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ENERGY STORAGE IN COMPRESSED AIR – SOLUTION SUPPORTING RENEWABLE ENERGY SOURCES

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Abstract

This article presents a brief description of a power system, the current national power system daily load, the use of wind power as a renewable energy source and its share in the national load. It also discusses the methods for storing energy, their characteristics and possible solutions. The power storage and generation solution proposed in the article is based on the collaboration between a gas turbine and an air storage system. The last chapter contains a visualization of a conceptual compressed air tank that could be used for offshore wind turbines.

Keywords: *wind power plants, energy storage, CAES, compressed air, renewable energy sources, power system*

1. Introduction

The provision of a sufficient amount of energy is one of the fundamental challenges that mostly highly developed countries are currently facing. The conducted analyses show that the increase in power demand is close to 1% per year, while in recent years in Poland it amounted to 2% [1]. That is why the continuous development of power generating capacity, modernization of the existing high power units, support of distributed power generation and renewable energy sources are of crucial importance.

Some alternative energy sources, though inexhaustible and commonly available, occur periodically and are usually not correlated with the period in which they are in demand [2]. Energy storage is closely linked to renewable energy sources, as it is essential in order to guarantee the stable operation of a power system.

Energy storage is a well known problem. Its history reaches as far as the beginning of generation, transmission, distribution and usage of electric energy. Many prototype systems are currently being launched that enable a large-scale transfer of energy generated by renewable sources to peak demand periods.

The demand for energy supplied to the NPS[1] varies in time. It is related to short-term fluctuations of energy consumption each day and seasonal changes. When highly unpredictable sources are introduced into the system, electric energy consumption is even more variable. Wind and solar power plants are both examples of such sources [3]. The rate of increase in wind power

[1] National Power System

plants installed capacity made it necessary for many countries to search for new technical solutions providing for the stabilization of the NPS. Energy storage in compressed air is one of such solutions.

2. Impact of wind turbines on the power system

The conversion of mechanical energy into electric energy is the last stage of energy conversion in most power plants. Electric energy generated in a power plant is transferred to the power system, where it is consumed by consumers. The system load varies in time. Certain peak and off-peak periods of power demand may be differentiated during the day, which is reflected in Figures 1 and 2.

For comparison purposes, characteristics of the Polish and Irish power systems were prepared, and the power generated by wind power plants was marked.

In January 2013 the installed capacity of wind power plants in Poland amounted to 2700 MW, while in December 2014 it is expected to reach 4040 MW. It clearly shows that the share of wind power plants in the national power system is increasing significantly (and will soon reach 20%). Unfortunately, as can be observed in Figures 1 and 4, the average power reached by wind turbines (installed capacity in Q3 2014 – 3680 MW) constitutes only 30% of installed capacity.

