Hybrid energy storage system using post-mining infrastructure (HESS)

D.6.1. Integration of particular components of the HESS

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1. PURPOSE OF THE WORK

As part of Task 6.1 of the HESS project a comprehensive analysis of the operation of the hybrid energy storage system was carried out, integrating three energy storage technologies: a pumped hydro storage system (PHS), a compressed gas energy storage system (CAES/CCES), and a thermal energy storage system (TES).
Schematic diagrams of the HESS configurations based on compressed air and carbon dioxide are presented in Figure 1 and 2.

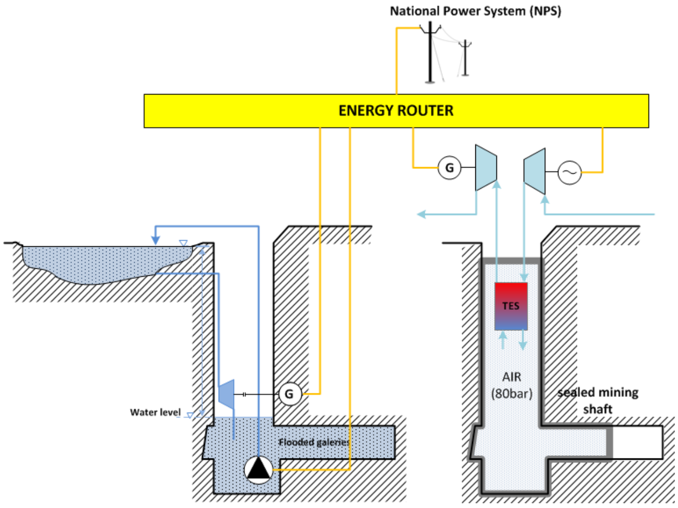

Fig. 1 Diagram of HESS using a compressed air energy storage system.

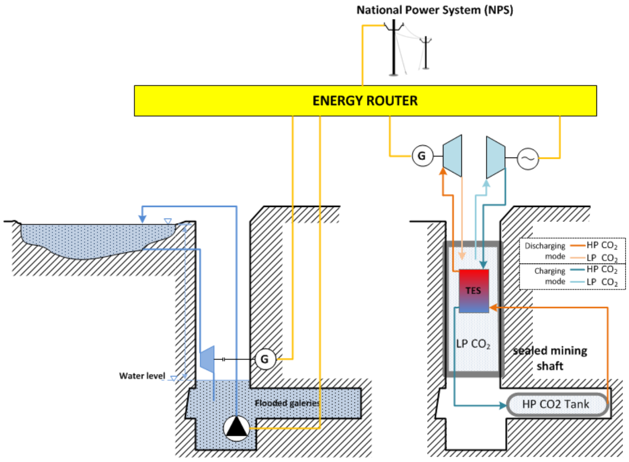

Fig. 2 Diagram of HESS using a compressed CO2 energy storage system.

The objective of the work was to analyze the operation of the hybrid energy storage system in order to develop a concept for the optimal thermal and mechanical integration of its individual components. The analysis was conducted assuming a minimum energy capacity of 10 MWh for each subsystem constituting the overall system.

As part of the study, preliminary mass and heat balances were developed, and key operational parameters were analyzed, taking into account both technical and economic aspects. This enabled a preliminary assessment of the performance of the considered HESS configurations and provided the basis for further optimization of system integration.

2. INTRODUCTION

Energy storage systems play a key role in the energy transition associated with the increasing share of energy generated from renewable sources (RES). Due to the high variability and low predictability of wind power plants and photovoltaic systems, it is necessary to implement technologies that enhance the flexibility and stability of power system operation.

Among the most important large-scale technologies are pumped storage hydropower plants (PSH) and compressed air energy storage systems (CAES). Both solutions enable the conversion of excess electricity into potential energy (in PSH system) or compressed gas energy storage (in CAES system), and subsequent recovery during periods of increased energy demand.

From a functional perspective, energy storage systems perform a number of important roles in the operation of the power system, including:

- Price arbitrage: storing energy during periods of low prices (e.g., during production surpluses) and selling it during periods of high demand,
- Integration of renewable energy sources – absorbing surplus energy production from wind farms and photovoltaic installations (including at negative prices) and distributing energy during periods of shortage,
- Providing reserve capacity and ancillary services – contributing to power system frequency stabilization and voltage regulation,
- Grid congestion management – reducing the risk of overloads and reducing the need for redispatching mechanisms; local flexibility reduces the risk of overloads,
- Peak shaving – limiting the operation of costly generating units to be used only during periods of peak energy demand.

In the context of ancillary services, frequency control reserves play a particularly important role, including: FCR (Frequency Containment Reserve), aFRR (Automatic Frequency Restoration Reserve), and mFRR (Manual Frequency Restoration Reserve). FCR provides the fastest automatic response to frequency deviations and is activated within seconds. aFRR serves as secondary frequency control, restoring the balance between generation and demand within minutes. mFRR is activated manually by the system operator to stabilize grid operation in the event of significant disturbances.

Another important ancillary service is the capability to perform a black start procedure, i.e., restart the power system after a complete or partial outage. This procedure involves starting selected generating units capable of islanding, followed by the gradual reconnection of subsequent grid components to restore stable operation of the entire power system.

In recent years, increasing volatility of electricity prices has been observed in Poland, both on an annual and daily basis. Significant price fluctuations are particularly evident on the Day-Ahead Market (DAM), including the occurrence of periods with negative prices. This phenomenon is primarily associated with periodic surpluses of electricity generation from renewable energy sources, especially from wind farms and photovoltaic installations.

The tables below (Tables 1-3) present a summary of the arithmetic mean electricity prices for each month in 2021, 2023, and 2024[1]. Prices below PLN 350/MWh are highlighted in green, while prices above PLN 550/MWh are highlighted in red.

Table 4 provides a summary of the maximum, minimum, and average electricity prices for each hour in 2024. In addition, it includes the number of hours in each month during which prices exceeded PLN 550/MWh, as well as the number of hours with prices below PLN 350/MWh, including occurrences of negative prices.

Table 5 presents a summary of the average annual electricity prices on the Day-Ahead Market for the period 2020–2024[2].

Table 1 Summary of average electricity prices (PLN/MWh) on the Day-Ahead Market (DAM) for 2021.[1]

2021	January	February	March	April	May	June	July	August	September	October
0:00	207,0	196,6	217,2	234,8	285,5	323,8	347,8	341,3	403,9	350,7
1:00	199,1	196,0	221,3	222,0	264,5	310,8	330,4	332,7	386,3	340,6
2:00	199,8	199,0	217,0	222,6	256,1	303,1	334,8	326,4	392,1	351,2
3:00	202,8	200,3	216,2	230,3	251,1	297,3	322,8	326,0	385,3	369,3
4:00	209,5	201,8	218,0	232,6	260,9	294,2	315,2	321,2	387,2	384,9
5:00	212,6	226,7	236,6	241,6	280,6	306,7	317,8	338,0	406,6	406,9
6:00	231,5	247,7	271,4	280,9	301,7	343,5	361,7	364,3	483,8	472,4
7:00	265,0	269,5	283,8	298,3	320,8	356,2	391,0	409,7	515,3	517,5
8:00	275,6	279,7	295,6	308,5	327,6	371,9	405,8	409,7	532,4	586,3
9:00	286,6	287,9	280,2	286,1	308,2	355,0	390,5	396,7	503,4	531,5
10:00	284,4	286,0	270,3	273,4	304,6	344,1	393,4	378,5	480,0	487,2
11:00	281,3	279,1	274,6	270,6	304,6	351,0	391,2	382,4	479,4	469,6
12:00	277,7	269,9	278,6	275,9	297,1	361,6	388,2	385,6	464,6	470,0
13:00	280,9	256,2	276,9	259,6	290,3	352,3	373,8	372,0	445,6	445,5
14:00	265,6	262,1	273,3	253,8	285,7	354,3	367,0	355,8	439,6	426,6
15:00	275,6	266,7	279,0	254,0	292,1	345,9	364,7	363,2	447,3	463,1
16:00	292,5	275,6	281,1	256,0	292,5	354,0	367,2	370,5	481,2	502,0
17:00	301,9	295,3	294,5	259,4	286,9	371,0	397,9	390,5	515,0	544,7
18:00	288,5	308,1	324,8	288,0	317,2	401,4	412,1	411,5	560,5	639,0
19:00	282,0	281,4	329,4	306,7	335,5	411,3	420,8	425,1	654,7	656,4
20:00	256,5	262,1	307,8	314,3	329,3	424,8	409,4	432,4	630,7	544,8
21:00	235,6	232,9	274,3	298,8	323,4	403,6	400,2	409,2	514,4	460,2
22:00	226,5	225,0	272,3	280,1	331,2	378,2	383,7	386,5	438,3	386,1
23:00	217,2	209,8	242,5	250,3	294,4	342,1	358,9	354,7	401,9	360,8

