brzeźnica and Strachocina UGSs,
- GSF Kawerna covering Mogilno and Kosakowo UGSs.

The largest UGS in the depleted Wierzchowice natural gas field is operating independently. The storage capacity of UGSs in salt caverns is 877.7 million m^3, corresponding to 9.8 TWh and their max. withdrawal capacity is 307.5 GWh/day. The storage capacity of the remaining five UGSs in depleted gas fields is 2450 million m^3, corresponding to 27.7 TWh and their max. withdrawal capacity is 287.4 GWh/day. The corresponding values for the total storage system in Poland are 3327.72 million m^3, 37.5 TWh, and 594.9 GWh/day. Table 1 shows the storage parameters for individual UGS.

Table 1. Storage parameters for individual natural gas storage facilities in Poland

Group of storage facilities	**Storage**	**Working volume**		**Max. injection capacity**		**Max. withdrawal capacity**	
		million m^3	GWh	million m^3 /day	GWh/day	million m^3 /day	GWh/day
GSF Kawerna	UGS Mogilno	580.9	6 471.4	9.60	106.9	18.00	200.5
	UGS Kosakowo	296.8	3 309.3	2.40	26.8	9.60	107.0
GSF Sanok	UGS Husów	500.0	5 650.0	4.15	46.7	5.76	64.6
	UGS Strachocina	460.0	5 211.8	2.64	29.7	3.36	37.9
	UGS Swarzów	90.0	1 013.4	1.00	11.2	0.93	10.4
	UGS Brzeźnica	100.0	1 126.0	1.44	16.2	1.44	16.1
	UGS Wierzchowice	1 300.0	14 729.0	9.60	107.5	14.40	158.4
	Total	**3 327.7**	**37 510.9**	**30.83**	**345.0**	**53.49**	**594.9**

By 2030, it is assumed that the storage capacity of underground facilities will be expanded to a minimum of 43.8 TWh. One of the planned underground gas storage facilities will be the Damasławek storage facility located in the salt formation, where approximately 1.5 billion m^3 of natural gas will be stored in 20 salt caverns (GAZ-SYSTEM S.A., 2016; Tarkowski and Uliasz-Misiak, 2021) Figure 3.

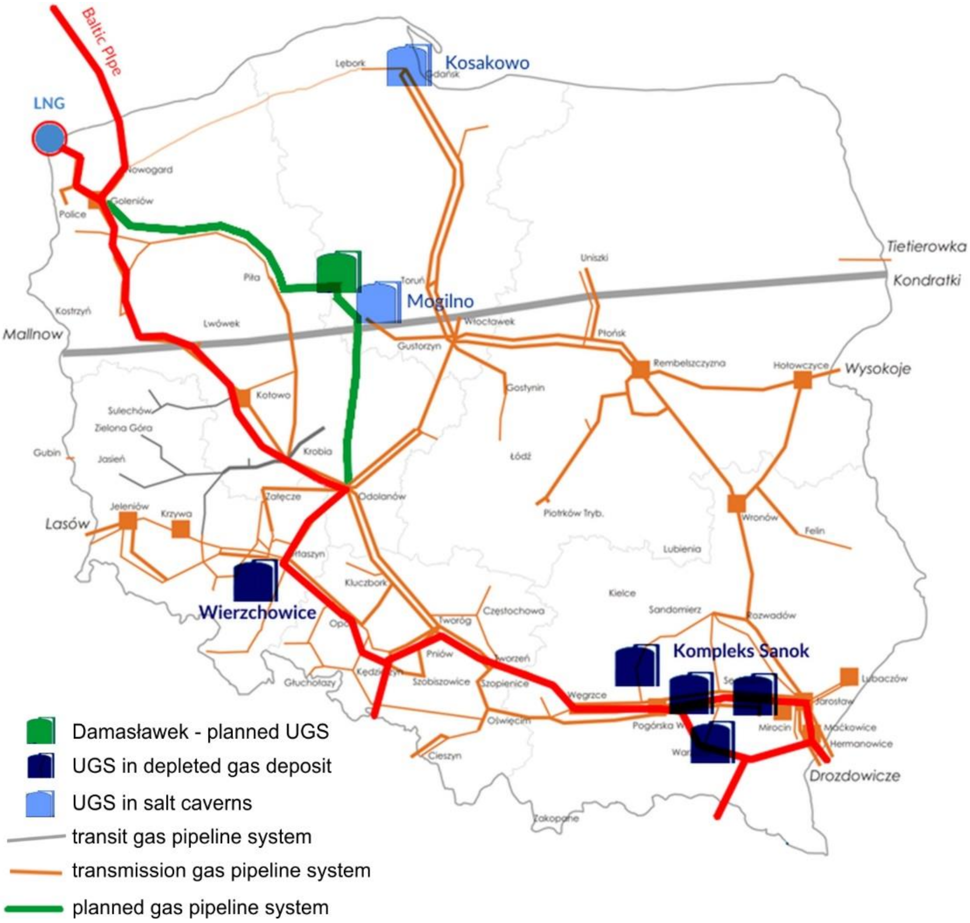

Figure 3. The planned Damasławek UGS and natural gas transmission and storage system in Poland

Increasingly, storing electricity in the form of hydrogen and generating electricity using hydrogen is becoming mainstream in the energy sector. Poland is ranked 3rd among European hydrogen producers, just behind Germany and the Netherlands; however, the share of hydrogen production through water electrolysis is still negligible. The annual production of hydrogen in Poland is about 1.3 million tons. Hydrogen production occurs mainly in large industrial plants through the steam reforming of hydrocarbons, where hydrogen is used in industrial processes (Ministry of Climate and Environment, 2021).

Given the Polish geographic and weather conditions, it is estimated that renewable hydrogen production will become profitable using electricity from offshore wind farms while potentially increasing the competitiveness of offshore wind energy. Obtaining renewable hydrogen will effectively balance the production of electricity obtained from photovoltaic farms (especially large-scale ones), multiplying the potential of the rapidly growing PV investment sector (Ministry of Climate and Environment, 2021).

In 2020, there were 300 electrolyzers in the EU, accounting for less than 4% of total hydrogen production. In Poland today, there are only prototype installations created as part of ongoing research and development projects. Many investors are planning pilot studies and demonstrations of the use of this technology in the near future. The key challenge will be access to cheap electricity, which should cost 10-20 EUR/MWh to make hydrogen production from electrolysis competitive (Ministry of Climate and Environment, 2021). Considering the direction set by the European Green Deal and the EU Hydrogen Strategy, Poland's strategic goal in terms of hydrogen production until 2030 is to ensure conditions for launching installations for hydrogen production from low- and zero-emission sources (Ministry of Climate and Environment, 2021). In the Polish Hydrogen Strategy until 2030 with a perspective until 2040 (Ministry of Climate and Environment, 2021) it is predicted that by 2030 Poland will have installed capacity from low-emission sources and processes at the level of 2 GW, which will enable the production of 193,634 tons of hydrogen per year and cover 99.4% of the demand for hydrogen in the national economy.

The study conducted by Benalcazar and Komorowska (Benalcazar and Komorowska, 2022) shows that in 2020 in Poland, the levelized cost of hydrogen (LCOH) of a 1-MW proton-exchange membrane (PEM) electrolyzer system may have ranged between €12.64 to €13.48 per kg (using solar energy) and €6.37 to €9.70 per kg (using onshore wind energy) (Figure 4). It is assumed that by 2030, the LCOH of a 6-MW PEM electrolyzer system could decrease to about €4.12–4.30 per kg (solar PV) and €2.33–3.06 per kg (onshore wind). In 2050, the levelized cost of green hydrogen of a 20-MW PEM electrolyzer system in Poland could fall to €1.95–2.03 per kg (solar PV) and €1.23–1.50 per kg (onshore wind) mainly due to the advances in wind and solar technologies and major cost reductions in PEM technologies. Regardless of the year and the electrolyzer capacity, Poland's central and southern regions have the lowest LCOH values for solar-based hydrogen (Figure 4). For wind-based hydrogen, however, the lowest LCOH values are in the country's northern areas.