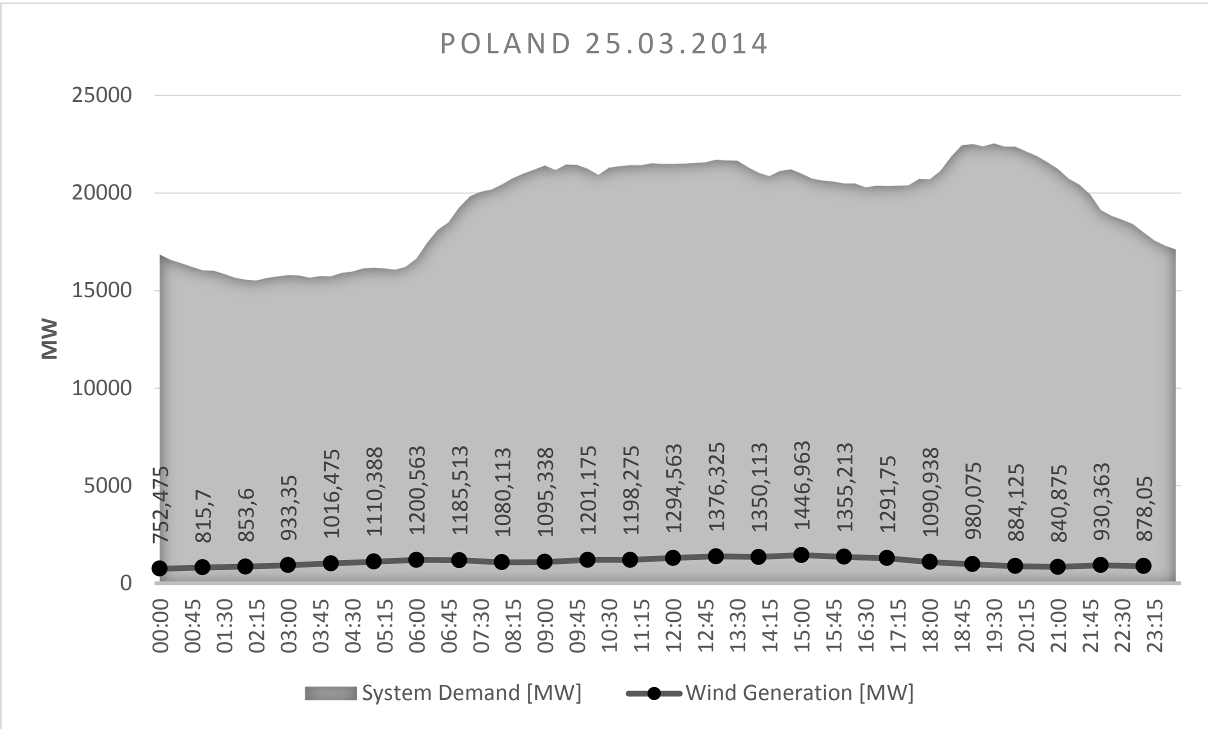

Figure 1. Daily load of the National Power System as of 25 March 2014 with energy generated by wind power plants – Poland (compiled on the basis of PSE Operator data)

The daily load is similar in both countries. Conventional baseload power plants are the main source covering the energy demand.

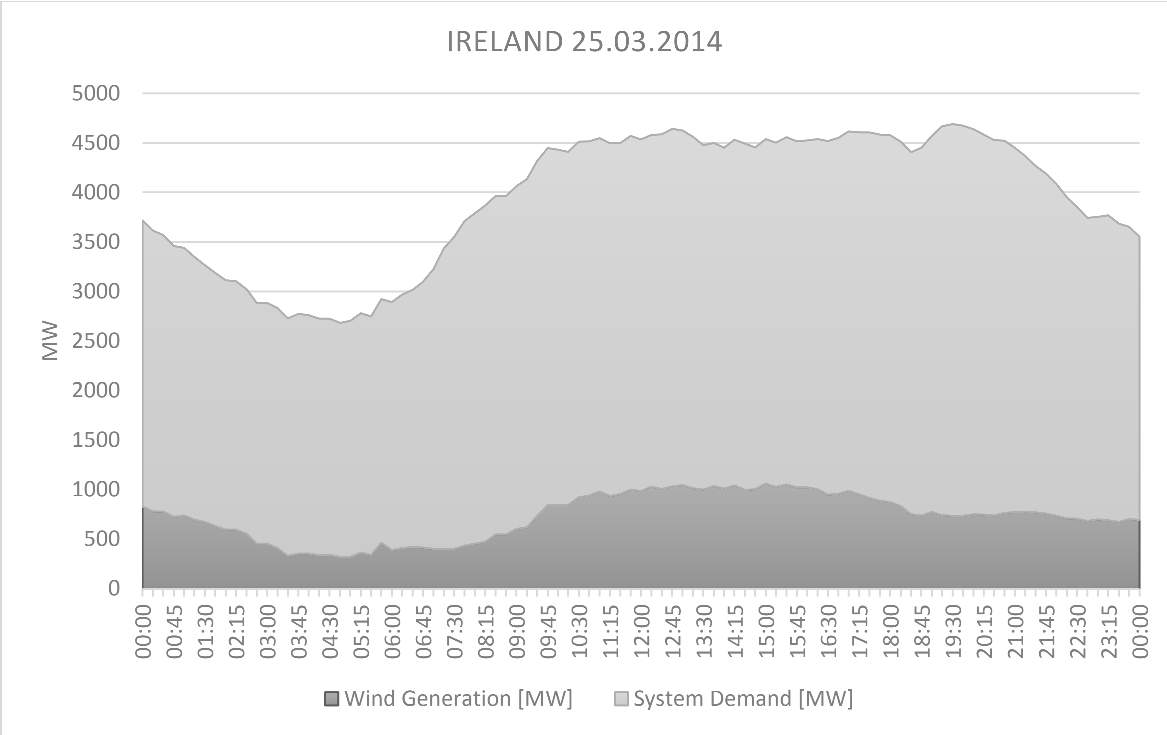

Figure 2. Daily load of the National Power System as of 25 March 2014 with energy generated by wind power plants (compiled on the basis of eirgrid.com data)

Generation of energy from wind sources is very unstable, variable and unreliable. The percentage likelihood that the load of wind energy sources in Poland will amount to between 0 and 20% (installed capacity) is 58.8%, between 0 and 30% (installed capacity) – 73.01%, and between 0 and 40% – 84.02%. Therefore, the wind power sources load is less than 40% for approximately 7360 h per year[4]. Wind power plants, as compared to non-renewable electric energy sources, have certain specificities.

These are, among all [4]:

- frequent lack of correlation between the amount of generated power, dependant upon the current wind speed, and the end users demand for power (as may be observed in Figure 4, where maximum wind sources generation correlates with a non-peak period in the power system),
- sudden (often unpredictable) changes in power introduced into the power system, related with instantaneous changes of the wind speed (sudden maximum blasts and average wind speeds shown in Figure 3),
- poor predictability of wind power sources operation in the long term, as part of planning their collaboration with the power system.

