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Energy storage using compressed air

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Krzysztof KACZMARCZYK [1*], **Piotr DOBRZANIECKI** [1]

Author's affiliations and addresses:

[1] KOMAG Institute of Mining Technology, Pszczyńska 37, 44-101 Gliwice, Polska

*** Correspondence:**

e-mail: kkaczmarczyk@komag.eu

Abstract:

The climate change is probably the greatest challenge humanity is facing today. In order to protect future generations from the catastrophic effects of the process, actions to achieve climate neutrality are being taken worldwide. These actions include development of renewable energy sources. Renewable energy depends on weather conditions, which results in a mismatch between supply and demand for energy. Use of energy storage is the technical solution to minimize this issue. The paper presents topics related to the potential storing of surplus electricity produced from renewable energy sources (RES) in the form of compressed air. The article also shows worldwide solutions for energy storage using compressed air. As part of the work, three variants of a warehouse consisting of standardly available pneumatic units were considered. The conducted analyzes made it possible to determine the energy efficiency of such a system. It can be observed that greater efficiency is achieved by using large flow compressors and the operation of the pneumatic motor at a higher supply pressure. In addition, it can also be said that the greatest losses are associated with the operation of the compressor, which generates large amounts of heat during operation. Increasing the efficiency of the energy storage system can be achieved by utilizing the heat generated in the compression process.

Keywords: energy storage, pneumatic storage, Compressed Air Energy Storage (CAES), Renewable Energy Sources (RES)

1. Introduction

According to the Green Deal, a strategy for climate neutrality planned as a goal for 2050 [1], reducing CO_2 emissions can be achieved by increasing the share of renewable energy sources (RES) in the energy mix. Due to the cyclical and unpredictable nature of energy production from RES, their cooperation with energy storage facilities significantly increases efficiency of the energy system and enables matching energy supply and demand. This cyclicality is especially observed in the case of photovoltaic farms, where electricity is produced during the day, and the installation is unproductive at night, moreover, in the annual cycle insolation changes (Fig. 1) [2-4].

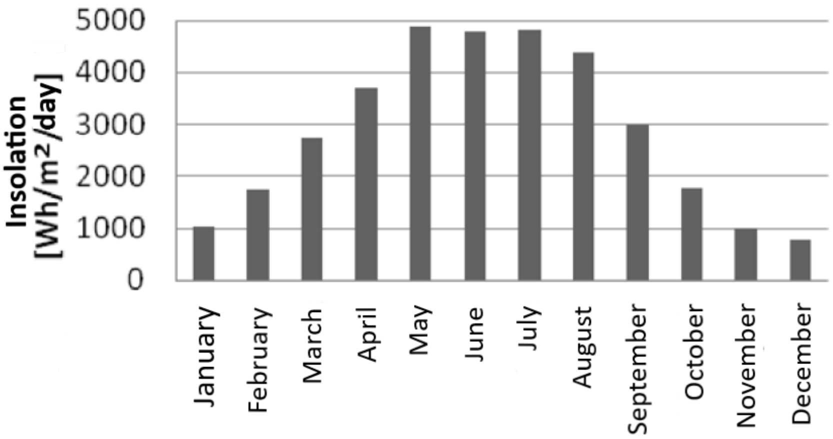


Fig. 1. Average daily insolation during the year [3]

The cyclical operation of RES sources creates the risk of unstable operation of transmission and distribution networks. RES production unpredictability can be compensated by energy storage. Regarding the RES installation, the share of energy storage is increased under the government program "My Electricity", which in its fourth edition allows for support for home energy storage solutions, thus increasing self-use of produced energy [5].

Energy storage facilities are divided according to their size (domestic and industrial) and due to the technologies used, such as: electrochemical batteries, pumped-storage power plants, supercapacitors, fuel cells, superconducting energy storage, kinetic and pneumatic energy storage, liquefied air, reservoirs using heat pumps and hydrogen storage. The most effective, and at the same time the most popular in recent times, are electrochemical battery storage units. These storage units were first used in cooperation with domestic and medium-sized RES installations. It is assumed that the capacity of produced battery energy storage will increase from less than 30 GWh in 2021 to 362 GWh in 2025 [6]. Forecasts for major battery cell manufacturers are shown in Fig. 2.