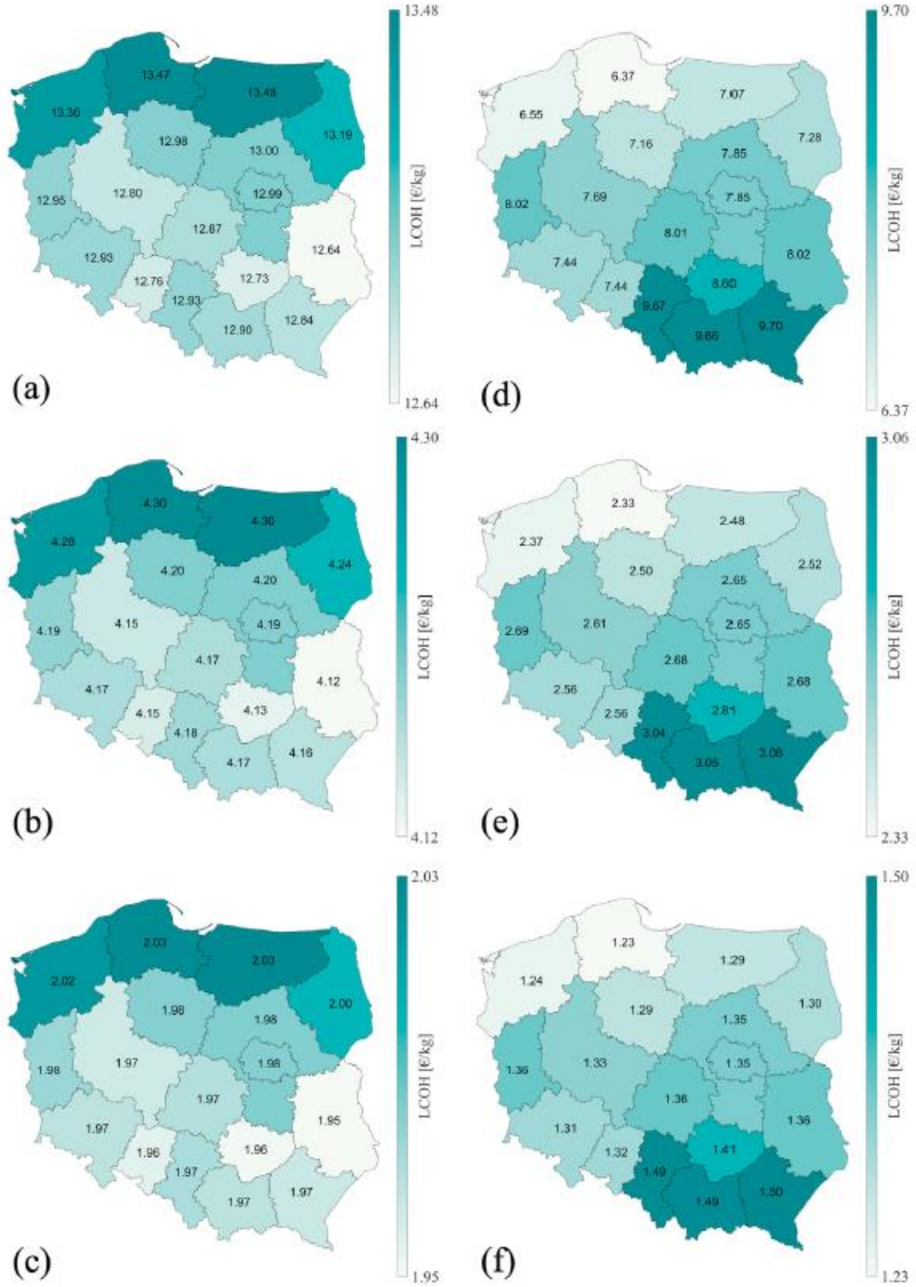

Figure 4: LCOH at the NUTS-2 (Nomenclature of territorial units for statistics) Polish regions level for: (a) ground solar PV (2020), (b) ground solar PV (2030), (c) ground solar PV (2050), (d) onshore wind (2020), (e) onshore wind (2030), (f) onshore wind (2050) (Benalcazar and Komorowska, 2022).

According to the results for different scenarios presented in Deliverable D.5.5-2 (Michalski and Kutz, 2022), the overall required volume capacity for underground hydrogen storage in EU-27 and the UK ranges between ca. 156 and 284 TWh_{H2} by 2050 (see Table 2). Poland accounts for ca. 8% of the European capacities with 12-23 TWh_{H2}. The storage facilities in Europe are operated on a seasonal basis with 1-2 full cycle equivalents per year and an annual throughput of ca. 293-393 TWh_{H2}/a to balance out fully renewable power and hydrogen supply and demand by 2050. For Poland, the analysis in Deliverable D.5.5-2 (Michalski and Kutz, 2022) provides similar results of up to 2.4 full cycle equivalents per year and throughput of ca. 29-38 TWh_{H2}/a. It corresponds to around 10% of the overall European throughput.

Table 2: Cost-optimized size and way of operation for underground hydrogen storage in salt caverns in Poland and EU27+UK by 2050 according to minimum and maximum scenarios from (Michalski and Kutz, 2022)

Item		Poland	EU27+UK
Storage volume capacity [TWh_{H2}]	Min.	12.13	155.62
	Max.	23.25	283.90
Storage throughput [TWh_{H2}/a]	Min.	28.65	293.26
	Max.	38.07	393.48
Number of full cycle equivalents per year	Min.	1.64	1.37
	Max.	2.36	1.91

The results of the techno-economic assessment of future scenarios for the deployment of underground renewable hydrogen storage (Michalski and Kutz, 2022) and the estimation of hydrogen storage capacity requirements (Cihlar et al., 2021) indicate high values of the maximum storage demand for Poland of about 35-38 TWh_{H2}.

1.2. Polish storage potential

There is significant potential for underground hydrogen storage in Poland. The knowledge and experience in identifying geological structures for the underground storage of carbon dioxide in Poland were useful for assessing the possibilities of geological storage of hydrogen in underground geological formations. The geological structure of Poland is favorable because many areas of the country are suitable for establishing a storage site, practically of any type (Tarkowski, 2017).

The possibility of storing hydrogen in bedded rock salt deposits and salt domes in Poland was discussed in a few scientific works. Tarkowski and Czapowski (Tarkowski and Czapowski, 2018) proposed seven undeveloped rock salt domes in Poland as the most promising for UHS. Lankof and Tarkowski (Lankof and Tarkowski, 2020) assessed the potential for UHS in bedded rock salt deposits in southwestern Poland and salt domes in central Poland (Lankof et al., 2022). These deposits are associated with the Zechstein salt-bearing formation, formed in the

Permian Basin and extending from the United Kingdom through the North Sea, the Netherlands, Denmark and Germany to Poland and Lithuania. This formation covers more than half of the area of Poland (Figure 5).

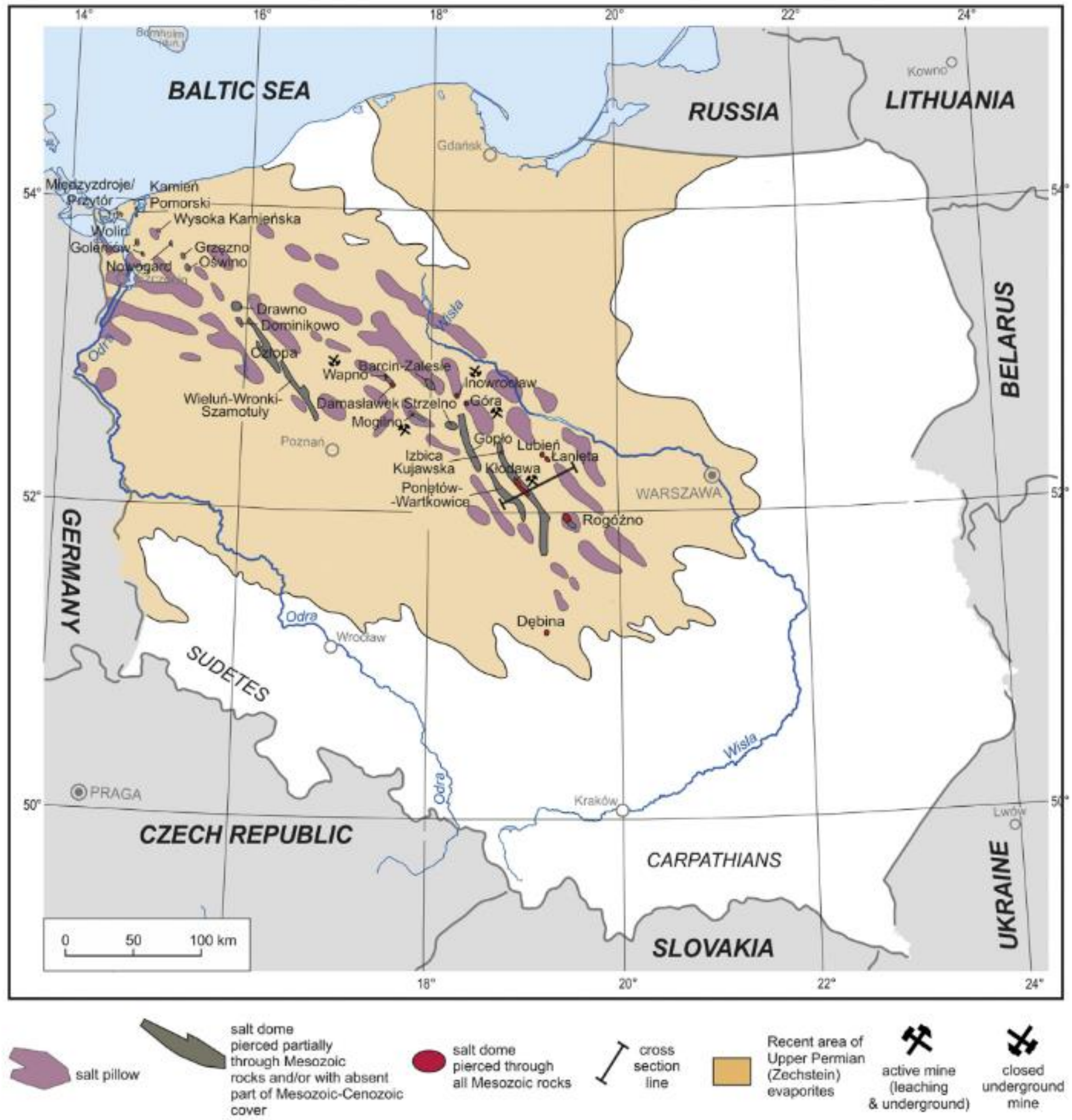

Figure 5: Salt structures in the Upper Permian (Zechstein) deposits in Poland (Tarkowski and Czapowski, 2018)

The possibility of storing hydrogen in the deep aquifers of the Polish Lowland was discussed by Tarkowski (Tarkowski, 2017) and Lewandowska-Śmierzchalska et al. (Lewandowska-Śmierzchalska et al., 2018). In the case of Poland, the locations of structures for hydrogen storage refer to those selected for the underground storage of CO_2 (Šliaupa et al., 2013; Tarkowski and Uliasz-Misiak, 2006). In addition, they consider locations where the reservoir level is at a lower depth (over 800 m) than in the case of carbon dioxide storage.