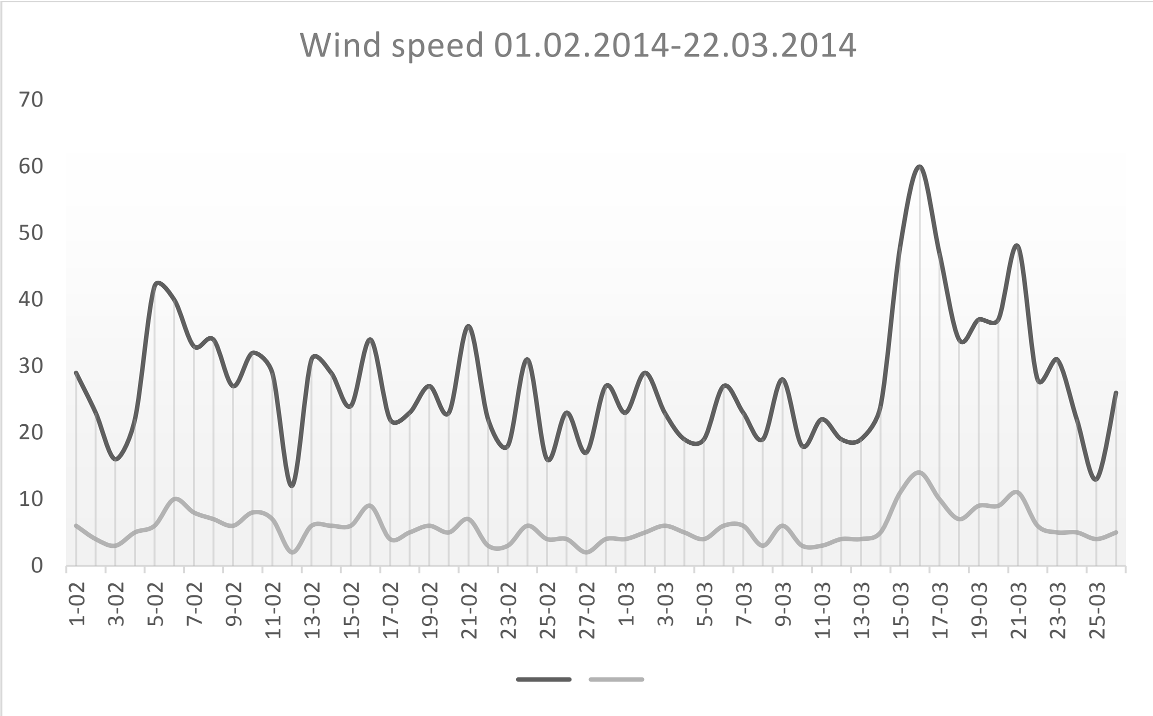

Figure 3. Variability of wind speed in March, in the south regions of Poland (compiled on the basis of pogodaradlin.pl data)

Generally speaking, the greater the wind power sources installed capacity share, the greater the consequences for the power system [1].