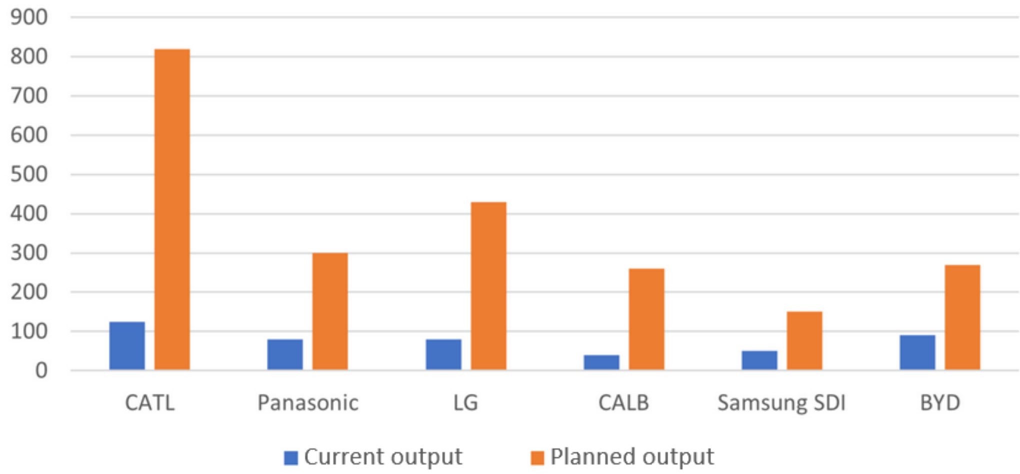


Fig. 2. Annual battery production of selected manufacturers in 2021 and planned for 2030 [6]

The increase in the demand for batteries will entail an increase in the demand for raw materials, which will ultimately translate into an increase in the cost of such storage units. In the energy sector, pumped-storage power plants PHS - Pumped Hydroelectric Storage are in the lead, accounting for over 96% of global electricity storage capacity (Fig. 3).

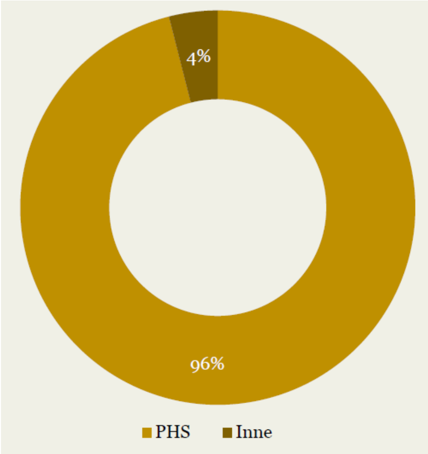


Fig. 3. Global share of energy storage [7]

Other storage technologies are also being developed, including the technology of energy accumulation in compressed air CAES - Compressed Air Energy Storage.

Currently, there are only a few such installations in the world, the most recognizable of which are: McIntosh in the US state of Alabama and Huntorf in Germany.

2. Research methods

2.1. Gas power plants using compressed air storage

The Huntorf power plant (Fig. 4, Table 1) in Germany was put into operation in 1978 [8]. At that time, it was the world's first commercial power plant with a compressed air energy storage facility. Originally, it was designed to absorb excess energy produced from the nearby nuclear power plant and serve as an emergency source of electricity. Increase in the share of RES in production of electricity meant that the power plant with an underground storage began to play an increasingly important role.

a) b)

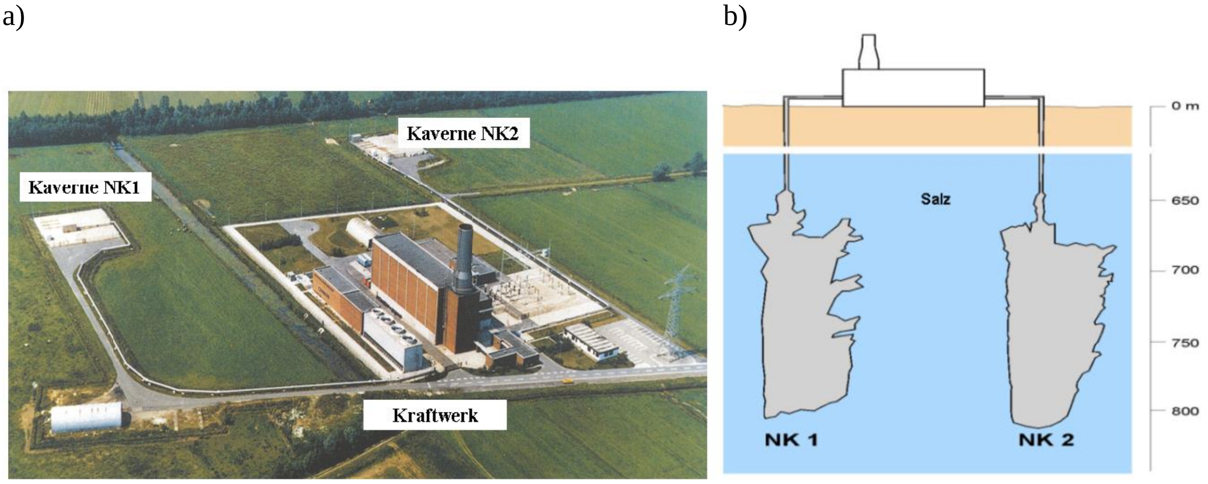


Fig. 4. Huntorf power plant: a) general view, b) location of caverns [9, 10]