There are favorable storage conditions for UHS in deep aquifers in NW and central Poland. In this part of Poland, sedimentary rocks of the Lower Triassic, Lower Jurassic, and Lower Cretaceous comprise sandstone aquifers suitable for UHS storage (Figure 6 - Figure 8).

As part of the WP1, the Hystories project created a database (Smith and Vincent, 2021) that contains information about 38 structures (traps) in deep aquifers in Poland for UHS (shown in Figure 6 - Figure 8). The Mineral and Energy Economy Research Institute of the Polish Academy of Sciences (MEERI PAS) team analyzed three structures in detail for UHS using a digital model and storage simulation. These are Sierpc (Luboń and Tarkowski, 2021), Suliszewo (Luboń and Tarkowski, 2023, 2020), and Konary analyzed for CO_2 storage (Luboń, 2020).

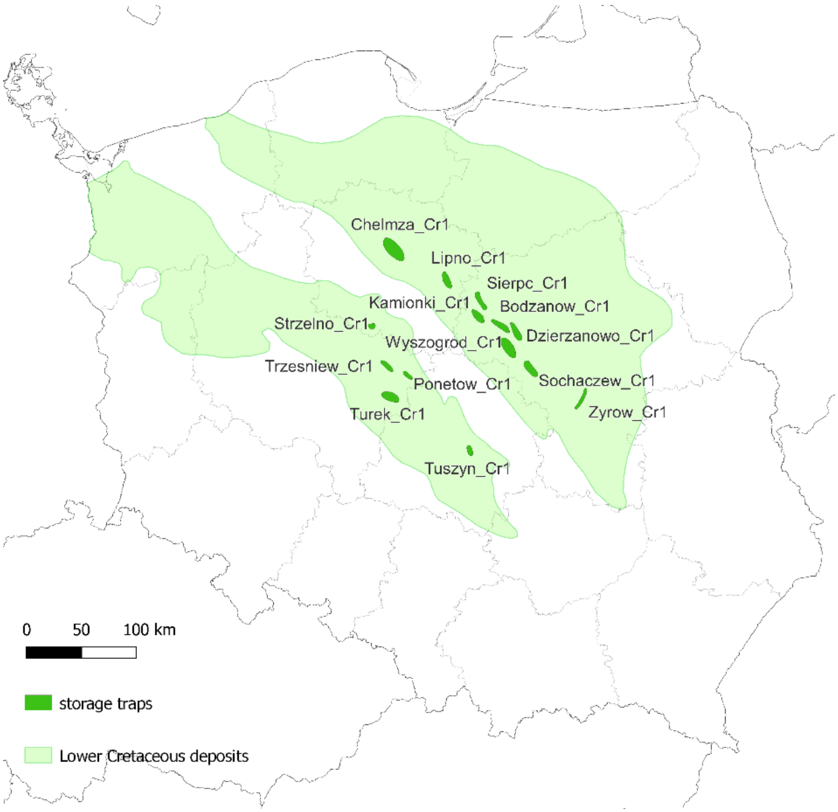

Figure 6: Storage traps in deep aquifers of the Mogilenska Formation storage unit

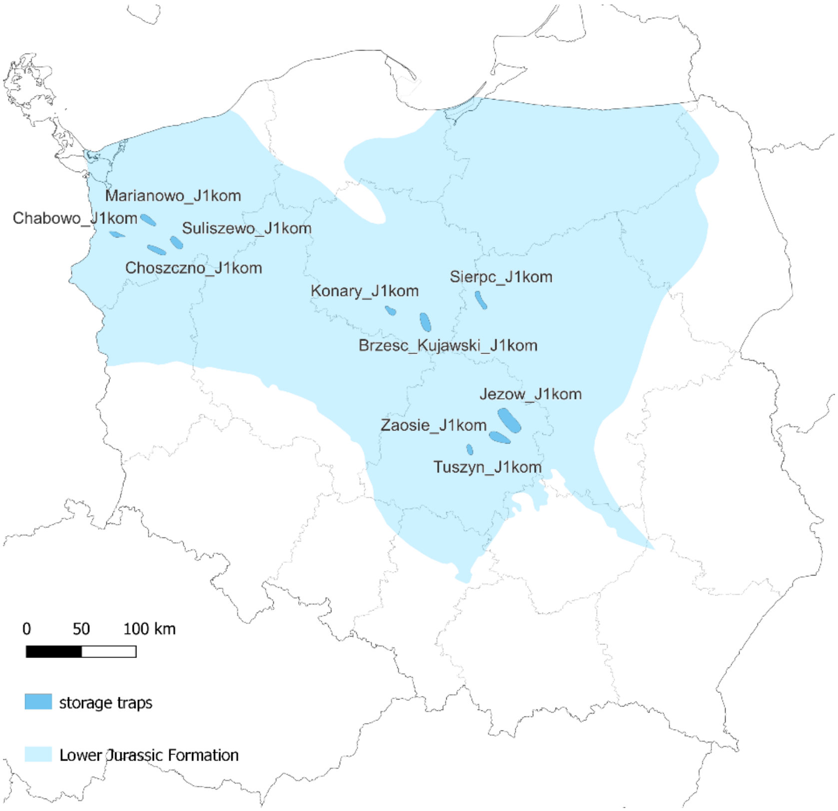

Figure 7: Storage traps in deep aquifers of the Komorowska Formation storage unit

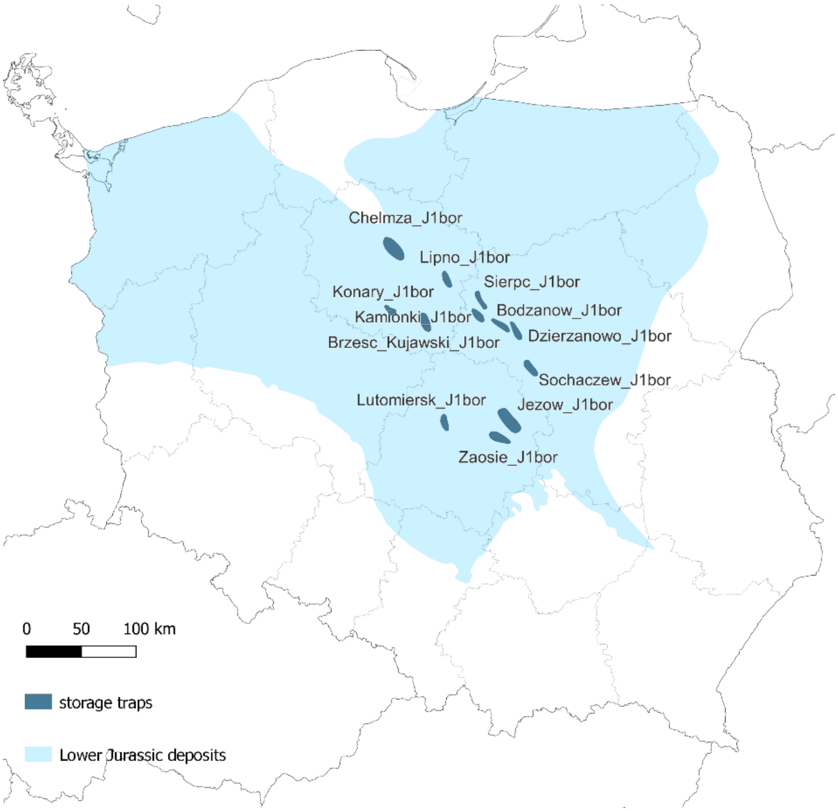

Figure 8: Storage traps in deep aquifers of the Borucicka Formation storage unit

A recent estimation made by MEERI PAS showed a large hydrogen storage potential of analyzed geological structures. The average energy capacity per cavern in bedded salt formations is between 0.047–0.094 TWh_{H2}, translating into 1 400–2 800 tons of hydrogen. For salt domes, this is between 0.06 TWh_{H2} and 0.20 TWh_{H2}, corresponding to 1 800 and 5 900 tons of hydrogen. In the case of deep aquifers, the storage capacity, depending on the structure considered (the mentioned analyzed Konary Sierpc and Suliszewo), ranges from 0.016 to 4.5 TWh_{H2}, which corresponds to around 470–133 600 tons of hydrogen.

In Poland, 306 natural gas deposits have been documented. About 200 deposits, which were or are still exploited, may constitute a significant underground storage base (Solecki et al., 2022) (Figure 9).

