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Compressed Air Energy Storage Systems

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Abstract

Compressed Air Energy Storage (CAES) technology and electricity generation by this system are described in this paper. General performances and possible system efficiency definitions of those kinds of systems are indicated. Hybrid systems which consist of CAES and other Renewable Technologies—RT—(e.g. wind turbines) are presented. A possible location for CAES–RT in Poland is indicated. A dynamic mathematical model of CAES is presented; using this model the results for compressing and expanding operating modes are obtained.

Keywords: Compressed Air Energy System

1. Introduction

The need for power supplied to the power system varies constantly. This applies both to short-term fluctuations within each day and to seasonal changes. General uncertainty in the system is worsened by the increased volatility of electricity consumption and the growing share of unpredictable renewable sources of energy. This is significant, as sometimes there are major changes in both the demand and supply of power.

One way to generate energy for peak sources is to accumulate energy in various forms. Conventional power plants with a capacity of accumulation are:

- pumped storage,
- power using the expansion of air stored in underground tanks (Compressed Air Energy Storage—CAES).

Other ways of energy accumulation are considered, e.g. water electrolysis [1] and combination with fuel cells [2–19]. Hydrogen can be proposed as an alternative fuel fora a CAES based gas turbine plant, to reduce the dependency on fossil fuels and increase the penetration of renewable energy sources [20].

CAES has an energy ratio 0.712 at the design point [22], which means that the useful work of the plant is about 30% higher than the pumping work, whereas hydraulic pumped

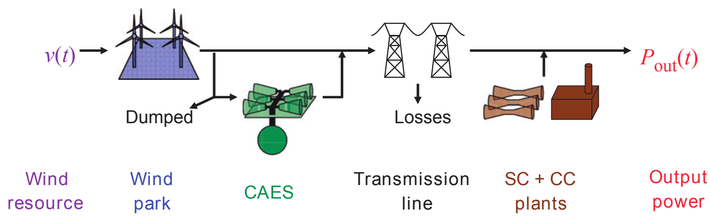

Figure 1: Schematic diagram of 2.0 GW baseload power model[21]

storage plants consume about 25% more power than they later return in peak generation periods. It is therefore crucial that it is widely understood that intermittent renewable energy resources can supply a major portion of electricity demand, based on resource availability, economics and technical characteristics. When coupled to compressed air energy storage systems (see Fig. 1), electricity from these resources is technically equivalent to and economically competitive with that from any nuclear or fossil fuel power plant [21]. It has been shown in [23] that a variable configuration system based on compressed air and a heat reservoir can be used for energy storage. This system has off-the-shelf components and does not use any fuel. An optimal CAES/electricity system combination was found in [24] for around 55% wind penetration. The required storage value needed for CAES to fully eliminate condensing power plant operation is found to exceed 500 GWh. CAES in three "wind by wire" scenarios with a variety of transmission and CAES sizes relative to a given amount of wind was examined in [25]. In the sites and years evaluated, the optimal amount of transmission ranges from 60% to 100% of the wind farm rating, with the

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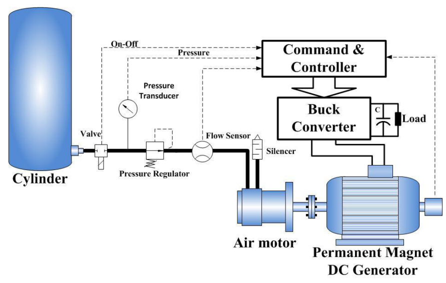

Figure 2: Pneumatically-driven electric generator of a stand-alone small scale CAES [31]

optimal amount of CAES equal to 0...35% of the wind farm rating, depending heavily on wind resource, value of electricity in the local market, and the cost of natural gas. CAES can also be used ata a smaller scale in conjunction with diesel engines and shows promising performances [26]. Moreover, a micro-CAES system [27], especially with quasi-isothermal compression and expansion processes, is a very effective system for distributed power networks, because it is a combination of energy storage, generation, and air-cycle heating and cooling system, with an energy density feasible for distributed energy storage system and good efficiency due to the multipurpose system. The calculated efficiency of a two-stage adiabatic CAES ranges between 52% and 62% [28]. A realistic approximation of the efficiency for a system with low additional energy use for cooling is about 60%. Additional efficiency improvements can be obtained by air injection (CAES-AI) and inlet chilling (CAES-IC). The sensitivity rate of generated power, energy ratio, and primary efficiency of CAES-AI system is clearly higher than that of the CAES-IC system due to ambient temperature and the overall pressure ratio [29]. In [30], a novel energy storage system which stores excessive energy in the form of compressed air and thermal heat is presented. It is different from the conventional compressed air energy storage (CAES) technology in that the new system allows trigeneration of electrical, heating and cooling power in an energy releasing process. Uniquely, the cooling power from this system is generated by direct expansion of compressed air instead of through absorption chilling technology.