Table 1. Technical data of the Huntorf power plant [11]

Power	
Gas turbine	290 MW (≤3 hrs)
Compressor turbine	60 MW (≤12 hrs)
Air flow rate	
Gas turbine	417 kg/s
Compressor turbine	108 kg/s
Storage capacity	310 000 m^3 (140 000 m^3 + 170 000 m^3)
Storage air pressure	
Minimum permissible	1 bar
Minimum operational (exceptional)	20 bar
Minimum operational (regular)	43 bar
Maximum permissible and operational	70 bar

The underground part of the power plant consists of two salt caverns with a total capacity of approx. 310 m^3, for which the working pressure range is 50-70 bar. Huntorf power plant deliberately resigned from recuperators (although this would increase efficiency) to minimize start-up time of the system. Reliability of the power plant over the 30-year period of operation amounted to approx 99%. The energy efficiency of the power plant is 42%. In 2006, the power plant underwent modernization and its capacity was increased from 290 MW to 321 MW [8].

Fig. 5 shows the main components of the installation. Compressed air in the storage unit powers the gas turbines of a power plant. In classic gas turbines, about 2/3 of the power is used to compress the air entering the combustion chamber (100 MW net power + 200 MW compressor operation = 300 MW gross power). In the CAES power plant, air delivered to the turbine is already compressed and thus. the turbine generates full power (300 MW instead of 100 MW).

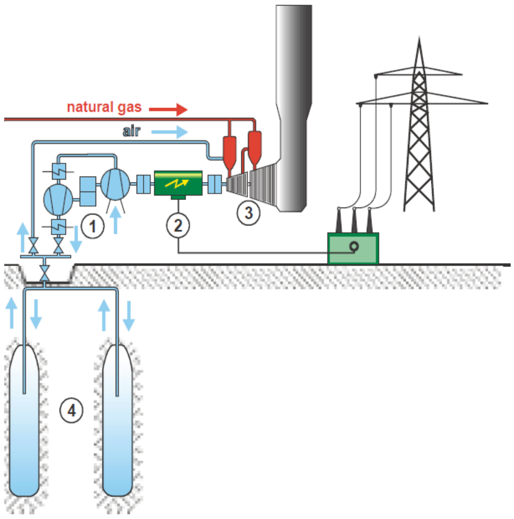


Fig. 5. Main components of the installation: 1) compressor unit, 2) motor-generator unit, 3) gas turbine, 4) underground compressed air storage unit [11]

Another CEAS storage solution is the 110 MW McIntosh power plant, which was built in the salt mines of the USA, in southwest Alabama. Air is compressed in one cavern with a volume of 560,000 m^3 to a working pressure of 45-74 bar. Full power operation can be maintained for more than 26 hours. Technological solutions (Fig. 6, Fig. 7) and operating parameters such as: pressure, temperature, etc., uses the experience of the Huntorf power plant, however, a heat recuperator was used here, allowing to reduce fuel consumption by approx. 22%. A combustion chamber for two types of fuel - natural gas and fuel oil was used [12].

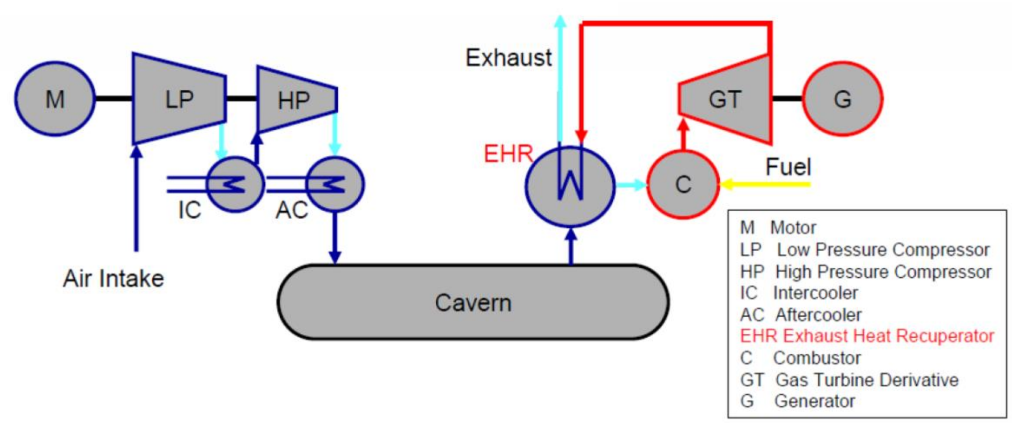


Fig. 6. Diagram of CAES with heat recuperator [10]