Table 2 Summary of average electricity prices (PLN/MWh) on the Day-Ahead Market (DAM) for 2023.[1]

2023	January	February	March	April	May	June	July	August	September	October	November	December
0:00	528,4	562,6	526,3	526,3	471,9	514,1	523,9	462,7	437,7	376,2	355,9	276,0
1:00	514,9	553,7	503,7	512,9	460,3	509,6	496,9	449,9	436,7	357,1	350,0	266,9
2:00	497,8	554,6	507,0	508,0	455,4	504,6	466,9	437,8	437,5	347,4	332,6	259,6
3:00	489,5	561,4	511,6	505,8	450,5	500,0	465,3	431,5	441,2	350,6	332,7	254,9
4:00	509,7	577,4	517,7	512,8	458,4	499,9	457,6	452,2	447,5	365,5	338,1	258,0
5:00	537,0	603,8	538,8	529,4	501,3	523,2	470,3	462,3	488,3	402,1	359,0	285,8
6:00	603,6	654,3	595,5	579,6	537,2	596,0	556,7	505,5	566,5	470,3	416,0	319,7
7:00	628,3	695,5	632,9	615,3	619,3	611,5	560,3	530,3	611,8	510,6	457,8	366,4
8:00	668,0	693,3	623,4	607,3	523,0	570,5	526,4	494,6	552,2	511,2	473,1	376,1
9:00	646,4	671,1	571,1	547,1	481,5	523,4	484,8	457,0	476,4	478,9	469,9	385,2
10:00	634,1	637,4	558,2	527,6	416,4	479,2	423,1	427,0	422,0	410,5	463,1	387,5
11:00	638,9	615,9	541,9	510,6	382,7	469,4	401,7	406,3	386,8	390,2	459,0	385,8
12:00	637,1	600,4	534,2	499,8	382,5	457,7	394,5	412,2	375,3	365,5	466,6	378,7
13:00	628,7	598,1	526,8	493,5	384,1	459,1	410,3	411,9	351,8	369,2	486,6	384,0
14:00	631,3	605,8	543,1	482,7	403,0	468,7	421,0	425,7	385,9	400,3	507,2	399,9
15:00	661,7	643,3	569,8	488,3	437,9	492,4	451,0	439,4	422,1	446,1	543,3	423,2
16:00	686,6	684,8	604,7	502,9	474,2	503,6	509,7	480,7	475,8	505,8	569,3	430,4
17:00	677,7	718,5	661,0	545,0	505,8	554,4	565,8	535,1	604,2	556,5	562,8	422,1
18:00	663,6	723,5	699,5	576,9	549,6	619,5	615,9	607,4	693,2	591,3	543,3	415,2
19:00	653,8	727,3	704,9	636,9	613,6	646,7	642,1	650,2	751,8	595,1	508,7	407,1
20:00	635,1	698,3	680,5	649,3	618,2	673,6	669,3	678,0	693,7	544,7	475,4	373,4
21:00	597,2	640,4	623,4	590,3	584,6	635,6	650,2	603,2	586,5	470,8	427,0	321,9
22:00	599,5	630,7	588,3	555,6	534,7	619,6	606,0	541,6	491,2	429,3	401,4	316,3
23:00	556,5	597,3	533,5	533,9	481,3	558,6	545,9	473,1	445,2	370,9	369,9	290,5

Table 3 Summary of average electricity prices (PLN/MWh) on the Day-Ahead Market (DAM) for 2024.[1]

2024	January	February	March	April	May	June	July	August	September	October	November	December
0:00	331,2	267,8	298,9	333,3	389,6	506,9	460,4	418,2	326,2	359,1	353,8	333,9
1:00	322,9	272,7	297,2	328,1	375,2	438,0	394,5	392,5	318,3	346,2	352,0	322,4
2:00	328,9	269,2	296,7	323,4	370,5	431,3	383,8	369,4	319,3	344,1	350,3	313,3
3:00	328,6	263,2	299,3	333,8	361,5	411,0	372,0	385,2	315,9	329,3	364,8	309,7
4:00	336,9	267,5	303,8	344,3	378,6	406,7	388,7	380,8	337,5	336,4	360,8	318,5
5:00	353,6	295,8	322,9	349,2	390,6	419,2	387,2	417,7	369,7	385,0	402,6	357,0
6:00	391,6	345,7	351,4	380,5	436,2	459,0	460,7	482,2	493,6	468,0	504,4	481,5
7:00	415,8	363,6	364,8	382,0	405,0	430,9	473,6	488,0	527,4	579,1	558,4	554,3
8:00	440,2	365,2	341,8	364,8	354,5	415,9	435,2	428,9	460,6	544,2	559,8	590,8
9:00	430,1	341,6	307,2	318,1	317,6	346,5	337,4	350,9	357,7	433,1	539,8	584,6
10:00	416,6	325,6	287,3	282,7	246,5	297,6	243,4	279,8	267,5	347,8	508,4	494,6
11:00	407,2	321,5	257,8	250,2	206,7	282,2	222,2	204,5	200,7	321,9	487,3	494,2
12:00	404,0	318,2	260,0	235,7	206,0	274,1	193,9	152,2	146,4	308,1	462,0	464,0
13:00	414,1	322,9	262,6	236,0	211,7	277,3	210,2	122,2	167,0	309,3	506,6	522,7
14:00	423,2	332,0	283,4	242,0	236,0	298,9	212,3	143,0	206,0	338,1	574,6	565,3
15:00	433,6	357,0	309,6	262,2	290,5	352,1	270,5	217,4	269,6	390,8	705,6	592,8
16:00	459,5	372,9	341,6	316,1	345,0	408,9	321,1	308,0	388,8	494,6	817,2	599,0
17:00	462,9	399,1	396,2	361,9	399,2	455,3	442,9	454,0	530,1	677,3	880,9	551,0
18:00	453,7	394,7	436,5	398,8	447,0	560,8	617,0	641,9	706,0	784,6	734,1	529,6
19:00	435,8	385,9	434,9	458,5	497,8	731,4	800,1	826,6	919,9	748,1	643,8	511,1
20:00	420,3	358,4	379,8	472,6	514,1	805,1	966,0	915,0	645,1	532,4	527,1	471,6
21:00	380,6	338,3	358,2	409,0	476,5	725,7	788,7	619,3	436,0	409,3	472,7	438,0
22:00	361,2	316,9	336,1	367,9	442,3	564,2	570,1	525,7	377,8	388,0	464,1	421,9
23:00	340,5	292,6	313,9	344,1	409,4	490,7	474,1	427,0	330,3	353,6	407,7	361,2

Table 4 Summary of hours per year with characteristic electricity prices from the Day-Ahead Market (DAM).