A pneumatically-driven electric generator of a stand-alone small scale CAES is presented in [31, 32]—see Fig. 2. In this system, an air motor is used to drive a permanent magnet DC generator. Test results are presented to validate the design and demonstrate its capabilities. Similar solutions are proposed as a suitable technology for energy storage in a small scale stand-alone renewable energy power plant (photovoltaic power plant) which is designed to satisfy the energy demand ofa a radio base station for mobile telecommunications [33].

CAES to be combined with hybrid WDS (wind-diesel systems) is proposed in [34] by a new technique to transform the existing Diesel engine to a HPCE (hybrid pneumatic combustion engine), able to operate as a bisource engine (compressed air and fuel)—see Fig. 3.

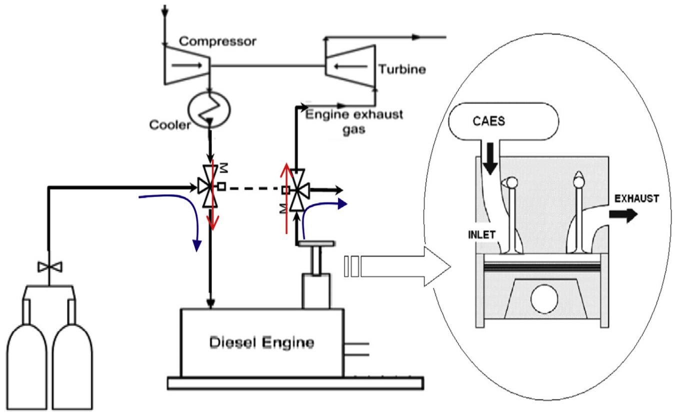

Figure 3: A hybrid pneumatic combustion engine [34]

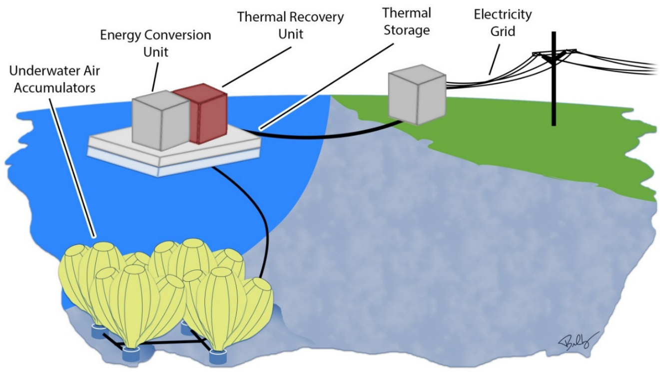

Figure 4: An Under Water CAES with on-shore equipment [35]

A 4 MWh Under Water CAES system was numerically simulated in [36, 37]—see Fig. 4—where optimal system configurations were determined that maximized the system roundtrip efficiency and operating profit, and minimized the cost rate of exergy destruction and capital expenditures. Conceptually, the accumulators used in the UWCAES system are placed at or near the bed of deep water bodies such as lakes and oceans, utilizing the hydrostatic pressure exerted by the surrounding water [38, 39]. The extent of the accumulators will expand and contract depending on the amount of compressed air present within. Air compressed to a design pressure equal to the hydrostatic pressure at the accumulator storage depth would remain at constant pressure due to the environment, regardless of the accumulator's filled capacity.

Liquid air energy storage does not need a pressurized storage vessel, can be located almost anywhere, and has a relatively large volumetric exergy density at ambient pressure. A hybrid energy store consisting of a CAES at ambient temperature, and a liquid air store at ambient pressure is proposed in [40] (Fig. 5). Preliminary results indicate that provided the heat pump/heat engine systems are highly efficient, a roundtrip efficiency of 53% can be obtained.