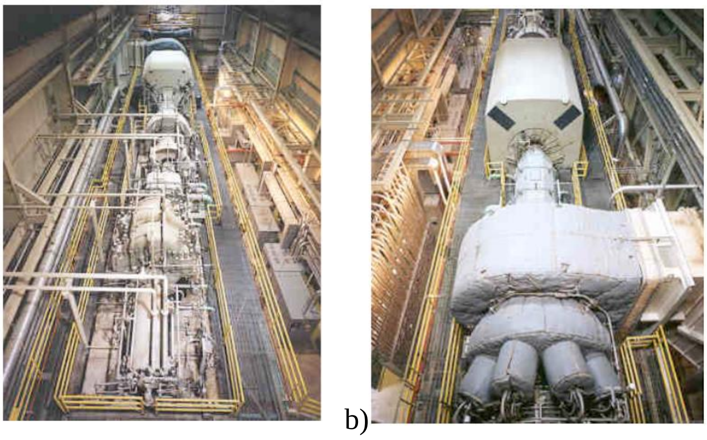
a)  b)

Fig. 7. McIntosh power plant machine room: a) McIntosh compressor system, b) turbine [12]

2.2. Pneumatic storage unit integrated with thermal energy storage unit

In order to increase energy efficiency of the compressed air storage unit, a research work is being carried out to recover the heat energy lost to during its compression (Fig. 8). This problem was resolved in the AA-CAES (Advanced Adiabatic Compressed Air Energy Storage) project.

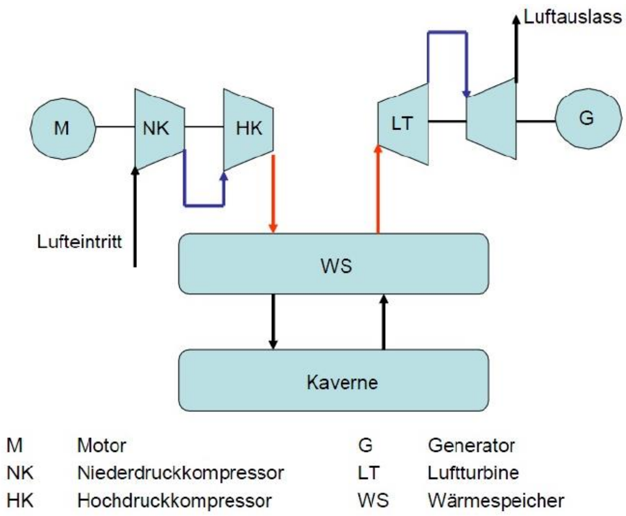


Fig. 8. Diagram of compressed air storage with heat storage [13]

Project uses a horizontal mine roadway approx. 120 m long and approx. 5 m high, which was sealed with concrete plugs and a steel door. Thermal energy storage unit was placed inside a separate roadway (Fig. 9) and consisted of a rock storage (sensible heat) with a capacity of 12 MWh and a PCM storage (latent heat) with a capacity of 0.171 MWh. The heat storage units reached a temperature of 560°C.

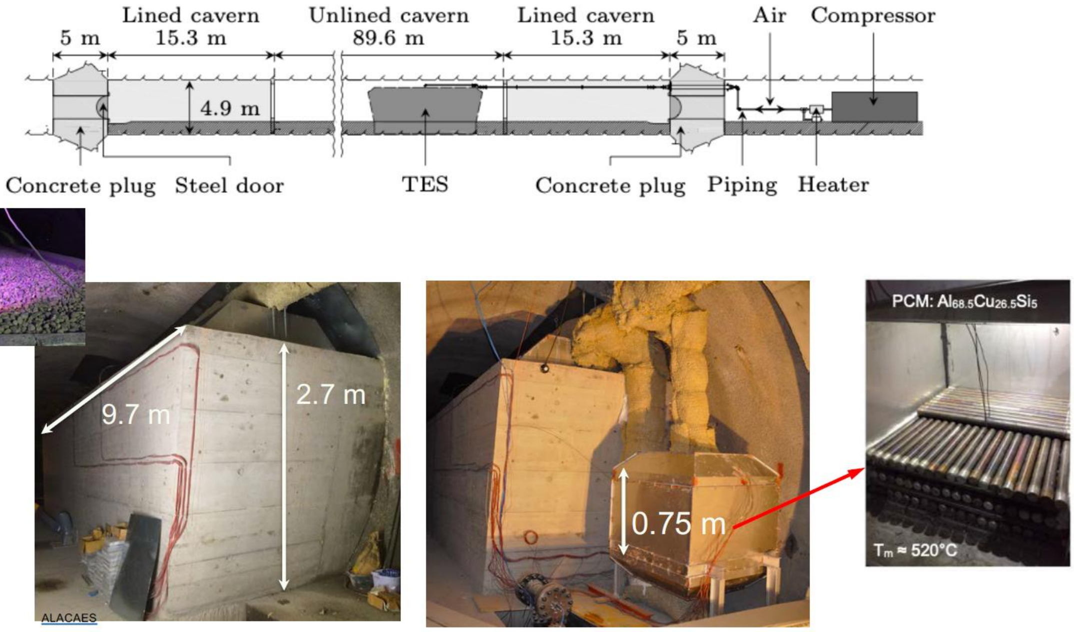


Fig. 9. AA-CAES (Advanced Adiabatic Compressed Air Energy Storage) [14]