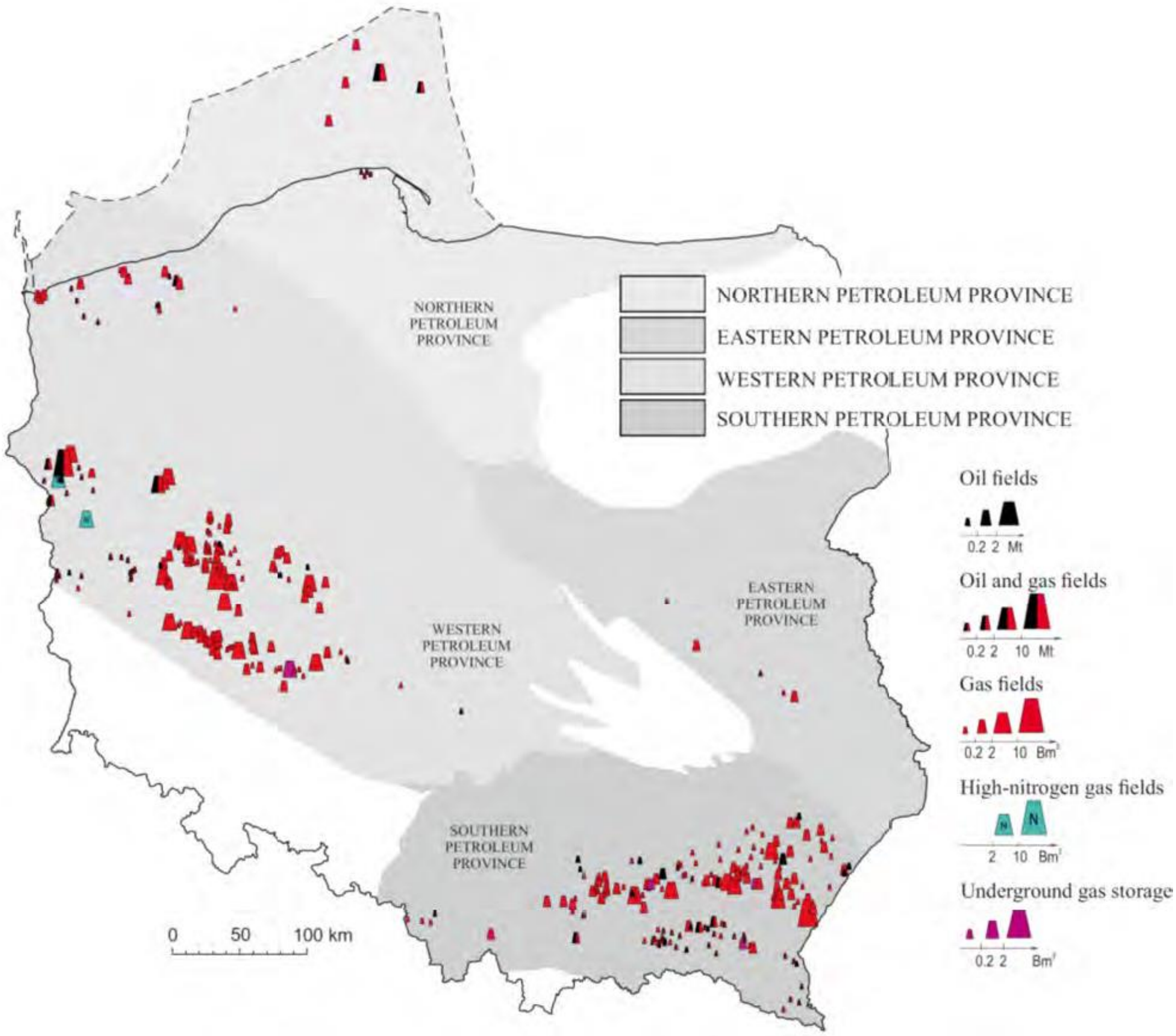

Figure 9. Hydrocarbon deposits in Poland (Solecki et al., 2022)

In the case of depleted oil and natural gas reservoirs in the Polish Lowlands, the Carpathians, and the Carpathian Foredeep, Tarkowski selected 39 locations of potential underground hydrogen storage sites (Tarkowski, 2017). Four oil deposits in the Polish Lowlands have been proposed, and seven oil deposits from the Carpathians and the Carpathian Foredeep for hydrogen underground storage. In case of natural gas, 10 deposits in the Polish Lowlands have been proposed. From the Carpathians and the Carpathian Foothills, 18 gas deposits have been recommended.

As part of the Hystories project, a database was created for the needs of WP1 (Smith and Vincent, 2021), which contains 64 locally defined traps in depleted hydrocarbon reservoirs, of which 7 are active underground gas storage facilities (including 2 underground gas storages facilities storing nitrogen-rich gas).

1.3. Polish regulatory framework

In Poland, the Geological and Mining Law is the specific regulation for the underground storage of natural gas, while the topic of electricity storage is addressed in the Energy Law. The geological license for underground gas storage is granted by the Minister of Climate and Environment, while the license for the provision of energy storage services is granted by the President of the Energy Regulatory Office (‘Energy storage trends - Spotlight on Poland’, 2022; Martinez and Simon, 2021). The Energy Law amendments will stimulate the energy storage market, particularly in developing hydrogen generation technologies (‘Energy storage trends - Spotlight on Poland’, 2022).

The identified legal barriers are related to the current form of the Polish Energy Act. The current regulation only provides for the law of storing gaseous fuels. The current legislation does not include the storage facility concept applicable to the electricity industry (Martinez and Simon, 2021; Ministry of Climate and Environment, 2021). Thus, Poland has no legislation for underground hydrogen storage so far (Martinez and Simon, 2021).

However, the essential activities planned by the Polish government to implement the Polish Hydrogen Strategy include creating regulations that will remove barriers to the development of the hydrogen market and encourage a gradual increase in the use of RES for electrolysis. In order to create a regulatory framework enabling hydrogen to be an alternative fuel in transport and regulations specifying the details of the functioning of the market, it is planned to develop a legislative hydrogen package, which will amend many legal acts. In addition, it is intended to introduce the “Hydrogen Law”, which will comprehensively and in one place regulate the operation of the hydrogen market (Ministry of Climate and Environment, 2021).

The current permits needed to develop underground gas storage in Poland are (more detailed in (Martinez and Simon, 2021)):

- Concession for underground tankless storage of substances (Exploitation concession)
- Building permits
- Decision on environmental conditions
- Decision on the location of a public-purpose investment
- Water law permit
- Project of geological works
- Integrated permit.

2. Input parameters and main assumptions

The cost analysis was based on the underground hydrogen storage cost model developed in WP7 (Life Cycle Cost Assessment of an underground storage site - D7.1-1) and the calculation tool developed in WP8 (D8.1-1). The analysis concerns hypothetical hydrogen storage in salt caverns in Poland. The choice of technology was dictated by the considerable storage potential in rock salt deposits in Poland (Lankof et al., 2022; Lankof and Tarkowski, 2020) and the high suitability of salt caverns for hydrogen storage, confirmed in industrial applications (Acht and Donadei, 2012) and current experimental storage in test caverns (‘HyPSTER’, 2023, ‘Hystock’, 2023, ‘Uniper’, 2023).

Cost analysis aimed to estimate crucial economic parameters such as capital expenditures (CAPEX), operational expenses (OPEX) for over 30 years of the storage life cycle, and abandonment expenses (ABEX).

- ***Reference scenario***

The analysis's key parameters and boundary conditions were determined based on the main design parameters given in the "Conceptual design of salt cavern and porous media underground storage site" (D7.1-1) .

The case study focuses on developing and operating a hydrogen storage facility comprising eight salt caverns with storage parameters specified for the mid-case in the "Conceptual design of salt cavern and porous media underground storage site" (D7.1-1). The construction and start-up period of the UHS is planned for eight years, and the period of operation is 30 years. The reference scenario does not assume the extension of the UHS.

Boundary conditions cover design parameters of the subsurface and surface parts of the storage facility, hydrogen storage costs, and financial parameters.

Subsurface facility parameters were indirectly aimed at determining the capacity of the planned storage facility by selecting the number of caverns, their volume, depth, and the amount of hydrogen intended as cushion gas. The assumed number of cycles (D5.2-2), in turn, allowed for determining the throughput of the storage facility. Their values allowed us to determine the capital costs of the underground part of the storage and contributed to estimating the revenue from hydrogen storage. The design parameters of the subsurface part of the storage facility in the reference scenario were adopted after the conceptual design of the salt cavern for the middle case storage site described in WP7 (D7.1-1) and are summarized in Table 3.

Table 3: The design parameters of the subsurface part of the storage facility

Parameters	Description	Unit	Value
V_{cavern}	Free gas volume per cavern	[million Sm^3]	0.38
V_{max}	Maximum Gas Inventory per cavern	[million Sm^3]	31
n_{WH}	Number of caverns (one wellhead per cavern)	[-]	8
LCCS	Last cemented casing shoe	[m]	1000
DC_i	Drilling complexity index	[-]	1.0
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	[million Sm^3]	250
V_{wg}/Q_w	Working gas volume / Total storage maximum withdrawal flowrate capacity	[days]	15
$Q_{debrining}$	Debrining flowrate per cavern	[m^3/h]	200
$d_{full\ cycle}$	Duration of one full storage of the cycle	[days]	58
N_{fc}	Number of full cycles per year	[-]	2.1
$N_{fc,\ MAX}$	Maximum number of full cycles per year	[-]	6.3
$d_{T,L}$	Leaching duration	[year]	4.5
$d_{T,C}$	Debrining duration	[year]	1.1
LF	Load Factor	[-]	0.33

The capacity of the analyzed storage was determined based on the assumptions regarding caverns' volume, maximum hydrogen inventory, number of caverns, and working gas volume, presented in Chapter 2. Based on the assumptions regarding caverns' volume, maximum hydrogen inventory, the number of caverns, and working gas volume, the capacity of the analyzed UHS was determined at 250 million Sm^3. In turn, the assumed number of annual cycles allowed for determining the storage throughput of 46.6 tons per year. In the reference scenario, a constant value of storage throughput was assumed throughout the lifetime of the underground hydrogen storage.

The design parameters of the surface part of the storage facility are the main parameters used to determine the capital costs of the surface part of the storage facility and also the operating costs of hydrogen storage. They include both the parameters defining the materials used and the operational parameters of the storage (e.g., maximum withdrawal flow rate, compression ratio), based on which the demand for the number of compressors and equipment of the hydrogen purification station is determined. This group of parameters also includes the cost of electricity (CoE), which determines variable operating costs. The analysis assumes a CoE of 100 €/MWh (Data source ENTSO-E 24.03.2023 13:00 CET). Operating costs and surface facilities parameters for the reference scenario are listed in Table 4.