The section presented below on the latter technology is partially based on a paper [41] presented at the Fourth Conference "Energy Gas" in Warsaw and earlier studies carried

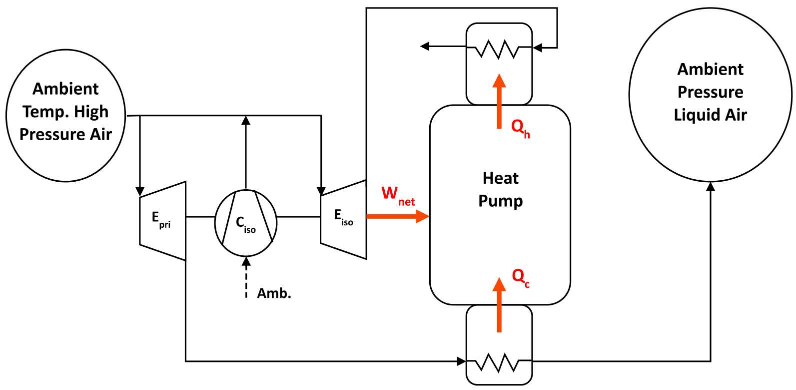

Figure 5: Schematic for the ideal (reversible) hybrid liquid air—CAES [40]

out by the authors.

1.1. CAES technology, working principle, basic features

CAES technology was introduced to power engineering many years ago. The first commercial installation, with capacity of 280 MW, was established in 1978 at Huntorf, Germany[42]. Huntorf power plant is, to date, the world largest installation of this type (e.g. Mc Intosh has installed power of 110 MW, commissioned in the US in 1991) and those plants are only experimental. There are a number of plans to build a power plant of even very high power (the largest power plant project is earmarked for Norton, USA wherea a plant of 2,700 MW is planned: block-based CAES turbines with a capacity of 300 MW each). However, Norton is still facing delays. The CAES plant working principle is explained in Fig. 6.

The basic principle of the CAES system is to use low price electricity—available outside the peaks of the power system load—for example, at night and on weekends when base load power plants [44] need to be kept in operation. Low cost power is used to compress air in large tanks. Compressed air accumulation is based on experience, including Polish, with underground storage of Natural Gas (NG) ina a horizon of up to 60 years. Due to the huge amount of air required and the resulting financial constraints, currently the use of natural reservoirs is the only economically viable option, i.e., salt caverns, aquifers, salt mine workings, and mines of limestone and other minerals formed in the structure of hard rocks, or even concrete lined caverns at a relatively shallow depth [43] (see Fig. 7).

The air pressure inside the storage must be relatively high, even for large volume cavern. The maximum value should be noticeably higher than that required for the combustion chamber cooperating in the gas turbine system. The minimum value of the pressure during the cycle should also exceed the level required for the combustion chamber. Production is triggered when the demand for electricity is high. The air is released from the tank and expanded in a turbine. Due to the high pressure ratio at the compressor, it is necessary to use inter-stage inter-cooling. In addition, there is also the need to keep the temperature of the air delivered to the cavern ata a low enough level (by usinga a cooler just before the cavern). Similarly to NG storage, air is cooled down to a temperature of about 40 to 50 °C. This helps to protect the piping and the lining of cement wells against the harmful effects of excessive heat. Another limitation is the reduction in the storage capacity of the tank at higher temperatures of accumulated air.

The advantage of compressed air, in contrast to storing NG, is the possibility of subsequent work independently of the gas turbine during the expansion process. The power generated is not limited by simultaneously driving the compressor. The power balance of a classic heavy duty gas turbine requires more than 50% of the expander power to be supplied to the air compressor. Separating the compression and expansion processes provides an opportunity for significantly higher expansion than with the classical system. The ability to spread compression time over a longer period allows for an additional increase in the difference in the power consumed (by the compressor) and generated (by the turbine).

CAES systems should not be considered as pure energy storage due to the additional power supplied to the system in the form of fuel. They should instead be viewed as hybrid systems used for both energy storage and power generation. Their essential features are their ability to provide quick start power generation and the favorable ratio between the power generated to the power demand for the compression work. The air from the cavern can be decompressed without using fuel, but the resulting energy effect would then be relatively smaller, and the air outlet temperature lower than that prevailing in the environment. The air directed to the turbine can be heated in the heat exchanger at the expense of the energy of exhaust gases (Fig. 6), and can then be used in the combustion chamber. An additional possibility is to use the heat accumulator to retain energy from the cooling process prior to entering the tank (caverns).