	January	February	March	April	May	June	July	August	September	October	November	December
ŚREDNIA cena, zł/MWh												
2021	252,3	250,6	268,2	266,6	297,6	352,4	372,8	374,9	473,0	465,3	-	-
2023	605,2	635,4	579,1	543,2	488,6	541,3	513,2	490,7	499,2	442,2	444,5	349,4
2024	395,5	328,7	326,8	337,3	362,8	449,6	434,4	414,6	392,4	436,4	522,4	459,2
MAX cena, zł/MWh												
2021	485	547,4	596,8	448,28	545,1	770,95	673,4	592,6	1037,1	1925,3	-	-
2023	1070,5	1010,7	882,2	884,3	2683,7	914,8	850,8	989,2	1058,4	860,2	783,8	777,9
2024	700,0	604,2	626,0	693,1	674,9	1560,2	1915,5	1975,2	2300,0	1778,1	2719,1	1447,8
MIN cena, zł/MWh												
2021	120	74,5	86,5	40,4	96,1	111,8	176,6	135,4	243,7	128,6	-	-
2023	22,0	343,8	106,6	36,7	4,5	44,7	37,3	97,6	0,1	0,0	22,3	-15,2
2024	96,5	43,2	43,1	-157,9	-99,4	-278,2	-186,4	-430,0	-256,2	-395,2	-21,7	-126,3
Ilość godzin z cenami >550 zł/MWh, h												
2021	0	0	0	0	0	7	4	7	146	175	-	-
2023	450	464	380	310	175	327	290	223	222	199	175	108
2024	79	7	9	16	39	165	152	146	125	159	270	194
Ilość godzin z cenami <350 zł/MWh, h												
2021	703	649	688	657	610	364	279	230	50	159	-	-
2023	32	1	8	19	82	54	87	97	78	167	147	366
2024	284	457	518	366	242	175	242	213	282	217	140	198
Ilość godzin z cenami <0 zł/MWh, h												
2021	0	0	0	0	0	0	0	0	0	0	-	-
2023	0	0	0	0	0	0	0	0	0	0	0	6
2024	0	0	0	17	31	23	25	53	36	19	10	17

Table 5 Average annual prices (weighted by volume) on the Day-Ahead Market (DAM).[2]

Year	Average DAM price [PLN/MWh]
2020	210,11
2021	401,17
2022	796,17
2023	533,62
2024	424,94

Based on the presented data, it can be observed that following the peak in electricity prices recorded in 2022, prices on the Day-Ahead Market (DAM) declined in 2023–2024. At the same time, significant hourly and monthly price volatility persists.

Frequent occurrences of very low prices, close to zero, as well as negative prices – observed particularly during weekends and periods of high renewable energy generation – Increase the economic attractiveness of energy storage during times of oversupply. Conversely, periods of high electricity prices enhance the profitability of discharging stored energy into the power system. As a result, increasing price volatility strengthens the potential for utilizing energy storage systems as an effective tool for optimizing power system operation.

Large-scale energy storage units - such as the Żarnowiec and Porąbka-Żar pumped storage hydropower plants - operate in cycles involving the storage of electricity during periods of low demand and its subsequent release during periods of increased demand.

In practice, the operation of these facilities is not determined solely by the potential for favorable price arbitrage, but increasingly also by the need to provide ancillary services to the national power system.

In Poland, the operating schedules of such units are largely determined by the Transmission System Operator (TSO), Polskie Sieci Elektroenergetyczne S.A. (PSE). The operator manages the operation of pumped storage hydropower plants to maintain the balance between electricity generation and demand, thereby supporting frequency stabilization and enhancing the flexibility of the power system.

These actions contribute to increasing the resilience of the system to fluctuations in energy generation and ensuring a stable electricity supply to consumers.

For the analysis of the operation of these installations, data available on the Energy Instrat platform were used[1]. Based on these data, the operating cycles of the Żarnowiec and Porąbka-Żar pumped storage hydropower plants were analyzed (Fig. 3 and 4).

The analysis of the operating profiles of these units indicates that, under typical conditions, pumped storage power plants store energy primarily during nighttime hours, usually between approximately 1:00 a.m. and 4:00 a.m., when electricity demand is at its lowest. The stored energy is subsequently released into the system during peak demand periods, with two main generation intervals: a morning period (approximately 5:00-9:00 a.m.), characterized by moderate output, and an evening period (approximately 6:00-9:00 p.m.), during which the highest generation levels are observed due to peak electricity demand.

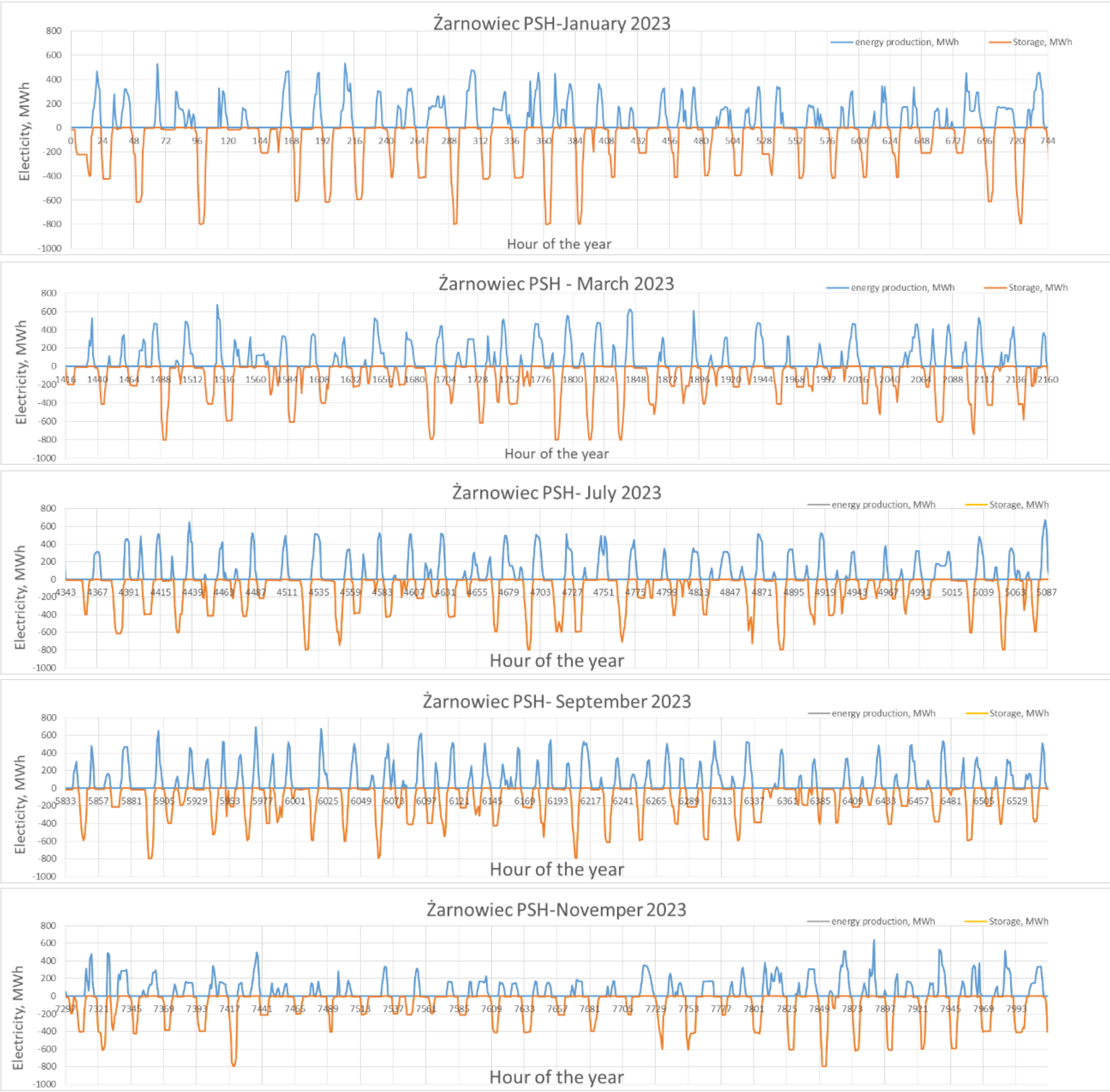

Fig. 3 Operation cycles of the Żarnowiec power plant in selected months of 2023 [1].