Efficiency of the pilot installation made under the AA-CAES project was estimated at 65-75%. The turbine and generator were not manufactured within the project, and their efficiencies were assumed in the simulations to be 0.85 and 0.97, respectively [14].

2.3. Hydrostor's A-CAES plant

In 2019, Hydrostor launched an A-CAES storage unit in Goderich, Ontario (Fig. 10). It is a solution that uses an underground air tank and heat storage unit. Installation has a power of 1.75 MW, while the charging power is 2.2 MW, and the energy storage capacity is 10 MWh [15]. In addition to the project in Goderich, the company has three more A-CAES installations in its portfolio, which it intends to launch in the future.

Fig. 10. A-CAES storage facility in Goderich, Ontario, Canada [16]

3. Results - evaluation of using the standard pneumatic devices for compressed air energy storage

Examples of installations using compressed air as energy storage are presented above. These solutions are mostly the components of commercial power plants in which dedicated turbine designs were used. In the further part of the article, the authors presented a technical and energy analysis of the system based on commonly available pneumatic devices. Such an approach to the issue would popularize the use of pneumatic storage units. In the system, air is compressed with an industrial compressor, air is stored in steel tanks, and pneumatic motors are used to generate the torque driving the electricity generator (Fig. 11).

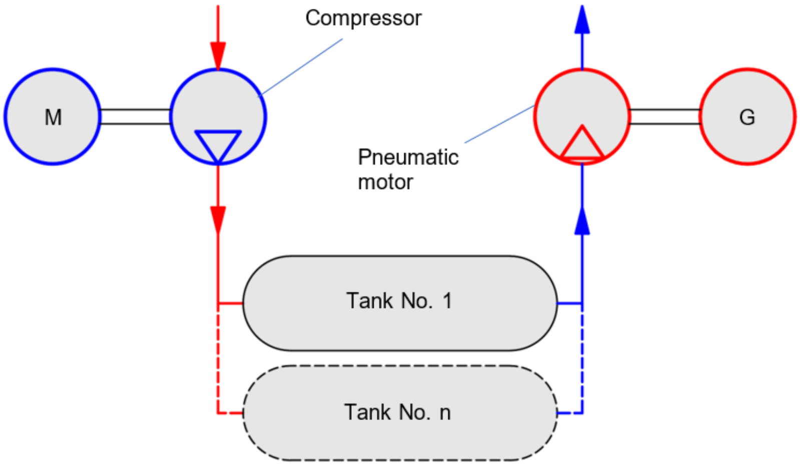


Fig. 11. Schematic diagram of compressed air storage unit

Three variants of the unit were analyzed.

<u>Variant 1</u>

Variant 1 uses a screw displacement compressor. Currently, it is the most common type of compressors in the industry (93.5%) [17]. Compressing air is a very energy-intensive process and it is assumed that about 80% of the energy supplied to the compressor is converted into heat, and only 20% is the compressed air energy (whereby the energy consumption for displacement compressors should be in the range of 0.09-0.13 kWh/m^3) [18].

A CompAir L250 screw compressor was suggested (Fig. 12).

Model sprężarki	Max. ciśnienie robocze [bar g]	Silnik napędowy [kW]	Wydajność[1)] [m³/min]	Poziom hałasu[2)] [dB(A)]	Ciężar [kg]	Wymiary dł. x szer. x wys. [mm]
L160	7,5	160	32,04	76	4186	2907 x 2071 x 2193
	10	160	28,20	76	4186	2907 x 2071 x 2193
	13	160	23,91	76	4186	2907 x 2071 x 2193
L200	7,5	200	39,23	77	4415	2907 x 2071 x 2193
	10	200	34,85	77	4415	2907 x 2071 x 2193
	13	200	29,38	77	4415	2907 x 2071 x 2193
L250	7,5	250	42,03	78	4625	2907 x 2071 x 2193
	10	250	37,01	78	4625	2907 x 2071 x 2193
	13	250	32,64	78	4625	2907 x 2071 x 2193
L290	7,5	250	47,10	79	4650	2907 x 2071 x 2193
	10	250	41,53	79	4650	2907 x 2071 x 2193
	13	250	36,44	79	4650	2907 x 2071 x 2193

Fig. 12. CompAir Screw compressor [19]

The Dusterloch DMO 15 gear motor was suggested as the pneumatic motor (Fig. 13). The air consumption characteristics of the pneumatic motor is shown in Fig. 14.