Energy from the cooling process, as shown in Fig. 6, can be put into the environment, but as an alternative its storage and putting into the air at the time of re-expansion is considered. With regard to the method of operation, the CAES plant is referred to the pursuit of adiabaticity process (adiabatic

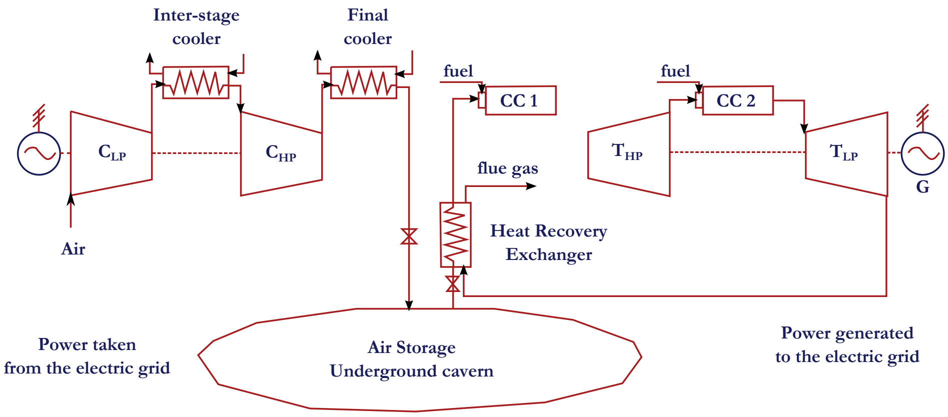

Figure 6: The operating principle and basic elements of the CAES power plant: C_{LP}, C_{HP}—low pressure and high pressure compressors, respectively; T_{HP}, T_{LP} —high pressure and low pressure part of the turbine, respectively; CC 1, CC 2—combustion chamber

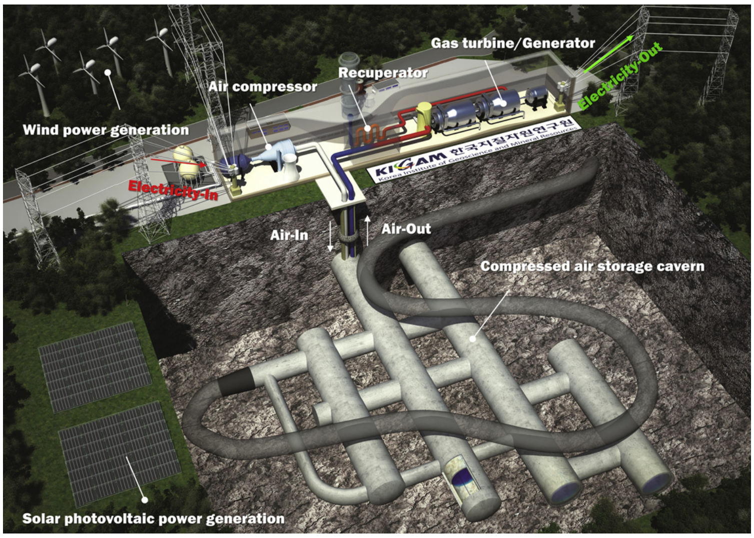

Figure 7: Components of an underground CAES system [43]

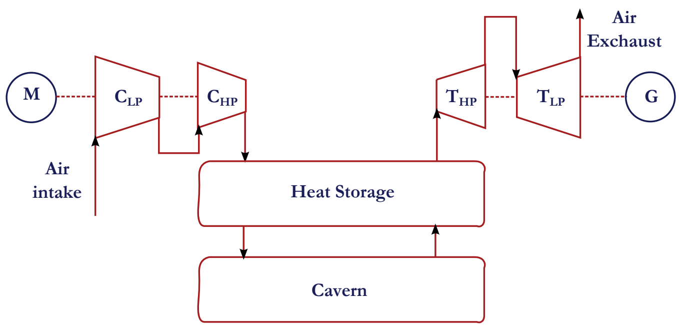

Figure 8: Working principles of an adiabatic CAES plant

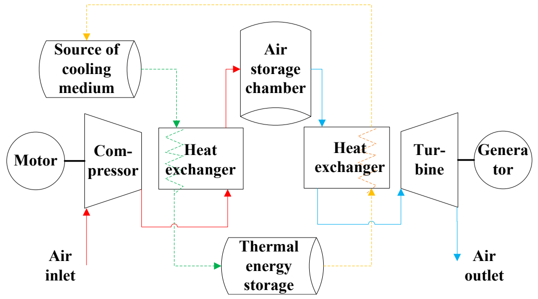

Figure 9: Schematic diagram of an Advanced Adiabatic–CAES system [45]