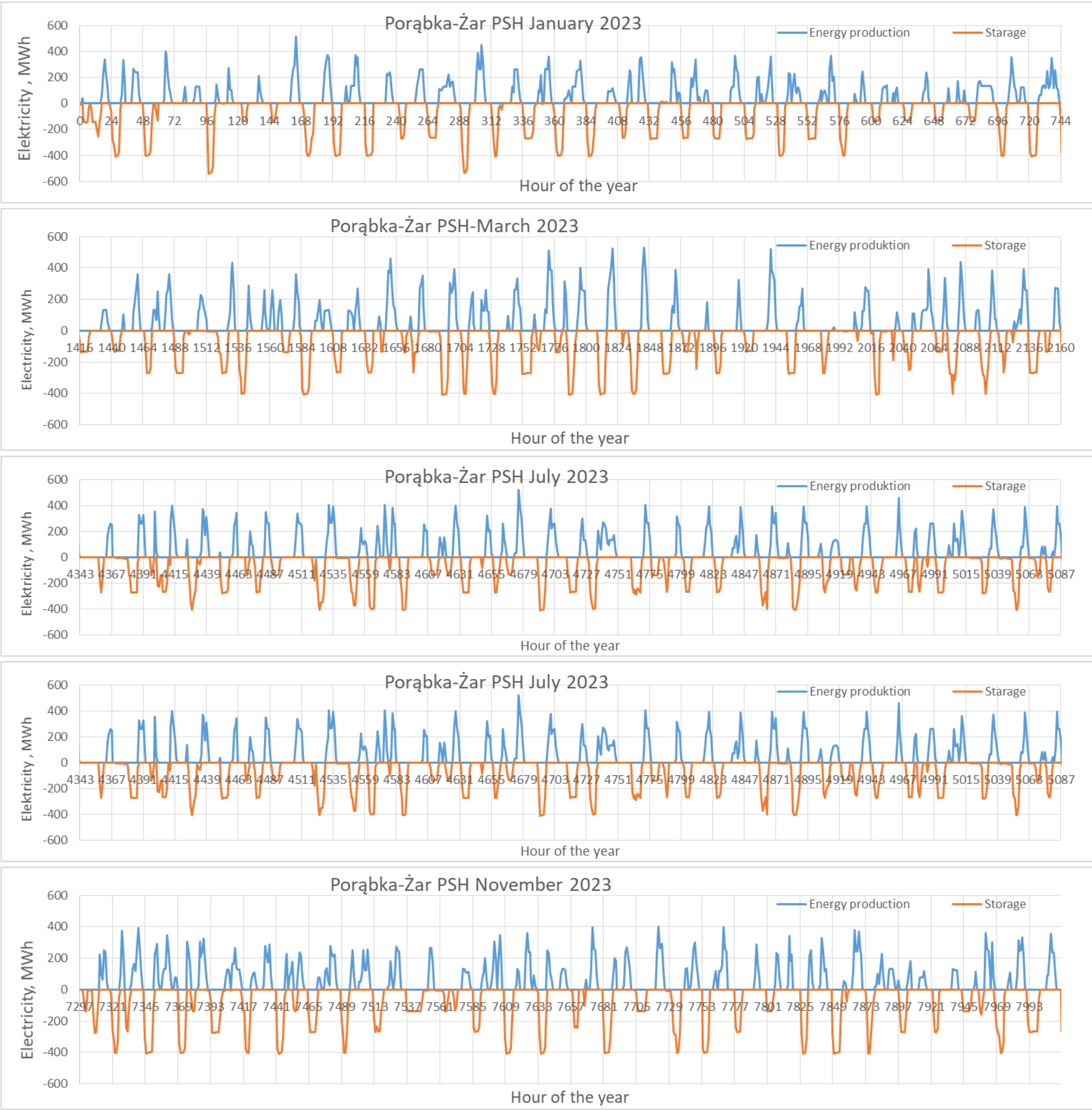

Fig. 4 Work cycles of the Porąbka-Żar power plant in selected months of 2023 [1].

3. MASS AND ENERGY BALANCE OF THE HESS SYSTEM

As part of Task 6.1, data obtained both from earlier stages of the HESS project and from available sources regarding the operation of existing energy storage installations were collected and analyzed. In particular, the parameters of selected mine shafts, determined in WP 2. of the project, and the technological parameters of the energy storage systems selected in WP 4. were used. This information was supplemented by operational data and performance characteristics of pumped-storage power plants operating in Poland - the Żarnowiec and Porąbka-Żar power plants - which served as a reference point for analyzing the operation of the designed system.

Based on the collected data, mass and energy balances were developed for the operation of the Hybrid Energy Storage System (HESS), taking into account the integration of three energy storage technologies: a pumped storage hydropower plant (PSH), a compressed gas energy storage system (CAES/CCES), and a thermal energy storage system (TES).
The analysis aimed to identify energy interactions between the individual subsystems and to assess the potential for energy recovery and reuse within the integrated hybrid system.

In earlier stages of the work, the following technological variants of energy storage systems were selected:

- A-CAES - a system with two-stage air compression and one interstage heat exchanger, enabling partial recovery of thermal energy generated during compression (**Błąd! Nie można odnaleźć źródła odwołania.**)[3],
- CCES – isobaric variant – a system based on a closed CO_2 loop, equipped with a heat exchanger downstream of the expander and additional exchangers enabling the transfer of thermal energy to the internal TES tank (**Błąd! Nie można odnaleźć źródła odwołania.**)[3],
- TES – a thermal energy storage system acting as a buffer for thermal energy generated during gas compression and utilized during expansion processes.
- PSH - a system in which electricity is generated by releasing water from an upper reservoir through a turbine into a mine shaft acting as a lower reservoir, while energy is stored by pumping water back to the upper reservoir (Fig. 7)[4].

To determine the optimal operating conditions of the HESS, the operational characteristics of individual subsystems were evaluated during both the charging phase and electricity generation. The analysis included variations in flow parameters, energy balances across individual system components, and the potential for thermal integration between subsystems.

Tables 6, 7 and 8 present the results of the mass and energy balance for the analyzed operating scenarios of the energy storage systems. For the A-CAES system, the influence of air temperature downstream of the final compression stage - corresponding to the inlet temperature to the TES unit - was analyzed. For the CCES system, the dependence of operating parameters on the pressure in the high-pressure carbon dioxide tank (HPT) was examined.
The obtained results provide a basis for further optimization of HESS operating parameters and for assessing its energy efficiency under various operating conditions.

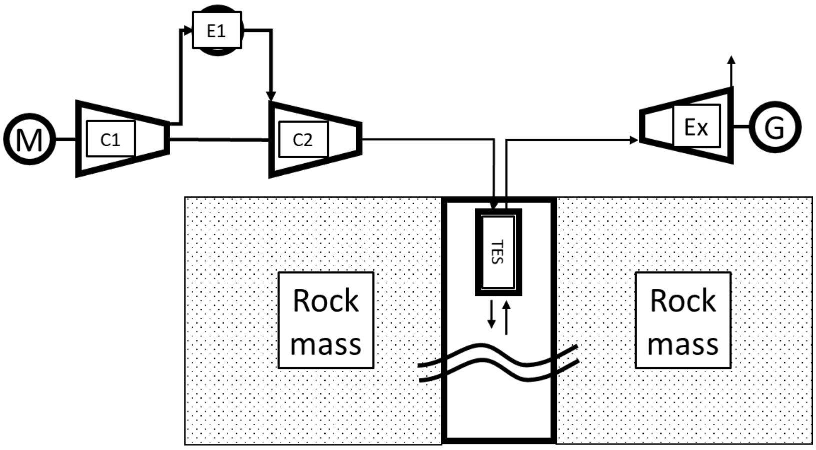

Fig. 5 Diagram of an adiabatic energy storage system using compressed air (A-CAES).