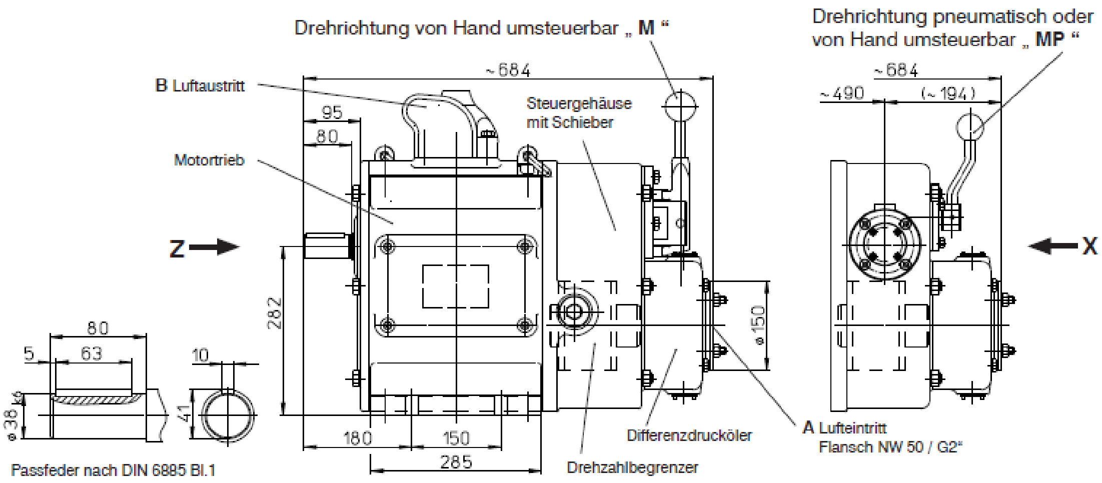
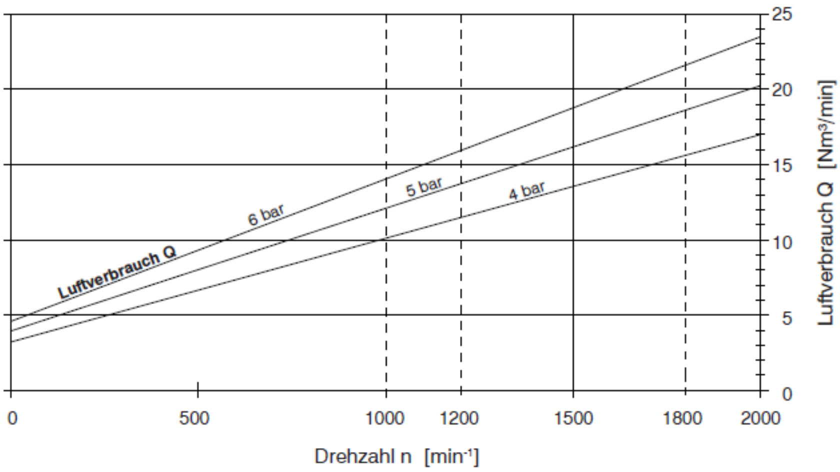


Fig. 13. Dimensions of the DMO 15 motor [20]



Typ	Betriebsdruck		Drehzahlbereich		Daten bei Nenndrehzahl und 6 bar Überdruck			
					Drehmoment		Leistung	Luft-verbrauch
	dauer p [bar]	max. p [bar]	Nenndr. n [min^{-1}]	Leerlauf n [min^{-1}]	Start T [min/max Nm]	Nenn T [Nm]	P [kW]	Q [Nm^3/min]
DMO 8/10	6	8	1000	ca. 1200	62 - 71	60	6,3	9
DMO 8/12	6	8	1200	ca. 1400	62 - 71	59	7,4	10
DMO 8/15	6	8	1500	ca. 1680	62 - 71	57	9,0	12
DMO 8/18	6	8	1800	ca. 1950	62 - 71	55	10,4	14
DMO 8/20	6	8	2000	ca. 2150	62 - 71	54	11,3	15
DMO 15/10	6	8	1000	ca. 1200	115 - 131	111	11,6	14
DMO 15/12	6	8	1200	ca. 1400	115 - 131	109	13,7	16
DMO 15/15	6	8	1500	ca. 1680	115 - 131	104	16,3	19
DMO 15/18	6	8	1800	ca. 1950	115 - 131	102	19,2	23
DMO 15/20	6	8	2000	ca. 2150	115 - 131	99	20,7	24

Fig. 14. Characteristics of the DMO 15 motor operation and its main technical parameters [20]

Due to the operating parameters of the compressor and pneumatic motor, it was assumed that the compressor would supply the air tanks in the range from 6 bar (due to the motor's operating pressure) to 13 bar (due to the compressor's operation). Currently in industrial pneumatic systems, the pressure in the mains is reduced to increase economic efficiency [21].