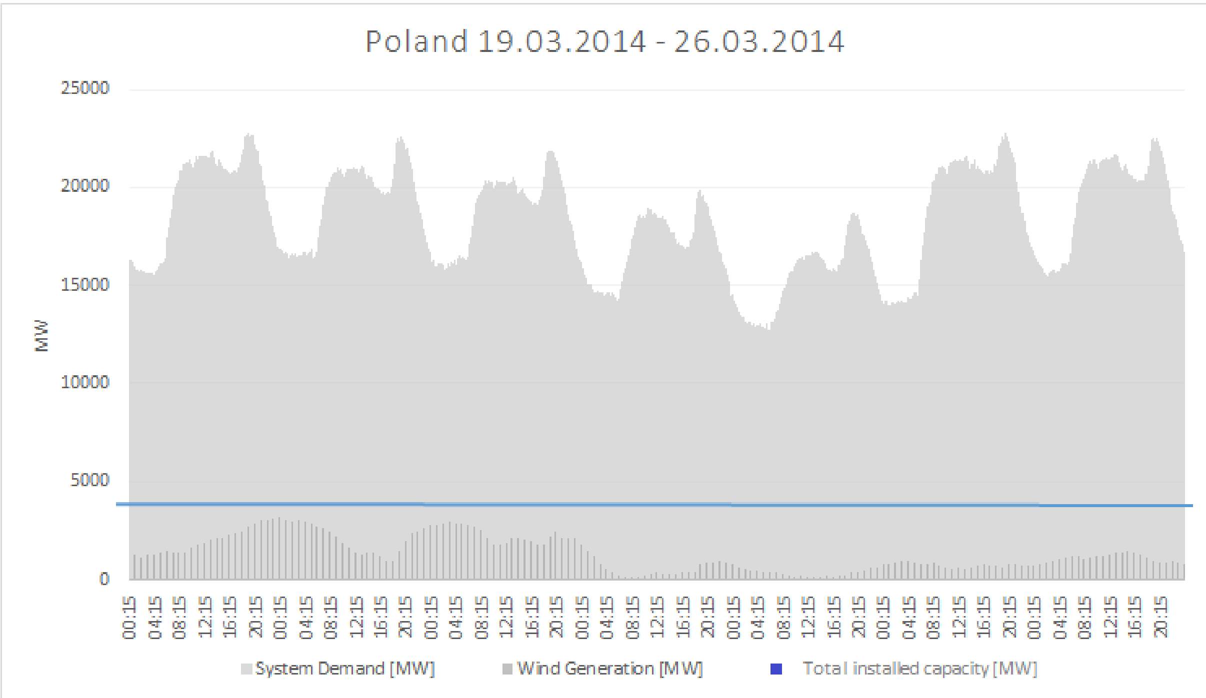

Figure 4. Weekly load of the National Power System (compiled on the basis of PSE Operator data)

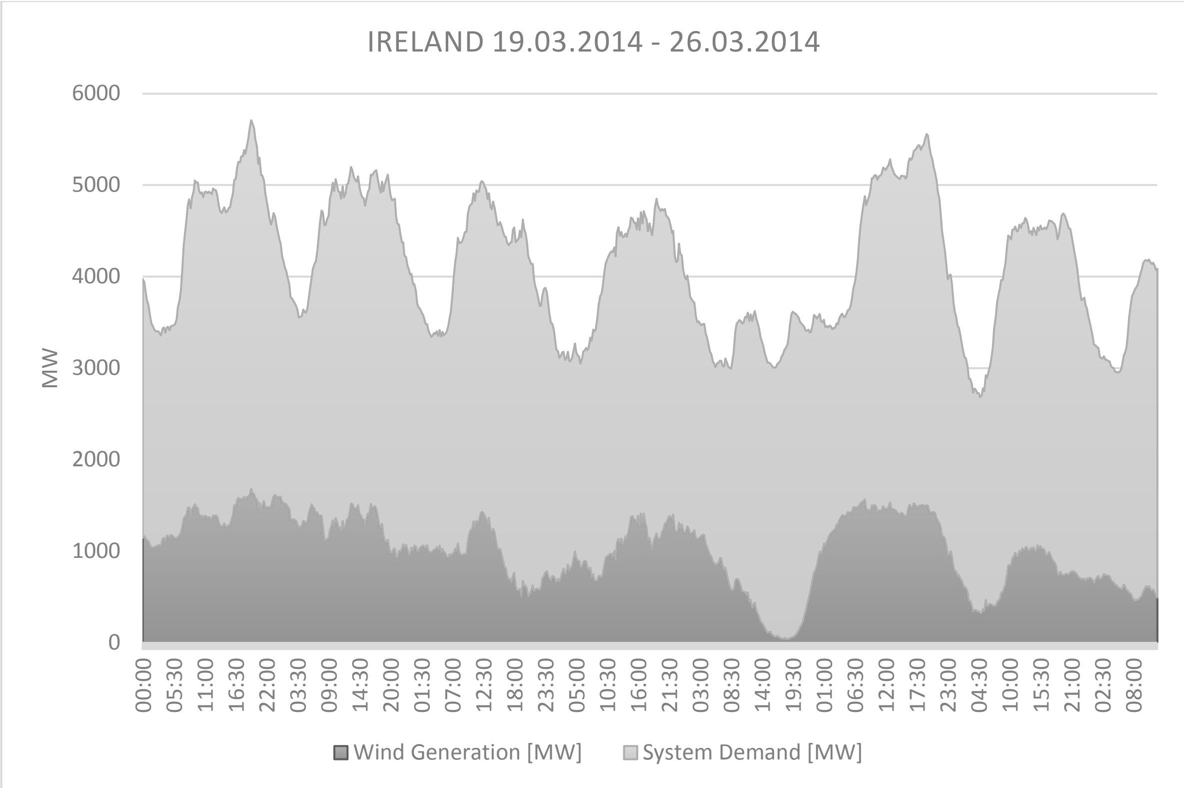

Figure 5. Weekly load of the Irish National Power System (compiled on the basis of eirgrid.com data)

In order to mitigate the negative consequences of wind power plants operation for the NPS, systems operators apply remedies that can be divided into three basic groups [5]:

- regulatory activities involving the generation sources that are already present in the power system,
- application of an energy storage technology,
- introduction of demand control systems.

3. Energy storage

The electric energy storage technology that is currently used may be divided into indirect (with the conversion of electric energy into a different kind of energy, such as kinetic or chemical) and direct energy storage (in an electric or magnetic field).