Table 4: The design parameters of the surface part of the storage facility and influencing operating cost

Parameters	Description	Unit	Value
MCFi	The material cost factor for injection (compression) stream	[-]	1
MCFw	The material cost factor for the withdrawal stream	[-]	1
Qw	Total storage maximum withdrawal flowrate capacity	[million Sm^3/day]	16.50
τ	Overall compression ratio (ratio of discharging pressure over suction pressure)	[-]	3.23
n	Number of required compression stages	[-]	2
WTIR	Withdrawal to injection capacity ratio	[-]	2.8
netOP	The 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
Lfl	Field lines size	[km]	2
COE	Cost of Electricity	[€/MWh]	100

The hydrogen cost parameters considered in the Polish case study included hydrogen production cost, other costs, storage cost, storage service margin profit, storage service price, minimum hydrogen selling price, margin profit, and hydrogen selling price in the values presented in

Table 5. Values of these parameters were common for all case studies.

Table 5: The hydrogen cost parameters

Hydrogen price	Unit	Value
Hydrogen production cost	[€/kg]	6.29
Other costs	[€/kg]	1.89
Storage cost	[€/kg]	1.81
Storage service margin profit	[%]	5.75
Storage service price	[€/kg]	1.91
Minimum Hydrogen selling price	[€/kg]	10.09
Margin profit	[%]	15.00
Hydrogen selling price	[€/kg]	11.60
Price spread	[%]	46.00

The last group consists of financial parameters. They include subsidies, venture period, residual value, storage service price, corporate tax, financing fund, interests, financing duration, and rate of return (discount rate). The parameters' values adopted for the reference scenario are presented in Table 6. Values of these parameters were common for all case studies.

Table 6: The parameters affecting financial flows

Parameter	Unit	Value
Subsidy	[€]	20,000,000
Venture period	[years]	30
Residual value	[%]	20
Storage service price	[€/kg]	2.04
Corporate tax	[%]	25
Financing fund	[€]	0
Interests	[%]	5
Financing duration	[years]	30
Rate of return (discount rate)	[%]	5.75

3. Results

The Chapter presents the results of calculations utilizing the tool developed in task WP8.1, assuming country-specific parameters. The results include a storage facility cost breakdown and cash flow analysis of the reference business scenario and its optimization by a sensitivity analysis of critical parameters influencing the profitability of the analyzed case.

3.1. Site costs breakdown

Based on the assumptions for this case study described in Chapter 2, key results for CAPEX, OPEX, and ABEX of the Polish case study (the storage facility with eight caverns of a total capacity of 250 million Sm^3 are summarized in Table 7.

Table 7: Key modeling results for CAPEX, OPEX, and ABEX of the Polish case study

	Unit	Value
CAPEX – subsurface	million €	437.84
CAPEX – surface	million €	355.06
OPEX	million € / year	20.86
ABEX	million €	138.38

The share of the main components of individual costs is presented below.

- **CAPEX breakdown**

The capital costs of hydrogen storage in salt caverns were broken down into the subsurface and surface costs of the storage, assuming the previously given assumptions.

- *CAPEX – subsurface*

The main components of the investment costs for the construction of the underground part of the hydrogen storage facility are engineering, construction & procurement related to the equipment used for cavern leaching (EPC1), the leaching process itself (EPC2), brine cavern emptying and leaching column (EPC3), Development Drilling and leaching completion costs (EPC4), and the cost of the cushion gas. In addition, Contingency costs of approximately 20% FPC1-EPC4 are also included. The cost summary and distribution are presented in Table and Figure 10.

Table 8: Subsurface capital costs

Costs breakdown	Description	Value [**million €**]
EPC_1	EPC cost main parameters and cost breakdown for leaching facilities	97.60
EPC_2	Leaching operation and maintenance costs	85.76
EPC_3	Salt cavern debrining and conversion costs	35.81
EPC_4	Development Drilling and leaching completion costs	44.71
CG	Cushion gas for salt caverns	100.99
$CONT_{subsurface}$	Contingencies related to subsurface	72.97
	Total	**437.84**

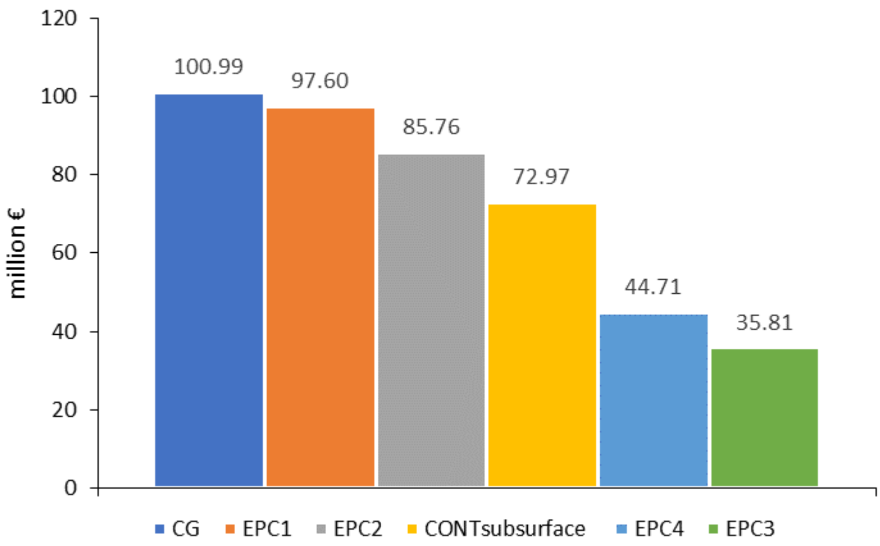

Figure 10: Subsurface capital costs (explanations as in Table)

The total cost of the underground part of the storage is 437.84 million €. Cushion gas (CG) is the highest cost, accounting for over 23% of subsurface CAPEX. Salt cavern debrining and conversion costs are the lowest, accounting for 8.2% of subsurface CAPEX.

- *CAPEX – surface*

The main components of the capital costs of the surface part of the hydrogen storage facility are engineering, construction & procurement related to main parameters and breakdown for filtering, drying & compression, and metering units (EPC1), interconnection WH - gas plant (EPC2-3), and main parameters and cost breakdown for a balance of plant costs (EPC5). In addition, contingencies related to subsurface costs of approx. 15% EPC1-EPC4 were included. The cost summary and distribution are presented in Table and Figure 11.

Table 9: Surface capital costs

Costs breakdown	Description	Value [**million €**]
EPC_1	EPC cost main parameters and breakdown for filtering, drying & compression, and metering units	202.70
EPC_2	EPC costs for interconnection WH - Gas Plant	53.39
EPC_3	EPC cost per additional kilometer between Gas Plant and nearest WH	18.08
EPC_5	EPC cost main parameters and cost breakdown for Balance of Plant	21.71
$CONT_{surface}$	Contingencies related to surface facilities	59.18
	Total	**355.06**

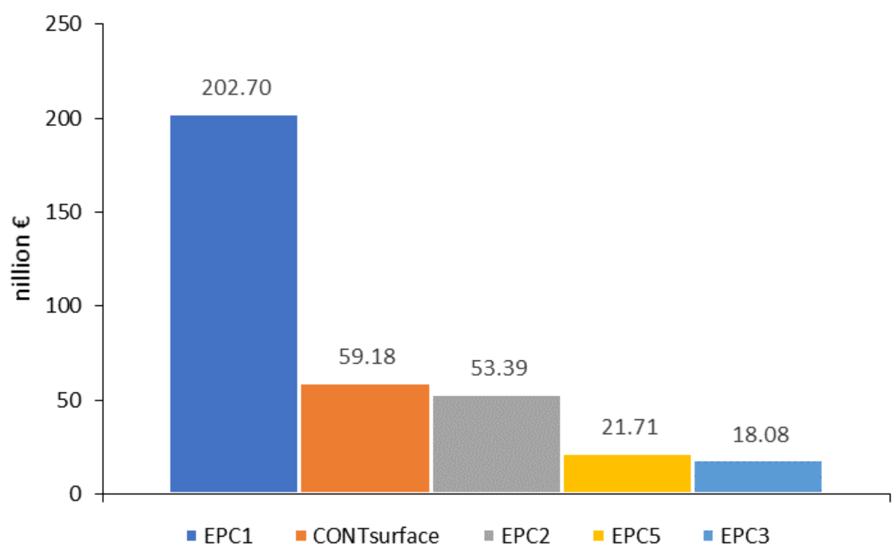

Figure 11: Surface capital costs (explanations as in Table)

The total cost of the surface part of the storage facility is 355.06 million €. The highest costs are related to the main parameters and breakdown for filtering, drying & compression, and metering units (EPC1), accounting for almost 58% CAPEX of the surface part. The lowest is the cost per additional kilometer between the gas plant and the nearest WH (EPC3), constituting 5.1% CAPEX of the surface part.

The total capital costs of the storage facility with eight caverns with a total capacity of 250 million Nm^3 amount to 792.9 million €.

- **OPEX breakdown**

The components of operating costs have been divided into fixed expenses related to the operation of the surface and subsurface parts of the storage and variable costs depending on the electricity cost (COE). The summary and distribution of yearly storage operating costs are presented in Table 10 and Figure 12.