Variant 2

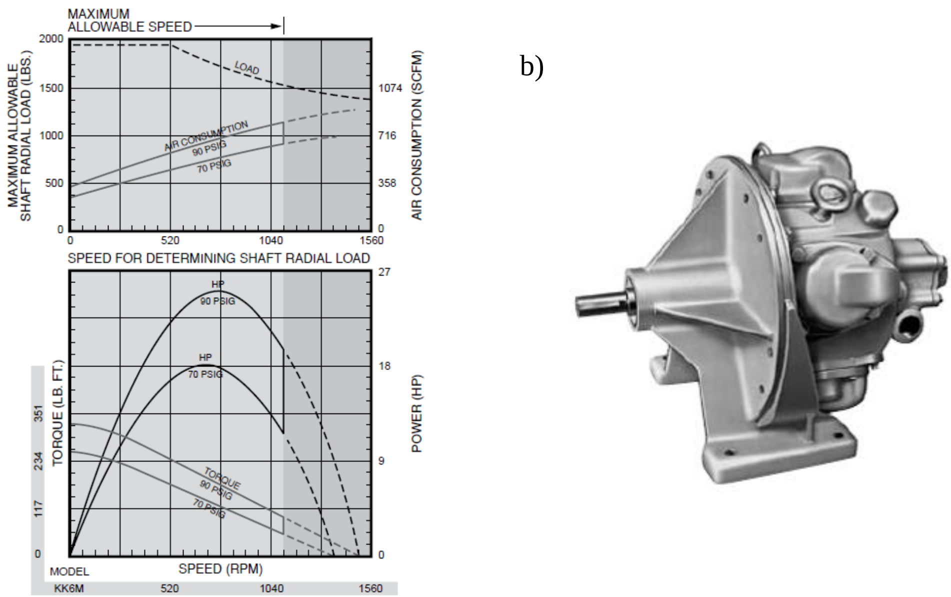
Variant 2 uses an Atlas Copco ZH 560 three-stage centrifugal flow compressor (Fig. 15). The same motor was used as in Variant 1.

Fig. 15. Atlas Copco ZH centrifugal flow compressor [22]

Variant 3

In variant 3, the same compressor was adopted as in variant 2, and the use of a KK6M pneumatic piston motor from the Ingersoll Rand catalog was planned (Fig. 16).

a) b)



c)

Model	Max. Power		Speed at Max. Power	Free Speed▲	Starting Torque		Stall Torque		Air Consumption at Max. Power		Weight	
	hp	kw	rpm	rpm	lb.-ft.	Nm	lb.-ft.	Nm	scfm	m³/m	lb.	kg
Direct Drive Reversible												
CCM	2.05	1.53	1075	2140	13.2	17.9	18.8	25.5	97	2.7	135	61.2
DD6M	2.6	1.94	750	1490	24	32.5	34.2	46.4	79	2.2	135	61.2
EEM	4.4	3.28	735	1450	41	55.6	59	80	137	3.9	200	90.7
EE5M	7.8	5.82	950	1875	60	81.4	80.5	109.2	220	6.2	210	95.3
HHM	11.3	8.43	730	1450	106	144	152	206	270	7.6	235	107
HH5M	15.2	11.33	750	1500	146	198	195	264	400	11.3	250	113
KK6M	25	18.64	755	1500	260	353	325	441	680	19.3	475	216
Geared Drive Reversible												
EE3G	5	3.73	275	560	122	165	175	237	155	4.4	200	90.7
EE53G	6.8	5.07	305	600	154	209	205	278	220	6.2	220	99.8
EE9G	4.7	3.51	92	190	357	484	510	692	155	4.4	210	95.3
EE59G	6.5	4.85	100	200	450	610	600	814	220	6.2	230	104

▲ALL models must be operated with sufficient load to prevent speed from exceeding maximum allowable speed shown on performance curve.
All of the above motors are furnished less valve and piping as standard.
Performance figures are at 90 psig (620 kPa) air pressure.

Fig. 16. Pneumatic piston motor: a) parameters of the KK6M motor, b) view of the pneumatic motor, c) technical data of the Ingersoll Rand pneumatic piston motors [23]

Results of the analyzes are presented in Table 2.