Activities related with the utilization of energy storage technology enable:

- mitigation of the variability of wind power sources generation introduced into the power system in shorter periods of time,
- restriction of the use of conventional peak load sources when changes in wind power sources generation take place,
- transfer of electric energy generation from non-peak to peak hours.

A proper energy storage system should be characterised with [6]:

- high energy density,
- simple charging and discharging, and a large number of cycles,
- high energy efficiency of the cycles,
- possibility of a simple conversion of energy into a different form of energy,
- should reach the required economic efficiency and not pose a threat to the environment,
- required storage time and time of distribution to the user.

The basic parameters for the methods of energy storage, recommended by the American Electric Power Research Institute, for the support of wind power engineering integration into the power system are shown in Table 1.

Table 1. Basic operational parameters of selected types of energy storage technology [5]

No.	Technology	Cycle efficiency %	Nominal power [MW]	Discharge time [h]
1.	Pumped-storage Hydroelectricity	80	100-1000	> 1 hour
2.	Compressed Air Energy Storage	60-75	0.1- 1000	few hours
3.	Flywheel Energy Storage	90	0.1- 10	0.1
4	Conventional Batteries	60-80	0.1- 10	0,1 … > 1
5.	Rechargeable electrochemical	70	0.1- 20	> 1
6	Fuel cell	50	0.1- 1	> 1

A pumped-storage power station is a common method for energy storage (Germany is planning on building such systems in old coal mines). As the obtained capacity may affect the entire power system, it is a large scale technology. Compressed air systems are an alternative storage type, as they provide the same capacity but are more profitable.

Activities related with the end users demand control are an important aspect of energy storage. The expansion of demand control involves the introduction of financial incentives by the transmission and distribution systems operators in the form of special tariffs (hourly, dynamic tariffs).

4. Energy storage in compressed air

Old mine deposits, salt caverns, salt mine excavations, hard rocks excavations, areas following aquiferous layers [7] are used for energy storage in the form of compressed air, where air is compressed to the level of approximately 70-80 bars.

In this type of power plants the generator is fuelled with liquid or gas fuel (a non-renewable source). There is no inlet air compressor, however, that under normal conditions consumes approx. 60% of mechanical energy of a conventional generator. This enables the reduction of CO_2 emissions and the increase in efficiency as compared to a conventional gas power plant [8].

In the analysed type of power stations, low-cost energy is used that is available outside of the power system peak load hours – during the nights and on weekends. When wind conditions are favourable, the excess energy is used for supplying the compressor that compresses air. It is shown in Figure 6. The consumed energy is used for compressing air in large tanks [3]. The collected energy is used during peak hours or when wind conditions are unfavourable and power generation by power plants does not meet the planned amount (e.g. an amount commissioned by a consumer). The control system starts a fuelled gas turbine and feeds compressed air to the turbine [8] (Figure 6).

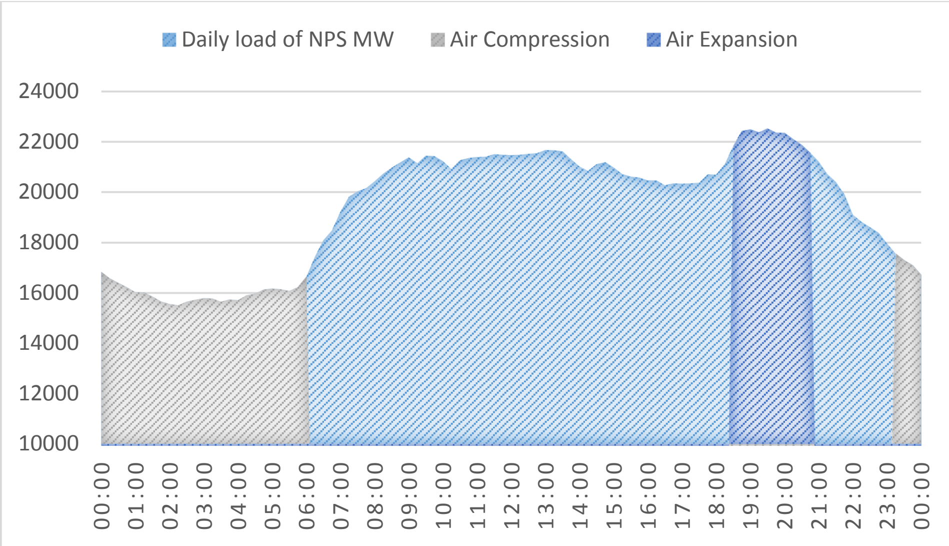

Figure 6. Proposal for a CAES power plant operation in the course of a daily load of the NPS (compiled on the basis of PSE Operator data)

Environmental friendliness of gas turbines, relatively low investment costs and high capacity reached by power units, simplicity and light weight of their structure, flexible movement, independence from water sources and possible automation led to the popularity of power stations with gas turbines, and their use is recommended in low capacity power plants, peak load power stations and in special circumstances. The use of this sort of solutions supports distributed generation. Listed below are possible technical solutions to the collaboration between gas turbines and compressed air tanks.