Table 10: Operation costs

Costs breakdown	Description	Value [**million** €]
OPEXfix, AG	Fixed OPEX - Surface	13.94
OPEXvar, AG	Variable OPEX - Surface	5.58
OPEXfix, UG	OPEX - Subsurface	1.34
	Total	**20.86**

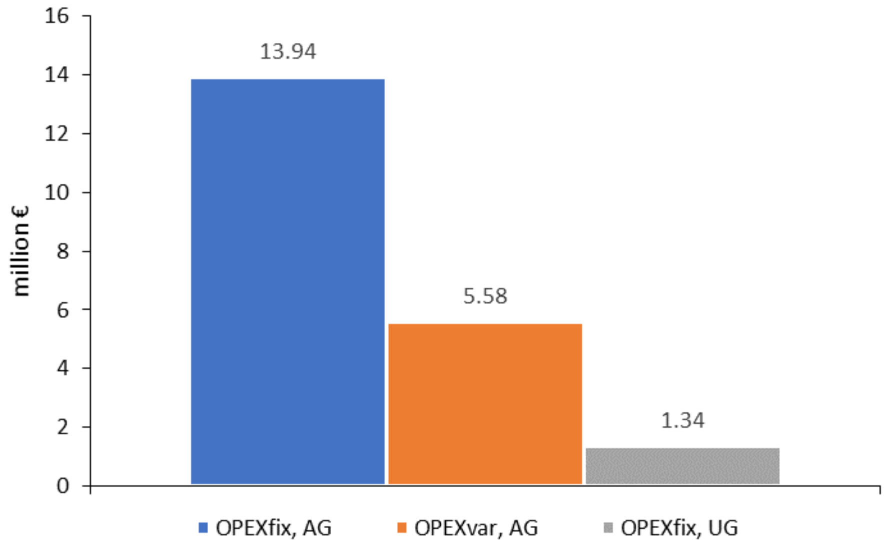

Figure 12: Operational *costs (explanations as in* Table 10)

The total operating cost of the storage surface part is 20.86 million €. The highest costs are related to the operation of the storage facility's surface part, amounting to 66.8% of the total OPEX. On the other hand, the operating costs of the subsurface part account for only 6.4% of the total OPEX. Variable costs with the adopted COE of € 107 amount to approx. 6.0 million €, which is approx. 26.7% of the total OPEX.

- **ABEX breakdown**

The components of the ABEX were divided into the costs of abandonment of the surface and subsurface parts of the storage facility. It was assumed that the surface part's abandonment costs constitute 20% of surface CAPEX, and the subsurface part's abandonment costs constitute 20% of subsurface CAPEX. They amount 71.0 and 67.3 million € respectively. The summary and distribution of costs are presented in Table 7.

Table 7: Abandonment costs

Costs breakdown	Description	Value [**million €**]
ABEXsurface	Abandonment Expenditure for surface facilities	71.01
ABEXsubsurface	Abandonment Expenditure for subsurface	67.37
	Total	**138.38**

3.2. Cash flow analysis

Cash flow analysis was aimed at determining the following key output parameters:

- Net Present Value (NPV) – the difference between discounted cash flows and capital expenditures, which may be interpreted as an increase or decrease in the investor's capital resulting from the implementation of the investment, taking into account changes in the value of money over time. A positive NPV means that the revenue will exceed the cost of capital, and the project is profitable. In this case, the investment decision should be favorable. A negative NPV value, in turn, indicates that the implementation of the project is unprofitable.
- Internal Rate Return (IRR) – which is the discount rate at which NPV = 0,
- Net Present Cost (NPC) - representing the present value of all costs minus the present value of all revenues throughout the entire period of activity.
- The Levelized Cost of Storage (LCOS) – averaged storage costs being the ratio of discounted operating costs incurred throughout the storage duration to the amount of hydrogen stored at that time.

The adopted assumptions and the method of calculating individual costs with 100% equity finance indicate the following values of the key indicators in the reference scenario (Table 8).

Table 8: The values of key indicators determined in the cash flow analysis in the reference scenario

Key Performance Indicators	Unit	Value
Net Present Value (NPV)	million €	-41.42
IRR	%	5.17
Net Present Cost (NPC)	million €	762.24
LCOS	€/kg	1.81

In the reference scenario, the NPV is -41.42 million €, the internal rate of return is 5.17%, and the LCOS is 1.81 €/kg. A negative NPV value obtained as a result of the calculations means that in the case of the storage facility under consideration, with the presented assumptions, the revenues from hydrogen storage will not cover the cost of capital, and the implementation of the project will lead to a decrease in the company's value, i.e., the investment is unprofitable. However, assuming a higher storage service margin of 12.99% instead of 5.75%, the NPV reaches the break-even point (NPV=0), above which the business case is positive. The IRR indicator at the break-even point is 5.75%, and the values of the remaining indicators values remain unchanged.

3.3. Business case optimization

The purpose of the analysis is to check the model's sensitivity in relation to the variability of key input parameters and to present the method of optimizing the model toward the business justification for storing hydrogen in salt caverns in Poland.

The analysis covered the impact of the following parameters on the KPI’s values:

- storage service margin profit,
- corporate tax,
- discount rate,
- cost of electricity,
- number of caverns,
- number of cycles.

The business case reference scenario assumes a storage service margin profit of 12.99% (at which NPV reaches the break-even point) as a reference value for further sensitivity analysis. The analysis covered the impact of individual parameters on the change in the values of NPV and IRR indicators. The business case optimization analysis was carried out in the parameters variability range from 0 to 200% of their reference values, except for the number of caverns and the number of storage cycles where the range was between 25 and 200% of the reference business case.

3.3.1. Storage service margin profit

The storage service margin profit in the business case reference scenario is 12.99%. Figure 13 shows the impact of the storage service margin profit changes in the range of 0 to 26% on NPV and IRR. The calculations show that a change in the storage service margin profit to 13% results in reaching the break-even point (NPV=0). The IRR value at the break-even point is 5.75%, and the storage service price is 2.04 €/kg.

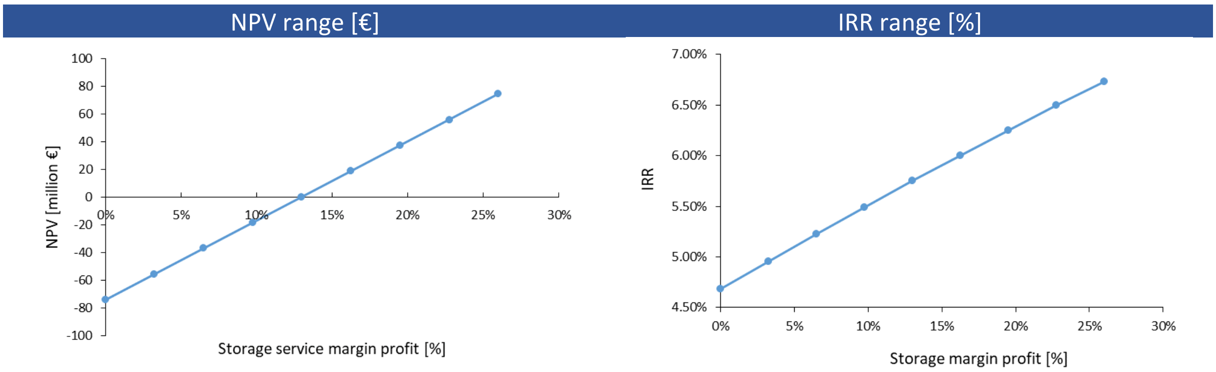

Figure 13: Impact of storage service margin profit change on NPV and IRR values

Table 9 summarizes the critical output parameters of the model as a function of the storage service margin profit change. The calculations show that changes in the storage service margin profit result in significant changes in the NPV and IRR of the business case. However, they do not affect the other output parameters of the model. The NPV ranged from -74.30 million € to 74.30 million €, and the IRR from 4.68% to 6.73% in the analyzed range of the storage service margin profit.

Table 9: Critical output parameters depending on the storage service margin profit

Business Case KPIs	Storage service margin profit [% of LCOS)								
	0.0%	3.2%	6.5%	9.7%	13.0%	16.2%	19.5%	22.7%	26.0%
NPV [million €]	-74.3	-55.7	-37.1	-18.6	0.0	18.6	37.1	55.7	74.3
IRR [%]	4.68	4.96	5.23	5.49	5.75	6.00	6.25	6.50	6.73
NPC [million €]	762.2	762.2	762.2	762.2	762.2	762.2	762.2	762.2	762.2
LCOS [€/kg]	1.81	1.81	1.81	1.81	1.81	1.81	1.81	1.81	1.81

3.3.2. Corporate tax

The corporate tax in the reference business case scenario is 25% reaching the break-even point (NPV=0) with a fixed storage price of 2.04€. Figure 14 shows the impact of the corporate tax on NPV and IRR values.

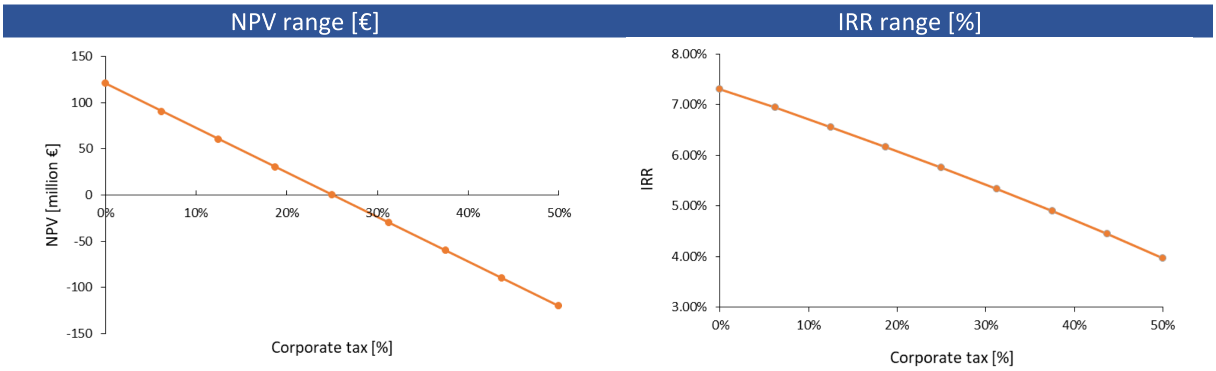

Figure 14: Impact of the corporate tax change on NPV and IRR values

Table 10 summarizes the model's critical output parameters for the corporate tax change from 0 to 50%. The calculations show that corporate tax changes result in significant changes in the NPV and IRR of the business case. The NPV ranged from -120.4 million € to 120.4 million €, and the IRR from 3.97% to 7.31% in the analyzed range of the corporate tax. The corporate tax changes do not affect the other output parameters of the model.