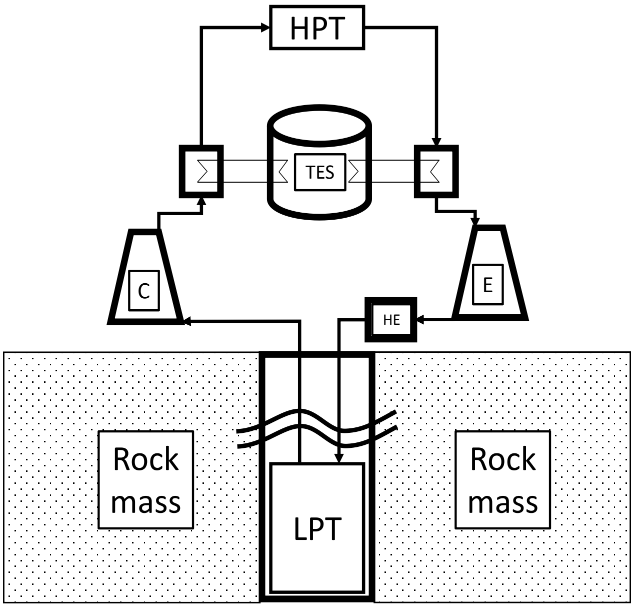

Fig. 6 Diagram of an adiabatic carbon dioxide energy storage system (CCES).

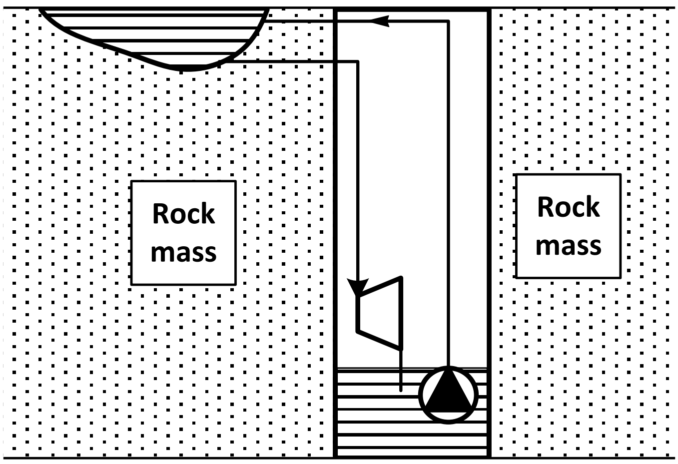

Fig. 7 Diagram of pumped hydro storage system (PSH).

Table 6 Summary of mass and energy balance results for the A-CAES system for variable temperature.

Maximum air temperature after the last compression stage – TES charging temperature, K	**600**	**650**	**700**	**750**	**800**	**850**	**900**
Energy efficiency of the A-CAES system, -	0,54	0,58	0,61	0,64	0,66	0,68	0,69
Maximum air pressure drop at TES, charging stage, kPa	3,92	4,24	4,55	4,85	5,15	5,44	5,73
Maximum air pressure drop at TES, discharging stage, kPa	15,67	16,92	18,13	19,32	20,48	21,61	22,73
Energy supplied to the compressor during the charging stage, MWh	155,83	157,09	160,12	164,64	170,43	177,32	185,17
Energy produced during the discharge stage, MWh	83,40	90,65	97,95	105,30	112,69	120,12	127,60
Required length of TES, m	29,84	30,16	30,45	30,70	30,93	31,16	31,37
Heat removed from compressor intercooler E1, MWh	75,52	62,28	50,68	40,42	31,29	23,11	15,75
Maximum air temperature at the inter-section heat exchanger, K	563,44	518,80	479,26	444,03	412,46	384,05	358,37
Average power of the 1st stage compressor, MW	9,75	8,11	6,67	5,39	4,26	3,24	2,32
Average power of the 2nd stage compressor, MW	9,72	11,53	13,35	15,19	17,05	18,93	20,82
Total power of the compressor unit, MW	19,48	19,64	20,01	20,58	21,30	22,16	23,14
Average power of the expander, MW	20,85	22,66	24,48	26,32	28,17	30,02	31,89
Volume of the compressed air reservoir, m^3	62691,6	62681,6	62672,7	62664,9	62657,6	62650,7	62644,1
Average temperature of the air charging the TES during the charging stage, K	570,00	617,50	665,00	712,50	760,00	807,50	855,00
Air flow during the charging stage, kg/s	35,40	35,39	35,38	35,38	35,38	35,37	35,37
Air flow during the discharging stage, kg/s	70,79	70,78	70,77	70,76	70,75	70,74	70,74

Table 7 Summary of mass and energy balance results for the CCES system for variable pressure in the tank and efficiency.

Isentropic efficiency of compressor/expander – 0,9; Temperature in TES – 400°C

HPT CO_2 pressure, MPa	**8,00**	**10,00**	**12,00**	**14,00**	**16,00**	**18,00**	**20,00**	**22,00**	**24,00**	**26,00**	**28,00**	**30,00**
LPT CO_2 pressure, MPa	0,20	0,26	0,31	0,37	0,43	0,49	0,55	0,61	0,68	0,74	0,80	0,87
HPT volume, m^3	323,1	372,4	433,4	497,3	562,8	629,5	697,0	765,4	834,5	904,1	974,2	1044,8
Energy production, MWh	18,15	22,84	27,65	32,54	37,51	42,54	47,65	52,82	58,05	63,34	68,68	74,08
Electricity consumption, MWh	23,00	28,97	35,10	41,33	47,65	54,06	60,56	67,15	73,81	80,55	87,36	94,23
CO_2 inlet temperature to HE, °C	62,02	61,42	60,93	60,50	60,10	59,73	59,39	59,05	58,74	58,44	58,15	57,87
Compressed CO_2 flow, kg/s	7,87	9,98	12,17	14,43	16,75	19,12	21,55	24,03	26,56	29,13	31,74	34,39
Expanded CO_2 flow, kg/s	15,74	19,95	24,35	28,86	33,50	38,25	43,11	48,07	53,12	58,26	63,48	68,78
System energy efficiency, %	**78,9**	**78,8**	**78,8**	**78,7**	**78,7**	**78,7**	**78,7**	**78,7**	**78,6**	**78,6**	**78,6**	**78,6**

Isentropic efficiency of compressor/expander – 0,9; Temperature in TES – 500°C

HPT CO_2 pressure, MPa	**8,00**	**10,00**	**12,00**	**14,00**	**16,00**	**18,00**	**20,00**	**22,00**	**24,00**	**26,00**	**28,00**	**30,00**
LPT CO_2 pressure, MPa	0,09	0,12	0,14	0,17	0,19	0,22	0,25	0,28	0,30	0,33	0,36	0,39
HPT volume, m^3	150,0	168,5	195,4	223,5	252,3	281,4	310,9	340,6	370,6	400,8	431,2	461,8
Energy production, MWh	11,21	13,90	16,83	19,80	22,83	25,90	29,01	32,17	35,37	38,61	41,90	45,22
Electricity consumption, MWh	14,06	17,44	21,12	24,87	28,67	32,54	36,45	40,43	44,45	48,53	52,66	56,83
CO2 inlet temperature to HE, °C	71,68	71,52	71,16	70,85	70,57	70,32	70,07	69,85	69,63	69,43	69,23	69,04
Compressed CO_2 flow, kg/s	3,65	4,51	5,49	6,49	7,51	8,55	9,61	10,69	11,79	12,91	14,05	15,20
Expanded CO_2 flow, kg/s	7,31	9,03	10,98	12,97	15,02	17,10	19,22	21,39	23,59	25,83	28,10	30,40
System energy efficiency, %	**79,8**	**79,7**	**79,7**	**79,6**	**79,6**	**79,6**	**79,6**	**79,6**	**79,6**	**79,6**	**79,6**	**79,6**

HPT –High Pressure Tank
LPT –Low Pressure Tank
HE - Heat Exchenger

Table 8 Summary of data for PSH system.