method—Fig. 8). The results in [46] showed that adiabatic CAES offered relatively high energy storage efficiency, compared to conventional CAES technology. Studies on heat storage capacity adiabatic systems was carried out through a number of projects (Advanced Adiabatic–Compressed Air Energy Storage) [45, 47]—see Fig. 9. As a storing medium recycled ceramics made of inertized asbestos containing wastes can be used. Ten successive cycles at between room conditions and 610°C/30 bars for an accumulated duration of 2,500 h led to validation of the ability of the material to resist those constraints [48]. Another option here is to improve the economics of CAES by distributing compressors near to heat loads to enable recovery of the heat of compression to supply low-grade heating needs such as district heating [49].

1.2. CAES power plants working with renewable energy, including wind power plants

A CAES power plant seems to bea a good solution for stabilizing wind turbine power generation. This kind of unit is considered in Fort Dodge, Iowa (USA) [50]. An aquifer is intended to be used for storing compressed air. A specific feature of the installation is the assumption of simultaneous storage in a similar manner to natural gas. The possibility of storing gas and air in various geological structures is considered. One possibility considered in the planned location is to use existing gas fields asa a "cushion" for the storage of gas supplied from the network. The project is at the study stage, financed in part with public funds (DOE). The planned features of the proposed installation are:

- two turbines with a capacity of about 100 MW each;
- a compressor system with a capacity of about 166 MW and outlet pressure of 36 bar;
- cooperation with wind turbine power plants (common power delivery to the electric grid) during the day anda a feed compression station in the valley of power demand (night), as part of the power produced from the wind turbine could be used to supply the CAES in the case of excess capacity in the system;
- ability to self-start in blackout conditions.

Similar projects were also considered in Europe (for example Ll.Torup in Denmark). Generally, they would give the opportunity to accumulate the energy produced by irregular power

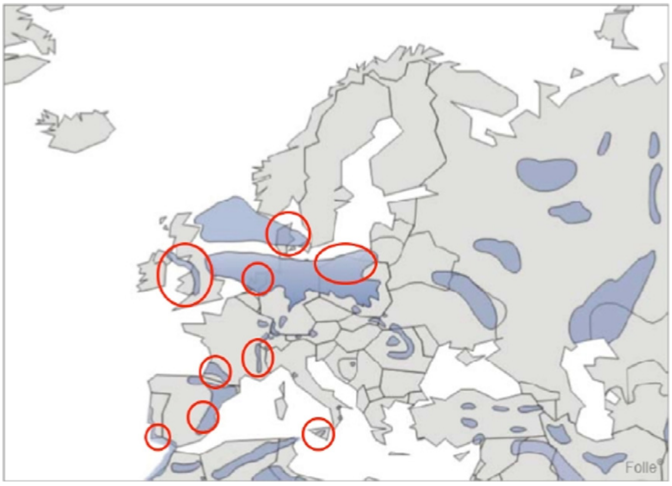

Figure 10: Coincidence of high wind potential anda a salt dome in Europe [52]

Figure 11: Wind projects in Poland (as of 2007, according to PGE). The map does not reflect the actual status of projects, only areas of concentration of activity by developers. Offshore wind farm locations are ignored

suppliers (renewables) and use it to cover peak loads, equalizing daily changes, and in the case of having larger tanks, also in seasonal cycles. The CAES concept of cooperation with wind power is also discussed in [51].

Poland is ideally situated, as it has high wind potential anda a salt dome—see Fig. 10.

Europe is currently at the forefront of developing wind power. In the period 2011...2014 the installed capacity of heat and power plants powered by renewable energy sources increased significantly in Poland. According to data published by the Polish Energy Regulatory Office URE (based on concessions for electricity generation), it reacheda a level of 5.51 GW, of which wind power accounted for more than 3.8 GW by the end of 2014 (Table 1), putting Poland in 13 place worldwide [53, 54]. The growth dynamics rate of capacity installed in renewable sources was significantly lower,

Table 1: Renewable heat and power plants, capacity installed at the end of 2006 and years 2011...2014, MW [53]

Installation type	2006	2010	2011	2012	2013	2014
Biogas power plants	36.76	82.884	103.487	131.247	162.241	188.549
Photovoltaic power plants	0	0.033	1.124	1.289	1.901	21.004
Hydropower plants	934.031	937.044	951.389	966.103	970.128	977.007
Biomass power plants	238.79	356.19	409.679	820.700	986.873	1008,245
Wind Power plants	152.56	1180,272	1616.361	2496.748	3389.541	3833.832
Together	204.604	2556.42	3082.04	4416.09	5510.684	6028.637

although objectively it was considered high. By the end of the decade, it is planned to increase the power capacity of wind power plants to about 7...8 GW.