Figure 7 shows a "simple" air compression system; the heat generated during compression is lost.

Total efficiency of the compression and expansion process in relation to electric energy reaches approx. 40% [9]. The use of natural gas in the combustion chamber enables the regulation of generated power and the increase in the power plant capacity.

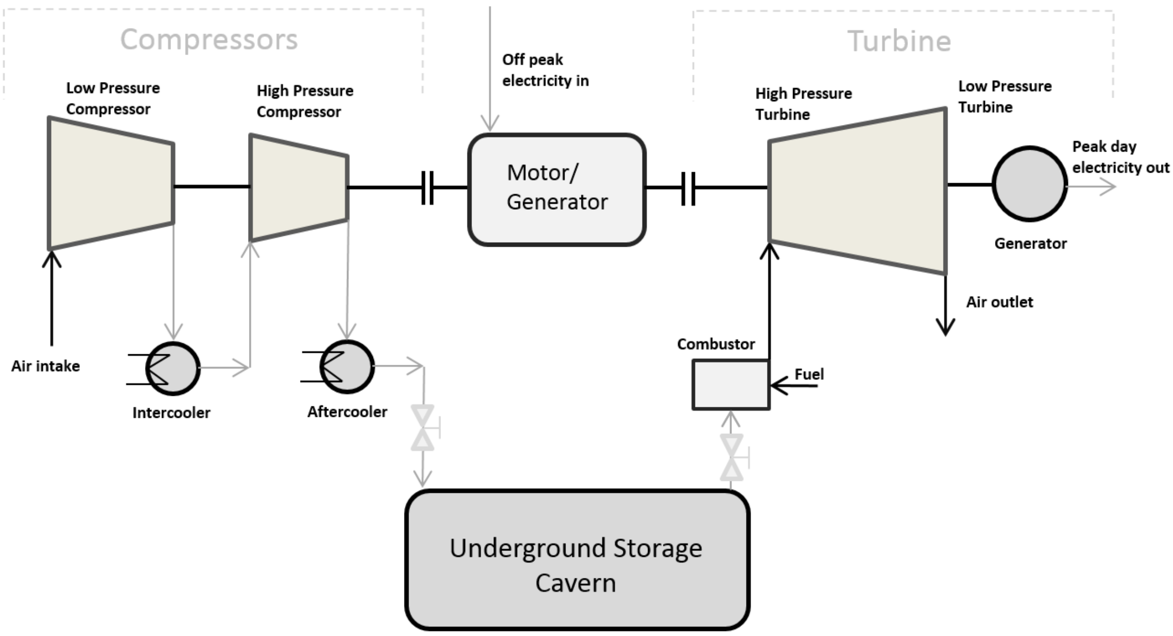

Figure 7. Basic CAES system [compiled on the basis of 9, 10, 11]

Figure 8 shows a system utilizing exhaust heat due to the use of a recuperator. Such a system reaches the energy efficiency of a power plant of more than 50%. Reliability of such systems amounts to approximately 99%.