Storage capacity, m^3	21 420						
Operating cykle/device	**Production/ turbine**			**Storage/ pump**			
Time of cycle, h	3	4	5	5	6	7	8
Water stream, m^3/h	7 140	5 355	4 284	4 284	3 570	3 060	2 677
Device power, MW	16,6	12,5	10,0	13,52	12,72	9,66	8,45

For further analysis aimed at selecting the optimal technical configuration of the HESS, specific operating parameters were assumed for each energy storage subsystem. For the compressed air system (A-CAES), the compressor outlet air temperature was set at 500°C. For the compressed carbon dioxide energy storage system (CCES), the operating scenario assumed a high-pressure tank at 20 MPa and a TES medium temperature of 400°C and 500°C.

The adopted temperature range reflects the limits within which standard construction materials and conventional technological solutions can be applied, without the need for non-standard or cost-intensive material options.

To ensure comparability of the analysis results, it was assumed that all considered storage and generation systems would have similar energy capacities and a maximum electricity generation capacity of approximately 10 MWh. This assumption enables a direct comparison of the operating parameters of individual technologies within the hybrid energy storage system.

In the case of compressed air systems, there are no significant constraints related to the installation of storage tanks, which increases the design flexibility of this solution. In contrast, pumped storage hydropower systems require sufficient space for the installation of an upper water reservoir with a volume of approximately 12,000–18,000 m³.

In the case of a carbon dioxide compression system, it is necessary to provide a low-pressure reservoir with a volume of approximately 55,000–60,000 m³. This range represents a practical limit for locating such a reservoir within a mine shaft. For comparison, the maximum volume of the analyzed shaft at the Budryk Mine in Ornontowice is approximately 65,000 m³, indicating that its use as a reservoir for a CCES system is technically feasible. However, this requires careful matching of the installation's operating parameters to the available geometric constraints [5].

4. ANALYSIS OF THE OPTIMAL CONFIGURATION OF THE HESS SYSTEM

A-CAES and CCES energy storage systems are characterized by the need to operate in complete charging–discharging cycles. This means that once a charging or discharging process is initiated, the system must operate until completion, and the process cannot be interrupted without significantly reducing overall efficiency. Therefore, effective operation of these systems requires appropriate scheduling of charging and electricity generation periods in order to take advantage of electricity price volatility. For the purposes of the analysis, the fundamental operating parameters of the considered systems, along with electricity price data from the Day-Ahead Market (DAM) for 2024, were used.
Based on these inputs, an algorithm was developed to identify optimal time windows for HESS operation, depending on intraday electricity price variability.

Analysis of historical data from the Day-Ahead Market (DAM) indicates that it is not possible to define fixed price thresholds that clearly distinguish periods of "low" and "high" electricity prices. Prices exhibit significant variability between individual days, and the number of hours with prices below certain levels (e.g., <350 PLN/MWh) or above higher thresholds (e.g., >550 PLN/MWh) strongly depends on current supply conditions and the level of renewable energy generation. Therefore, the developed algorithm is not based on fixed price thresholds but instead relies on the analysis of average electricity prices over predefined charging and generation cycle durations. For each day, average prices are calculated for time intervals corresponding to the system's operating periods. Subsequently, time windows characterized by the lowest prices are selected for charging, while those with the highest prices are selected for electricity generation. This approach enables a more realistic representation of market conditions and improves the economic efficiency of the energy storage system.

Based on the developed algorithm, the electricity storage and generation processes were simulated, with particular focus on the impact of key system parameters, such as storage capacity and the power of compressors and generators (and thus the duration of charging and discharging cycles), on the amount and efficiency of electricity produced.

The graphs below (Fig. 8 and 9) present the operation of the pumped storage hydropower unit (PSH) for selected months with varying charging and electricity generation cycle durations. It can be observed that, for a constant system capacity, the number of cycles increases as the duration of charging and generation cycles decreases, depending on the month (Table 9).

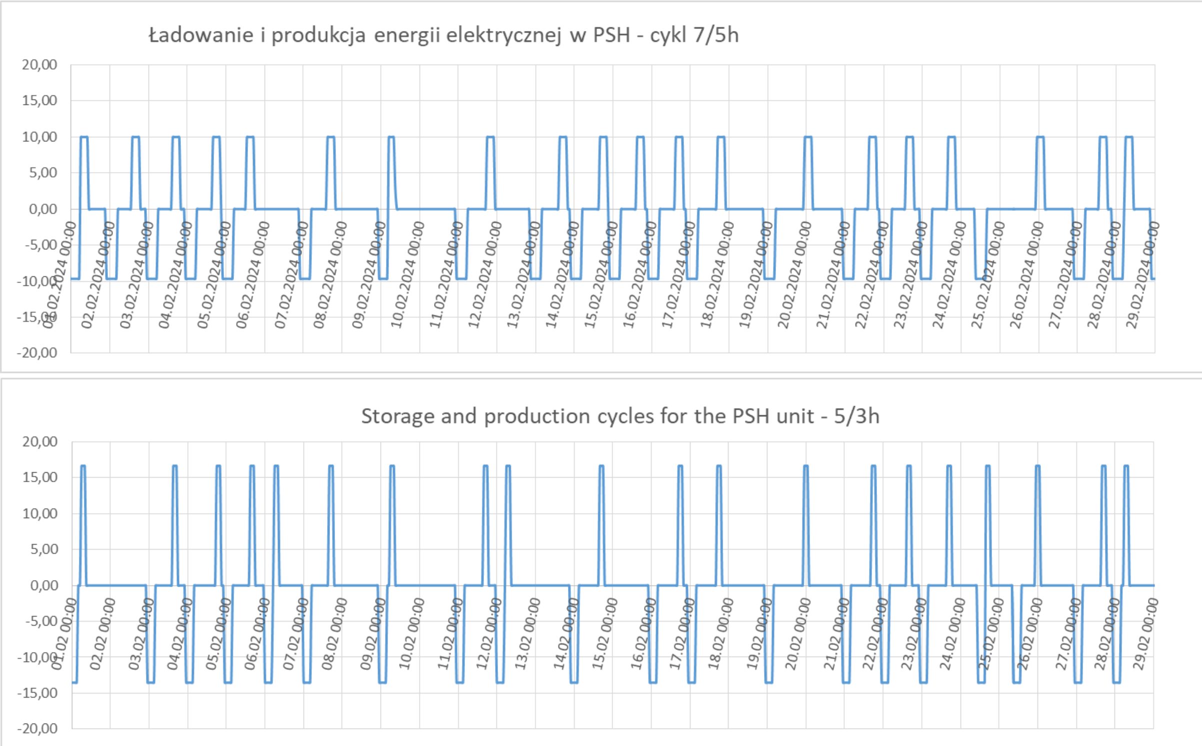

Fig. 8 Work cycle progression for the PSH unit for different cycle lengths in February.