Table 10: Critical output parameters depending on the corporate tax

Business Case KPIs	Corporate Tax [%]								
	0.0	6.3	12.5	18.8	25.0	31.3	37.5	43.8	50.0
NPV [million €]	120.4	90.3	60.2	30.1	0.0	-30.1	-60.2	-90.3	-120.4
IRR [%]	7.31	6.94	6.55	6.16	5.75	5.33	4.89	4.44	3.97
NPC [million €]	762.2	762.2	762.2	762.2	762.2	762.2	762.2	762.2	762.2
LCOS [€/kg]	1.81	1.81	1.81	1.81	1.81	1.81	1.81	1.81	1.81

3.3.3. Discount rate

The discount rate in the business case reference scenario is 5.75% reaching the break-even point (NPV=0) with a storage margin profit of 12.99%. Figure 15 shows the impact of the discount rate changes on NPV and IRR values.

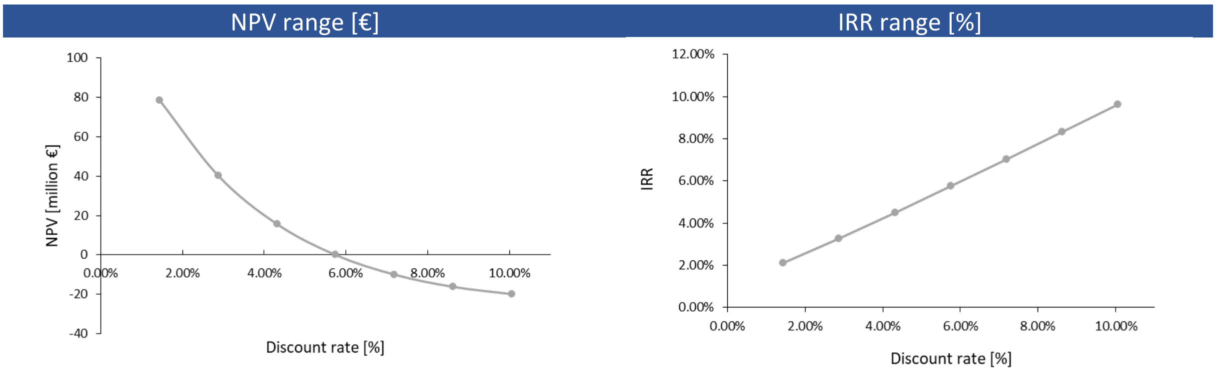

Figure 15: Impact of the discount rate change on NPV and IRR values

Table 11 summarizes the model's critical output parameters for the discount rate change from 1.44% to 11.5%. The calculations show that discount rate changes result in significant changes in the NPV and IRR of the business case. The NPV ranged from -21.9 million € to 78.5 million €, and the IRR from 0.96 to 10.96%. A change in the discount rate additionally causes changes in NPC and LCOS. The NPC varies from 504.6 million € to 1179.3 million €, and the LCOH from 1.17 €/kg up to 3.09 €/kg.

Table 11: Critical output parameters depending on the discount rate

Business Case KPIs	Discount rate [%]								
	0.00%	1.44%	2.88%	4.31%	5.75%	7.2%	8.6%	10.1%	11.5%
NPV [million €]	138.8	78.5	40.2	15.7	0.0	-9.9	-16.1	-19.9	-21.9
IRR [%]	0.96	2.09	3.27	4.50	5.75	7.03	8.32	9.64	10.96
NPC [million €]	1418.6	1179.3	1002.2	867.5	762.2	678.2	609.6	552.6	504.6
LCOS [€/kg]	1.01	1.17	1.35	1.57	1.81	2.08	2.38	2.72	3.09

3.3.4. Cost of electricity

The cost of electricity in the business case reference scenario is 100 €/MWh (according to ENTSO-E 24.03.2023 13:00 CET), reaching the break-even point (NPV=0) with a storage margin profit of 12.99%. Figure 16 shows the impact of the electricity cost changes on NPV and IRR values.

NPV range [€]	IRR range [%]

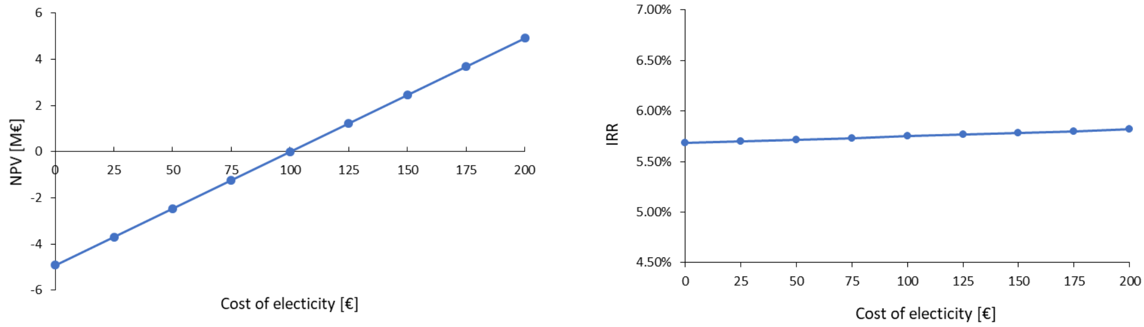

Figure 16: Impact of the discount rate change on NPV and IRR values

Table 12 summarizes the critical output parameters of the model for the change of the cost of electricity from 0 to 200 €/MWh. The calculations show that changes in the NPV ranged from -4.9 million € to 4.9 million €, and in the IRR from 5.68% to 5.82% in the analyzed range of the cost of electricity. A change in the cost of electricity additionally causes changes in NPC and LCOS. The NPC varies from 711.8 million € to 812.7 million €, and the LCOH from 1.69 €/kg up to 1.93 €/kg.

Table 12: Critical output parameters depending on the cost of electricity

Business Case KPIs	Cost of electricity [€]								
	0	25	50	75	100	125	150	175	200
NPV [million €]	-4.9	-3.7	-2.5	-1.2	0.0	1.2	2.5	3.7	4.9
IRR [%]	5.68	5.70	5.72	5.73	5.75	5.77	5.78	5.80	5.82
NPC [million €]	711.8	724.4	737.0	749.6	762.2	774.9	787.5	800.1	812.7
LCOS [€/kg]	1.69	1.72	1.75	1.78	1.81	1.84	1.87	1.90	1.93

3.3.5. Number of caverns

The business case reference scenario assumes eight caverns, reaching the break-even point (NPV=0) with a storage margin profit of 12.99%. Figure 17 shows the impact of the number of caverns on NPV and IRR values.

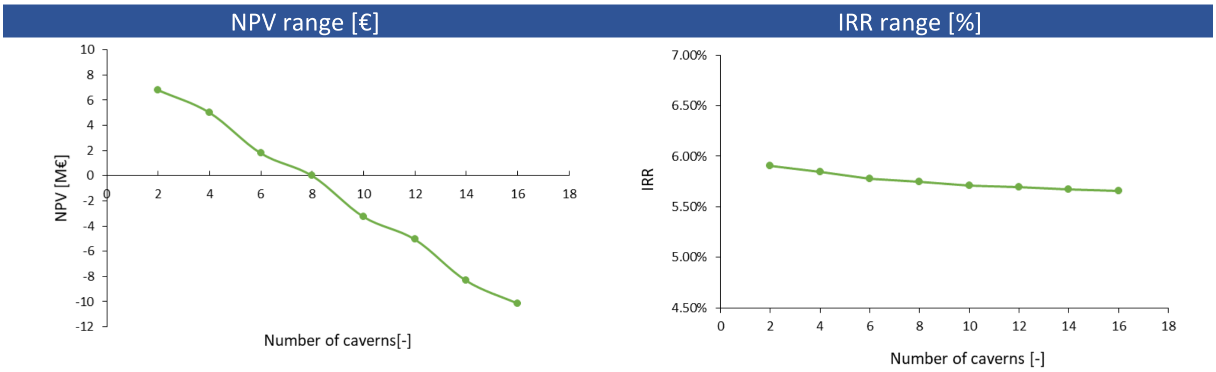

Figure 17: Impact of the number of caverns change on NPV and IRR values

Table 13 summarizes the critical output parameters of the model for the change in the number of caverns. The calculations show that changes in the NPV ranged from -10.1 million € to 6.8 million €, and in the IRR from 5.66% to 5.90% in the analyzed range of the caverns' number. The trend of changes in NPV is influenced by the annual throughput, which is constant and amounts to 46.6 million kg of H2 per year. The change in caverns' number additionally causes variations in NPC and LCOS. The NPC varies from 488.3 million € to 1142.2 million €, and the LCOS from 1.35 €/kg up to 4.63 €/kg. These parameters' changes also result from significant differences in capital cost ranging from 500 million € in the case of 2 caverns to 1.2 billion € in the case of 16 caverns.