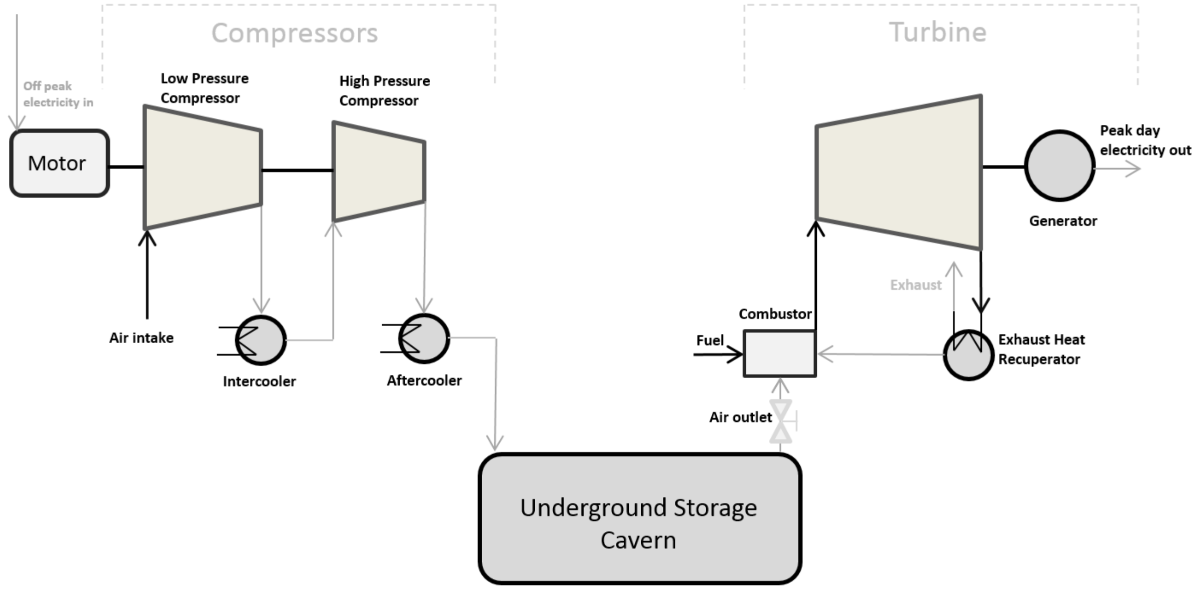

Figure 8 CAES system with a recuperator [compiled on the basis of 9, 10, 11]

Figure 9 shows a CAES[2] system with the storage of exhaust heat generated during air compression, and its subsequent use for heating the air fed to the turbine. As a result, thermodynamic changes are similar to adiabatic changes. Such systems reach the efficiency of 60% without a combustion chamber.

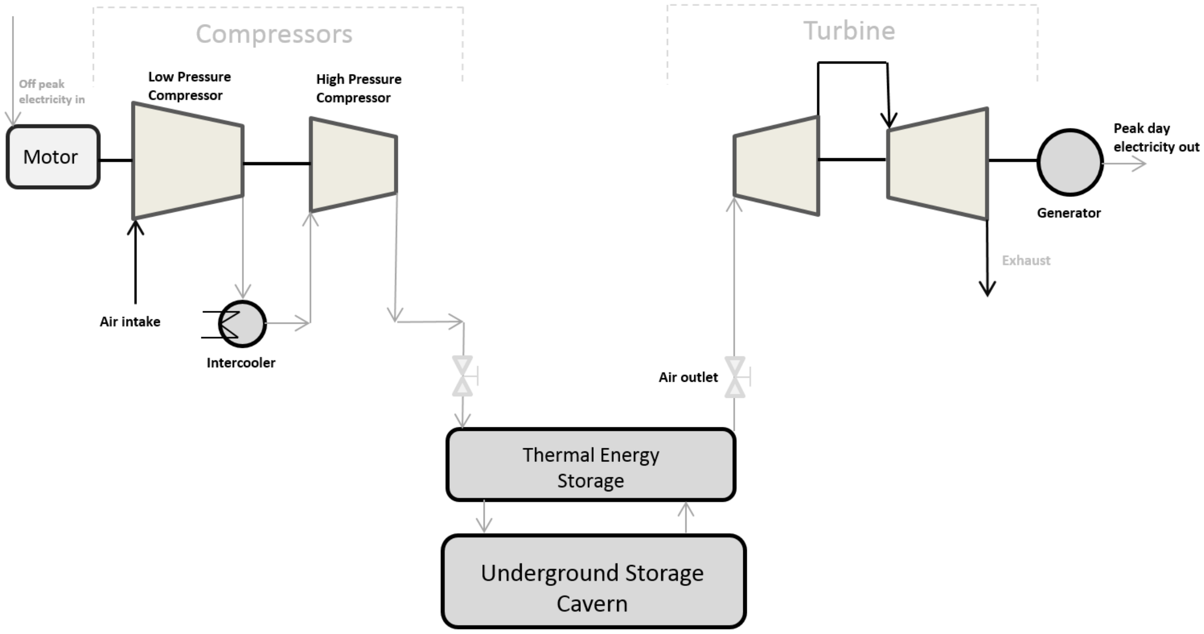

Figure 9 CAES system with exhaust heat storage [compiled on the basis of 9, 10, 11]

[2] Compressed air energy storage

Figure 10 shows a system of the greatest efficiency, over 70%. This is a system containing both a combustion chamber and a recuperator. Such solutions are currently being designed and tested by those countries in which wind power engineering progress is greatest. The main objectives of the tests are air tanks and heat exchangers and storages that recover exhaust heat generated during compression.