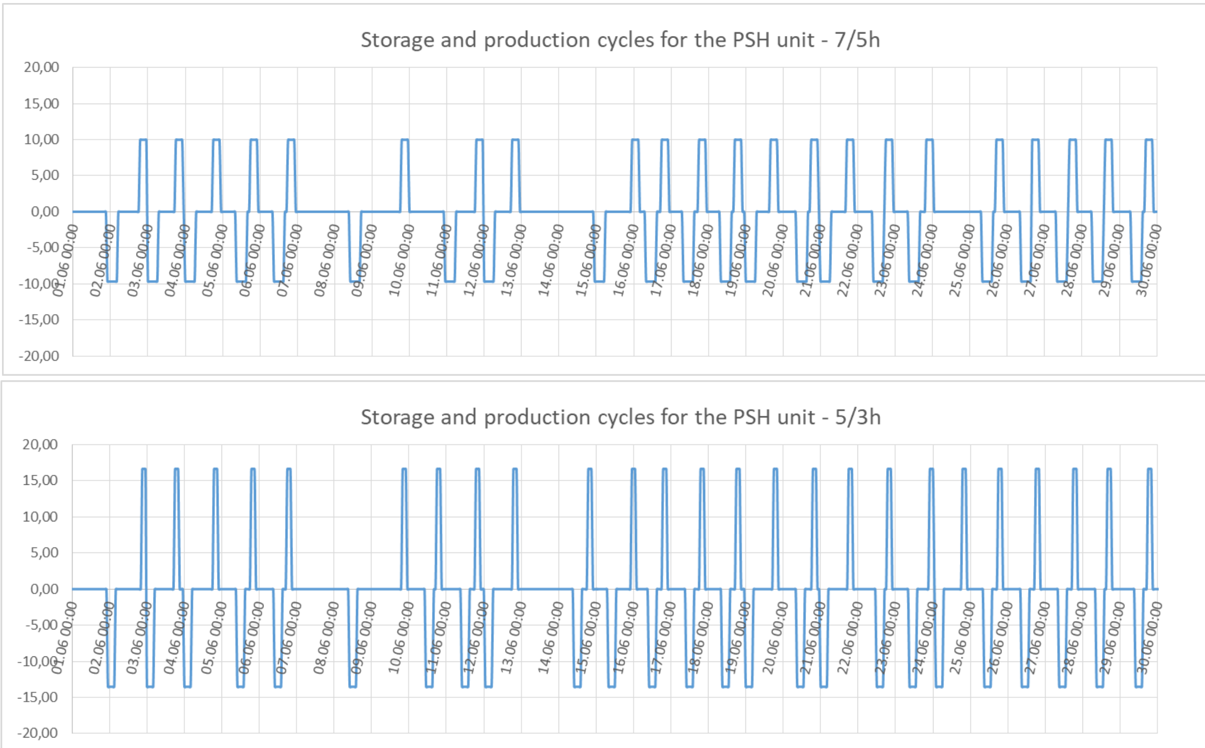

Fig. 9 Work cycle progression for the PSH unit for different cycle lengths in June.

The preliminary economic assessment considered only revenues from price arbitrage, defined as purchasing electricity during periods of low prices and selling it during periods of high prices. However, it should be emphasized that, in comprehensive business analyses of large-scale energy storage installations, the revenue structure is significantly more diversified. In practice, revenues from price arbitrage typically account for approximately 60–70% of the total revenue of such installations. The remaining share, estimated at 20–30%, is derived from the provision of ancillary services to the power system operator. These services include, among others, regulatory reserves (FCR, aFRR, mFRR, RR), voltage control, black start capability, as well as revenues from participation in capacity markets and long-term energy supply agreements.

Revenues generated by such installations should cover the full lifecycle costs of the system, including both capital and operating expenditures, such as project development costs, property taxes, depreciation, debt servicing, operation and maintenance (O&M) costs, and infrastructure upkeep. At the same time, the installation should ensure an adequate level of profitability in line with investor expectations.

It should also be noted that, under conditions of dynamic energy transformation, the revenue structure of energy storage systems may undergo significant changes. This will largely depend on the design and evolution of the electricity market, in particular the functioning of capacity mechanisms, auction systems, opportunities for participation in ancillary services markets, and the conditions of trading on wholesale electricity markets.

The share of revenue from price arbitrage may additionally depend on energy price volatility, including the occurrence of sharp price fluctuations resulting from, for example, extreme weather conditions, as well as the saturation level of the ancillary services market. When a significant number of energy storage facilities offer their own regulation services, the prices of these services may decline, leading to a shift in the balance between individual revenue sources. Short-term observations to date (e.g., on a monthly basis) indicate that, under such conditions, the share of revenues from price arbitrage may vary significantly (Table 9).

Table 9 Share of price arbitrage in the revenues of entities.

Market	Period	Share of arbitration in revenues	Source
ERCOT (USA)	2023 (annual average)	Arbitrage accounted for ~40% of total BESS revenues; the rest from ancillary services and the capacity market	Modo Energy 2024
ERCOT (USA)	June 2024	In the month, arbitrage contributed ~28% of revenues (up from 11% a year earlier)	Modo Energy 2024 (monthly report)
CAISO (California)	2023	Arbitrage revenues approx. 35-45% (depending on the month); decrease compared to 2021	CAISO Special Report 2023
CAISO (California)	2024	Reduction in price spreads – lower share of arbitrage (25-35%)	CAISO Battery Storage Report 2024
Wielka Brytania (GB)	2025 forecast	The market report predicts approx. 52% from energy trading (arbitrage/wholesale), with the remainder from services and contracts.	Modo Energy UK Outlook 2024
Polska	2024 (estimates)	Early market phase, significant role of contracts and system services; arbitrage 20-30%	URE Raport 2024

Table 10 – 12 presents the results of a preliminary techno-economic analysis of the impact of generating equipment configurations based on the pricing algorithm. For comparison purposes, similar energy storage capacities were assumed. The basis for selecting individual capacity levels for each unit was the storage capacity of the CCES unit, determined by the limited surface area of the tank intended for storing decompressed carbon dioxide.

The preliminary techno-economic analysis, conducted solely with consideration of revenues from price arbitrage, showed that the efficiency and operating time of the equipment responsible for charging and electricity generation have no significant impact on the fundamental technical parameters of the system, such as cycle efficiency or the total amount of electricity produced. These parameters remain largely dependent on the characteristics of the energy storage technology employed. However, the duration of the charging and discharging cycles has a significant impact on the economic performance of the installation, particularly in terms of total profit and unit profit per 1 MWh of electricity produced. The conducted analyses indicate that the highest electricity output from the energy storage system—regardless of the storage and generation technology used—is achieved with a charging time of approximately 5 hours and a generation time of approximately 3 hours.
These parameters were adopted as reference values for further comparative analyses.

To enable a comparative assessment of the analyzed systems, an indicator was introduced to quantify the amount of electricity that can be produced relative to the volume of the storage infrastructure. In this context, storage capacity is defined as the total volume of tanks required to store the working medium within a given system.
The highest value of this indicator was obtained for the compressed air energy storage system (A-CAES), reaching 0.494 MWh/m³. The second highest value was observed for the pumped storage hydropower system (PSH), at 0.333 MWh/m³, while the lowest value - 0.208 MWh/m³ - was recorded for the compressed carbon dioxide energy storage system (CCES).

It should be emphasized, however, that PSH and CCES systems require two storage tanks. In the PSH system, these are upper and lower tanks, while the CCES system requires tanks for the high- and low-pressure medium. In the CCES system, the tank for the expanded CO_2 must be significant in volume – in the analyzed variant, at least approximately 41,000 m³ with a storage capacity of 31 MWh.

Table 10 Summary of electricity production efficiency indicators for variable PSH generation equipment configurations.

Storage capacity, m^3	23 610			18 020			13 750	
Storage capacity, MWh	55			42			32	
Production time at max capacity, h	5	5	4	4	4	3	3	3
Charging time at max capacity, h	8	7	6	7	6	5	6	5
Annual energy production, MWh	15 366,4	15 631	15 636,8	12 014,5	11 934,6	11 906,6	9 085,2	9 085,2
Production efficiency, %	73,93	73,92	73,91	73,92	73,91	73,90	73,91	73,91
Number of hours with max. tank filling, h	2394	2600	2782	2708	2782	2761	2908	2761
Number of hours with min. tank filling, h	3580	3612	4000	3773	4000	4308	4161	4308
Number of production cycles,	280	285	285	287	285	284	297	310
Number of charging cycles,	279	284	284	286	284	283	283	283
Amount of energy produced from storage capacity MWh/MWh	**279,4**	**284,2**	**284,3**	**286,1**	**284,2**	**283,5**	**283,9**	**283,9**
Amount produced from storage volume (upper and lower storage) MWh/m^3	**0,325**	**0,331**	**0,331**	**0,333**	**0,331**	**0,330**	**0,330**	**0,330**
Profit from price arbitrage, PLN								
January	-52 839	-39 886	-7 856	-33 708	-17 006	-2 326	-12 836	-13 375
February	-20 533	-15 028	10 456	-1 2319	-674	20 271	-2 000	6 285
March	-24 404	-10 602	22 069	-3 221	6 373	32 826	3 777	14 764
April	29 089	37 002	99 582	46 598	66 187	85 159	51 024	55 122
May	149 774	188 086	226 386	134 537	158 875	206 368	125 616	146 160
June	265 660	314 550	489 409	282 250	356 604	416 599	289 336	303 853
July	599 880	628 844	714 536	503 617	527 115	615 711	430 140	454 234
August	532 237	579 411	766 276	486 607	567 548	691 690	463 407	514 348
September	366 858	430 589	526 163	356 859	388 160	453 781	313 586	333 453
October	177 242	222 086	303 843	185 706	216 792	284 927	193 731	201 969
November	283 167	303 473	326 709	246 648	234 384	283 831	193 049	200 139
December	192 765	215 546	255 799	174 251	182 380	2146 92	145 696	148 778
Total	2 498 896	2 854 070	3 733 371	2 367 826	2 686 736	3 303 529	2 194 526	2 365 729
Unit profit PLN/MWh	**163**	**183**	**239**	**197**	**225**	**277**	**242**	**260**

Table 11 Summary of electricity generation efficiency indicators for variable configurations of A-CAES-B generation equipment.