Table 13: Critical output parameters depending on the number of caverns

Business Case KPIs	**Number of caverns [-]**							
	2	**4**	**6**	**8**	**10**	**12**	**14**	**16**
NPV [million €]	6.8	5.0	1.8	0.0	-3.3	-5.0	-8.3	-10.1
IRR [%]	5.90	5.84	5.78	5.75	5.71	5.70	5.67	5.66
NPC [million €]	488.3	573.0	677.4	762.2	867.1	952.0	1057.1	1142.2

LCOS [€/kg]	4.63	2.72	2.14	1.81	1.64	1.50	1.43	1.35

3.3.6. Number of storage cycles

The business case reference scenario assumes 2.1 storage cycles per year, reaching the break-even point (NPV=0) with a storage margin profit of 12.99%. The impact of this parameter on KPIs was analyzed in the range from 25% to 200% of the parameter value adopted in the reference scenario. Figure 18 shows the impact of the number of storage cycles changes from 0.53 to 4.2 yearly on NPV and IRR values.

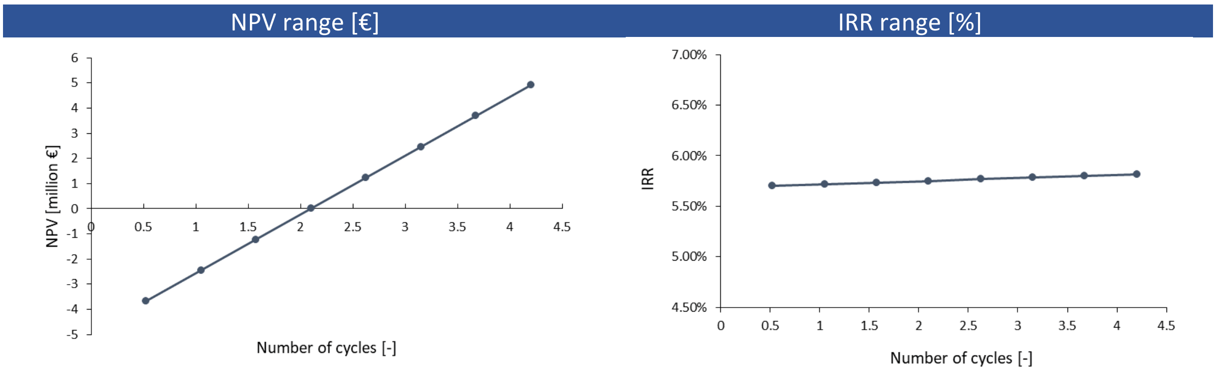

Figure 18: Impact of the number of caverns change on NPV and IRR values

Table 14 summarizes the critical output parameters of the model for the change in the number of storage cycles. The calculations show that changes in the NPV ranged from -3.7 million € to 4.92 million €, and in the IRR from -5.70% to 5.82% in the analyzed range. A change in the number of storage cycles also causes changes in NPC and LCOS. The NPC varies from 724.4 million € to 812.7 million €, and the LCOS from 0.96 €/kg up to 6.87 €/kg.

Table 14: Critical output parameters depending on the number of caverns

Business Case KPIs	**Number of cycles [-]**

	0.53	1.05	1.58	2.10	2.63	3.15	3.68	4.20
NPV [million €]	-3.7	-2.5	-1.2	0.0	1.2	2.5	3.7	4.92
IRR [%]	5.70	5.72	5.73	5.75	5.77	5.78	5.80	5.82
NPC [million €]	724.4	737.0	749.6	762.2	774.9	787.5	800.1	812.69
LCOS [€/kg]	6.87	3.50	2.37	1.81	1.47	1.24	1.08	0.96

The sensitivity analysis shows that three parameters have a significant impact on the financial result, i.e., corporate tax, discount rate, and storage service margin profit. In the analyzed range, the NPV changed from -21.9 to 138.8 million € for the discount rate, from -120.4 to 120.4 million € for corporate tax, and from -74.3 to 74.3 million € for storage service margin profit.

The remaining parameters, i.e., cost of electricity, number of caverns, and number of cycles, had little impact on the final NPV value. The largest change in NPV from -8 M€ to approx. 7 million € was recorded in the case of the number of caverns. Figure 19 shows the impact of changes in the values of the analyzed parameters on the Net Present Value.

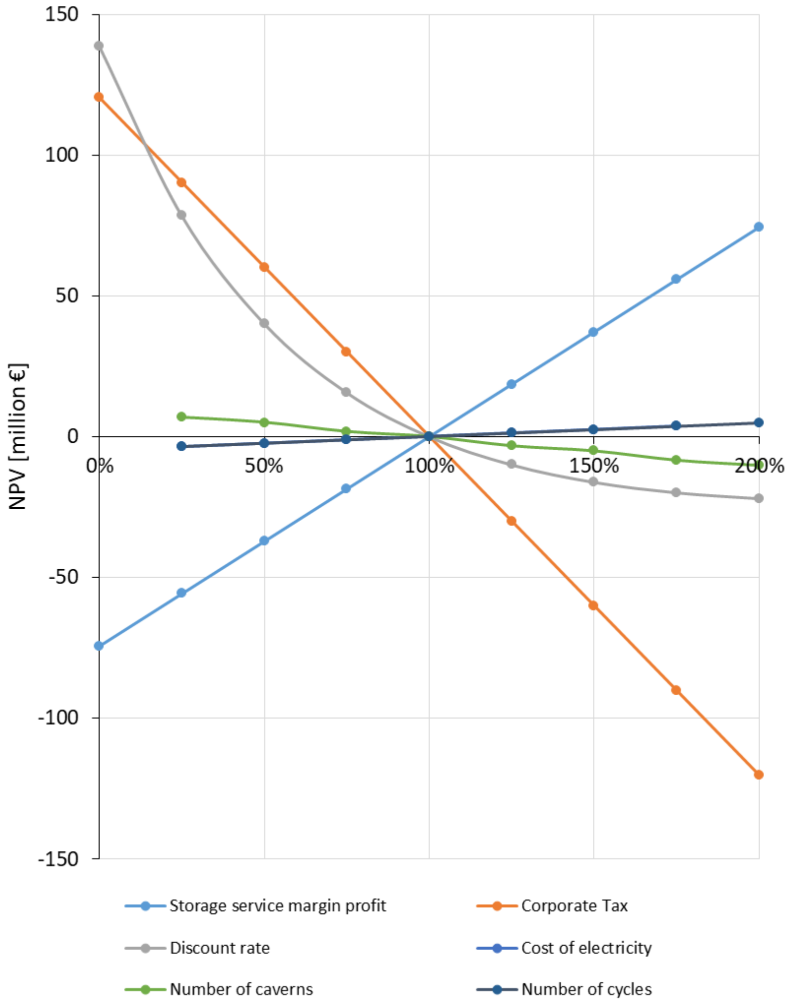

Figure 19: The impact of the analyzed parameters on the NPV value

4. Conclusions

The analysis of the Polish case study presented in the document concerned a hypothetical medium-sized underground hydrogen storage in salt caverns. The conceptual design of UHS, defined as mid-case, was presented in detail in D7.1-1. The UHS consisted of eight salt caverns with a volume of 380,000 Sm3. The technical parameters of the UHS were also adopted based on analyzes carried out as part of WP7. The financial parameters of the Polish case study were the same as in other national case studies. Cash flow analysis was performed based on a cost model developed in WP7 and the business case tool developed in WP8 (task 8.1).

The Polish business case study included the CAPEX, OPEX, and ABEX calculations, their breakdown, and the sensitivity analysis of the reference business case. The analysis assumed the assessment of the impact of changes in financial parameters such as (storage service margin profit, corporate tax, discount rate, and cost of electricity) and technical parameters, i.e., the number of caverns and the number of storage cycles on Key Performance Indicators, i.e., Net Present Value (NPV), Internal rate of Return (IRR) and levelized cost of storage (LCOS). The reference business case assumed a storage margin profit of 12.99%, which allowed the break-even point of the case to be reached. The results of the financial analysis show that:

- According to the assumptions in Chapter 2, the capital costs of an underground hydrogen storage facility amount to 792.9 million €, of which 55% fall on the subsurface part of the storage and 45% on the surface part.
- In the case of the surface part of the UHS, the most significant part of total capital costs (25.6%) is the cost of compression, filtering, purification, and measuring equipment. In the case of the subsurface part of the storage, the most significant part of total capital costs (12.7%) is the cost of cushion gas. The annual operating costs of the UHS reach 20.9 million € and are mainly related to the hydrogen injection, drying, heating, cooling, purification, and measurement.
- In the reference scenario, the NPV is -41.42 million €, the internal rate of return is 5.17%, and the LCOS is 1.81 €/kg.The negative NPV of -41.4 million € means that with the assumed parameters' values, the revenues from hydrogen storage will not cover the capital costs, and the project implementation will reduce the company's value.

- The sensitivity analysis shows that three parameters have a significant impact on the financial result, i.e., corporate tax, discount rate, and storage service margin profit. In the analyzed range, the NPV changed from -21.9 to 138.8 million € for the discount rate, from -120.4 to 120.4 million € for corporate tax, and from -74.3 to 74.3 million € for storage service margin profit. The remaining parameters, i.e., cost of electricity, number of caverns, and number of cycles, had little impact on the final NPV value.

The Business case optimization analysis allowed for checking the sensitivity of the considered model concerning the changes of key input parameters (storage service margin profit, corporate tax, discount rate, cost of electricity, number of caverns, number of storage cycles) and to optimize the model in terms of justification business hydrogen storage in salt caverns in Poland. The analysis showed that changing the value of the storage service margin profit from 5.75% in the reference scenario to 13% results in reaching the break-even point (NPV=0). The sensitivity analysis shows three financial parameters significantly impact the financial result: storage service margin profit, corporate tax, and discount rate. Other parameters: the cost of electricity, the number of caverns, and the number of storage cycles had little impact on the final NPV value.

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