Table 2. Results of analysis of the suggested variants

			Variant		
			W1	**W1**	**W3**
Compressor					
Compressor power	P_spr	kW	250	560	
Maximum working pressure	p_max	bar	13	13	
Output					
(ISO 5389 (1 bar, 35°C, humidity 60%)	g_spr(5289)	m^3/min FAD	-	81.06	
(ISO 1217 (1 bar, 20°C, humidity 0%)	g_spr	m^3/min FAD	32.64	100.2	
Average daily working time	t_spr	hours	6	6	
Daily volume of compressed air	G(FAD)	m^3	11750.4	36072	
Daily energy consumption	E_in	kWh	1500	3360	
Motor					
Pneumatic motor power	P_sil	kW	16.3		18.64
Supply pressure	p_sil	bar	6		6.2
Air consumption					
(ISO 1343 (1 bar, 0°C, humidity 0%)	g_sil	Nm^3/min	19		19.3
(ISO 1217 (1 bar, 20°C, humidity 0%)	g_sil	m^3/min FAD	20.51		20.51
Engine operating time	t_sil	min	572.91	1758.75	1758.75
		h	9.55	29.31	29.31
Storage					
Compressed air volume (ISO 1217 (1 bar, 20°C, humidity 0%)	G(13bar)	m^3	903.88	2774.77	
Assumed tank capacity	V	m^3	9.00		
Number of tanks	n	pc.	100	308	
Electricity (from generator)	Eout	kWh	149.42	463.46	524.53
Efficiency of the power generator		-	0.96		
Energy efficiency [E_{out}/E_{in} x 100%]	SprE	%	9.96	13.79	15.61

Based on results of analysis of the variants described above, a relatively low efficiency of the system can be observed, amounting to a maximum of about 15%, which means that ultimately 15% of electricity from such a storage unit is stored. Legitimacy of using the compressed air storage units described in the first part of the article results from their cooperation with gas turbines, work of which, in the first phase consists in compressing the inlet air to the combustion chamber. This process is energy-intensive, therefore air compression was excluded from the turbine operation and shifted in time so that it took place at a time when electricity is cheap and there is an excess of it in the power grid.

In order to identify the weakest point in the three analyzed variants, the indexes Wspr = P_spr / g_spr and W_sil = P_sil / g_sil expressed in kW/(m^3/min) FAD (Table 3) were used. These indexes apply to the air stream in normal conditions (includes the actual operating parameters: pressure, air humidity, temperature).

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Table 3. Comparison of energy storage variants

	Variant 1	Variant 2	Variant 3
Compressor W_spr, kW/(m^3/min) FAD	7.65	5.58	5.58
Motor W_sil, kW/(m^3/min) FAD	0.79	0.79	0.9

Based on the presented indicators, it can be observed that the compressor and the air compression process are the weakest elements of the system. According to the compressor manufacturers information, the L250 compressor generates about 190 kWc of heat when operating at power 250 kWe. This is confirmed by the objectives of the research work on CAES, focused on the recovery energy lost in the compression process. Storing as much air as in the analysis would require a large number of tanks, which is not justified due to the cost of the installation. CAES operating worldwide are based on underground sources.

4. Conclusions

To avoid irretrievable loss of energy surplus from RES installations, energy storage units should be used. Pumped storage hydroelectricity plants are currently, the most common energy storage facilities in the world (they account for over 90% of stored energy). However, other solutions are also available, including compressed air energy storage (CAES). Pneumatic storage systems currently operating in the world cooperate with gas turbines and are a source of compressed air, thus increasing the efficiency of the turbine (no need to compress the turbine intake air). In these storage units, mining underground workings or caverns (salt workings) are used as air reservoirs.

As part of this work, three variants of a storage units, consisting of a compressor, air tank and pneumatic motors, were considered. Analysis of the systems based on commonly available pneumatic devices shows that their energy efficiency ranges from approx. 10 to approx. 15%. It can be observed that greater efficiency is achieved with the use of large flow compressors and motor operation at a higher supply pressure. In addition, it can also be said that the greatest losses are associated with the operation of the compressor, which generates large amounts of heat during operation. Increasing the efficiency of the energy storage system can be achieved by recovering the heat generated in the compression process. The resulting heat could be used, for example, for heating purposes. However, discrepancy between demand and supply for such energy is a noticeable problem. In the summer, with high productivity of PV farms, the demand for thermal energy is low, therefore the possibilities of heat storage should be analysed. Another alternative is to use the heat to warm up air supplied from the storage unit to the air motor by increasing its enthalpy, or to use the heat to warm up the motor body. In this way, the efficiency of the system could be increased (a pneumatic motor would have the characteristics of a heat engine). selection or development of the appropriate type of thermal storage bed that would allow for the effective collection of heat, and then quickly distributing it to the air supplying the motor or heating its body is a technical problem.

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