Storage capacity –compressed air, m^3	31 645			24 165			18 411	
Storage capacity, MWh	55			42			32	
Production time at max capacity, h	5	5	4	4	4	3	3	3
Charging time at max capacity, h	8	7	6	7	6	5	6	5
Annual energy production, MWh	14 847,3	15 314,6	15 635,2	11 820,5	11 939,4	11 912,8	9 070,2	9 076,6
Production efficiency, %	67,65	67,64	67,63	67,64	67,63	67,62	67,63	67,62
Number of hours with max. tank filling, h	2032	2310	2631	2347	2631	2761	2761	2761
Number of hours with min. tank filling, h	3989	3942	4150	4150	4150	4307	4307	4307
Number of production cycles,	278	283	285	285	285	306	309	310
Number of charging cycles,	270	278	284	281	284	283	283	283
Amount of energy produced from storage capacity MWh/MWh	**270,0**	**278,4**	**284,3**	**281,4**	**284,3**	**283,6**	**283,4**	**283,6**
Amount produced from storage volume MWh/m^3	**0,469**	**0,484**	**0,494**	**0,489**	**0,494**	**0,493**	**0,493**	**0,493**
Profit from price arbitrage, PLN								
January	-78 167	-70 632	-53 560	-58 434	-51 841	-39 609	-42 436	-39 660
February	-33 619	-25 650	-8 002	-20 937	-14 192	-7 619	-13 890	-13 388
March	-60 841	-47 729	-13 307	-35 277	-20 553	1 555	-16 873	-8 273
April	-14 287	5 834	63 711	23 157	38 846	56 631	29 572	34 186
May	98 013	137 114	190 576	95 694	131 750	171 993	104 801	120 062
June	284 357	334 610	445 851	285 778	323 496	378 699	263 528	274 826
July	535 611	591 016	693 392	472 315	511 497	583 923	417 731	430 253
August	562 681	638 651	787 872	524 284	584 951	669 699	477 527	497 298
September	301 613	363 070	509 200	334 691	375 581	430 633	303 615	315 935
October	144 000	189 352	263 490	163 046	186 201	245 713	169 792	173 852
November	216 075	237 092	293 512	194 590	209 177	243 995	170 163	172 772
December	151 310	170 677	216 292	140 097	151 548	177 121	119 182	122 743
Total	2 106 748	2 523 404	3 389 027	2 119 006	2 426 462	2 912 734	1 982 711	2 080 606
Unit profit PLN/MWh	**142**	**165**	**217**	**179**	**203**	**245**	**219**	**229**

Table 12 Summary of electricity production efficiency indicators for variable configurations of CCES generation equipment.

Compressed CO_2 storage capacity -HTP, m^3	2 030			1 557			1 151	
Storage capacity, MWh	54,8			42			31	
Expanded CO_2 storage capacity -LTP, m3	72 847			55 870			41 300	
Production time at max capacity, h	5	5	4	4	4	3	3	3
Charging time at max capacity, h	8	7	6	7	6	5	6	5
Annual energy production, MWh	14797,7	15263	15583	11832,4	11951,5	11924,8	8809	8815,2
Production efficiency, %	78,79	78,78	78,77	78,78	78,77	78,76	78,77	78,76
Number of hours with max. tank filling, h	2032	2310	2631	2347	2631	2761	2761	2761
Number of hours with min. tank filling, h	3989	3942	4150	4150	4150	4307	4307	4307
Number of production cycles,	278	283	285	301	305	284	284	306
Number of charging cycles,	270	278	284	281	284	283	283	283
Amount of energy produced from storage capacity MWh/MWh	**270,0**	**278,5**	**284,4**	**281,7**	**284,6**	**283,9**	**284,2**	**284,4**
Amount produced from storage volume (HTP+LTP) MWh/m^3	**0,198**	**0,204**	**0,208**	**0,206**	**0,208**	**0,208**	**0,208**	**0,208**
Profit from price arbitrage, PLN								
January	-5 057	3 542	20 980	-3 920	2 500	20 573	2 612	2 727
February	17 951	26 659	44 893	17 357	23 882	37 404	19 102	18 052
March	3 860	17 490	54 698	15 802	29 787	52 886	22 462	29 129
April	46 424	66 350	122 212	68 007	82 078	103 374	63 390	66 546
May	181 669	217 984	265 772	158 140	189 759	229 045	143 917	156 923
June	366 618	415 978	522 809	350 210	383 566	438 988	299 428	309 000
July	609 609	662 133	758 981	528 908	563 399	636 430	442 842	453 455
August	617 543	691 646	838 071	570 157	625 644	706 349	491 054	507 435
September	352 749	413 422	557 646	375 613	412 399	468 915	324 310	334 229
October	225 790	267 291	341 288	222 851	244 325	309 341	211 081	212 345
November	292 853	312 666	368 780	249 712	263 896	307 593	211 321	209 737
December	225 894	244 381	288 565	194 022	204 470	237 313	159 855	159 674
Total	2 935 903	3 339 542	4 184 693	2 746 859	3 025 706	3 548 212	2 391 375	2 459 252
Unit profit PLN/MWh	**198**	**219**	**269**	**232**	**253**	**298**	**271**	**279**

5. SUMMARY

This report presents a comprehensive technical and process dataset describing the operation of a hybrid energy storage system (HESS), integrating pumped storage hydropower system (PSH), compressed gas energy storage system (CAES/CCES), and thermal energy storage system (TES).

The work focused on identifying key operational parameters and interactions between subsystems, as well as developing a concept for the optimal thermal and mechanical integration of HESS components, assuming a minimum energy capacity of 10 MWh for each subsystem. Based on the analyses performed, operating parameters were determined and mass and heat balances were developed, providing a a solid foundation for further optimization of the system configuration.

The analysis considered both technical and economic aspects, enabling a preliminary assessment of system performance. The results indicate that the optimal operating model and sizing of energy storage systems within HESS depend primarily on their intended role in the power system - whether focused on price arbitrage or the provision of ancillary services.

The increasing volatility of electricity prices and the growing frequency of extreme price events highlight the need for energy storage systems with high operational flexibility and clearly defined operational objectives. At the same time, a trade-off exists between system capacity, operating time, and investment costs. Increasing installed capacity may reduce operating time but leads to higher capital expenditures, while longer operating cycles at lower efficiency may limit economic benefits.

The preliminary results of the price arbitrage analysis, conducted without accounting for additional electricity trading costs, indicate that higher storage capacity leads to increased electricity output. However, storage replenishment time remains a key factor influencing revenue, as shorter cycles enable more effective use of favorable market conditions.

The current stage of work provides a dataset necessary to support detailed techno-economic and life cycle assessment (LCA) analyses in subsequent stages of the project. In WP7 of HESS project, a comprehensive techno-economic evaluation will be conducted, taking into account capital and operating costs as well as the full revenue structure. The results will enable the determination of the optimal technological configuration and operating parameters of the HESS system for its potential implementation in post-mining infrastructure.

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