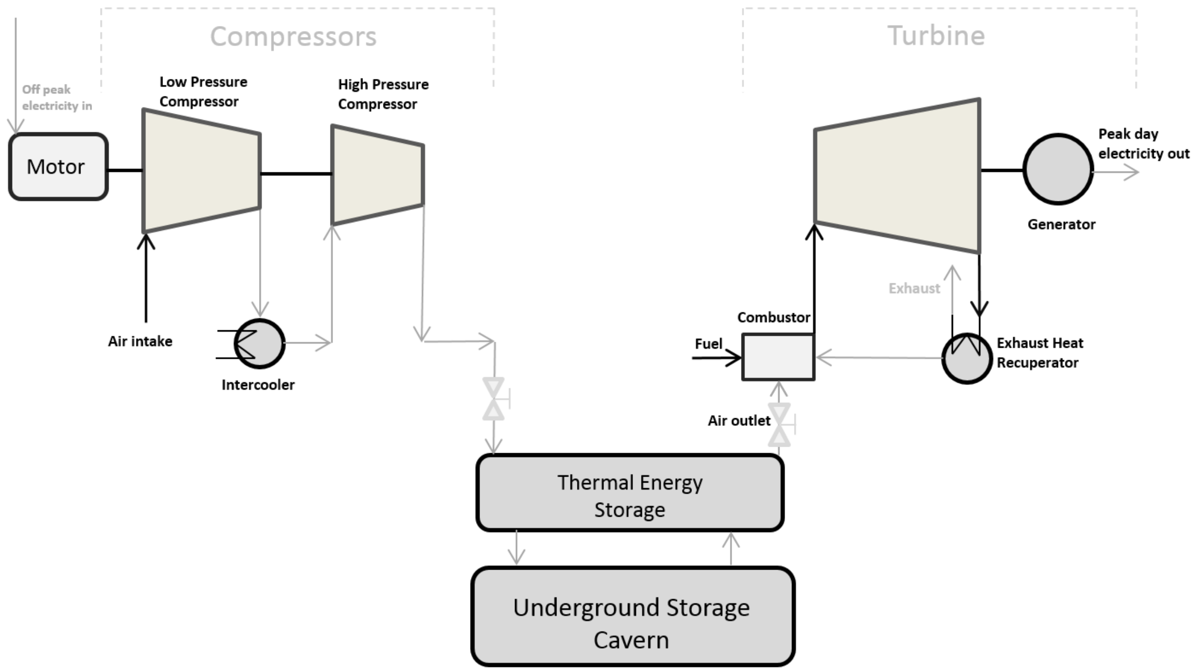

Figure 10 CAES with exhaust heat storage, combustion chamber and recuperator [compiled on the basis of 9, 10, 11]

A significant advantage to combined wind and CAES power plants is the increase in local energy security, because it is possible to start up a combined system without external supply and reach the desired capacity in a short period of time. In contrast to gas collection, its advantage is the possible autonomous operation of a gas turbine during expansion.

The start up of a pumped-storage power station takes anywhere between 1 and 15 minutes, while the start up of CAES system to full capacity is two or even three times shorter than an average start up time of a unit with a gas turbine, and it takes approximately 10 minutes.

Many countries, especially the USA and Germany, being the European leader in wind power engineering, are involved in researching compressed air energy storage.

5. Air tanks

The maintenance of a constant pressure in an underground tank, e.g. through the hydrostatic pressure of water, would make it possible to increase the power plant efficiency to well over 70% due to the use of an isobarically isolated thermodynamic cycle. The concept of such a compressed air tank that could be used for offshore wind turbines is shown in Figures 11 and 12. The volume of this tank is approximately 30 m^3.

Figure 11 Visualization of a conceptual compressed air tank that could be used for offshore wind turbines (compiled on the basis of 18, 19)

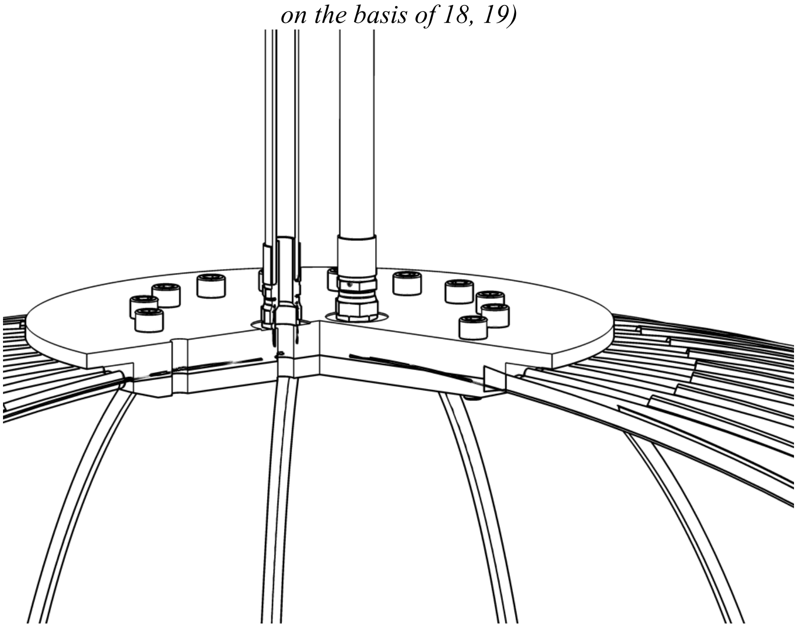

Figure 12 Visualization of a conceptual compressed air tank that could be used for offshore wind turbines (compiled on the basis of 18, 19)

Location-wise, both in Poland and in Europe there is a potential for onshore and offshore compressed air storage power plants.
The construction of such power stations seems especially interesting in view of the current and planned major investments in wind power engineering.

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