According to data from ARE [53], at the end of 2013, the total installed capacity in the National Electric Power System was 38.647 GW, including 3.408 GW installed in wind power plants. So, the percentage share of installed capacity of wind power plants was about 8.8% of all power of KSE, as compared to 6.7% in the same period of time in 2012. At the end of 2014 it was about 10%.

It can be seen that the share of capacity installed in renewable sources in Poland is still small, comparing to the neighboring system in Germany, and the scale of related problems is incomparably smaller. The dynamics of development of wind farms in Germany, which is ahead of the Polish market, indicate that there are significant reserves still existing in the Polish market. At the end of 2011, capacity installed in the German power system was about 168 GW. At this time, the share of wind power capacity in this country exceeded 15%. At the end of 2014, installed capacity in wind power plants in Germany exceeded 39 GW. There is still one more phenomenon present in Germany that is absent from Poland. Namely, the very fast growth of capacity installed in solar power plants, especially photovoltaic. At the end of 2011, power installed in solar exceeded 25 GW, so total installed capacity, along with wind power plants, exceeded 54 GW. In 2012, the capacity installed in these two categories of renewable sources in Germany exceeded 60 GW and at the end of 2013 70 GW (69.33 GW). At the end of 2013, renewable sources accounted for about 37% of the total installed capacity in the German energy system. The German electrical power system in that year had total power of about 184 GW. The high share of renewables in Germany means that in windy and sunny weather during summer renewables could cover full demand for periods of time. Considering that renewable sources have been given priority access to the network, this could mean other power plants could be eclipsed or facea a dramatic power reduction.

Electricity generation in Poland is currently based mainly on coal fuels (83% in 2012, 83.7% in 2013)with about 10% accounted for by renewable sources, almost half of which is from wind power plants. Even this small share places an important constraint on the work of coal-fired steam power plants.

Fig. 12 shows an example of one month (January 2015), the dynamics of changes in demand of National Power System (KSE), compared to electrical energy generation by centrally dispatched units (JWCD), generation by one large baseload coal-fired power plant and total generation from wind power plants in Poland. In the case of power plants, reduced load was used (the current value related to the available capacity scale on the right side of the Figure). In all cases, hourly average values were used. Demand and generation in system data are based on information from KSE Operator. The considered power plant has high power units, where the technological minimum takes no less than 45% of power achieved.

Table 2: Installed wind power capacity, MW, top 10, 2013 and global [56]

Country	End of 2013	End of 2014
China	91,412	114,763
United States	61,110	65,879
Germany	34,250	39,165
Spain	22,959	22,987
India	20,150	22,465
United Kingdom	10,711	12,440
Italy	8,558	8,663
France	8,243	9,285
Canada	7,823	9,694
Denmark	4,807	4,845
World total	318,596	369,553

The analyzed monthly period coversa a time period of 744 h. The graduation system with 168 h corresponds to the number of hours in the week, grid lines on the time-line are made to separate the days. The first day of January 2015 wasa a Thursday.

Results of the analysis show that even large, coal-fired power units playa a regulatory role in KSE. They systematically (every night) offload, until they reacha a level near to or at the technological minimum and they return to higher power working every day. In the case of energy supply from wind turbines and serious reduction of load of these power plants (units) during the day, some of the units are turned off. Lignite-fired units, due to their lower operational costs, are less intensively (medium) load reduced.

Variability of wind generation in the Polish power system in 2013 is characterized in Fig. 13 and 14. Fig. 13 shows an ordered diagram of the level of power usage, installed in wind power plants. It is of note that the level of power generation higher or equal to 50% of installed power, was achieved during only 10% of the year. During half of the year generation remains at lower than 20% of the power installed. According to ARE data [53] in 2013 the average obtained time of power usage installed in wind power plant was 1,762 h compared to 1,968 h at wind farms of professional energy companies [53]. There needs to be compensation for the increasing influence of wind power plants on the work of baseload power plans demands, not only in Poland (Fig. 15 and in Table 2). Using

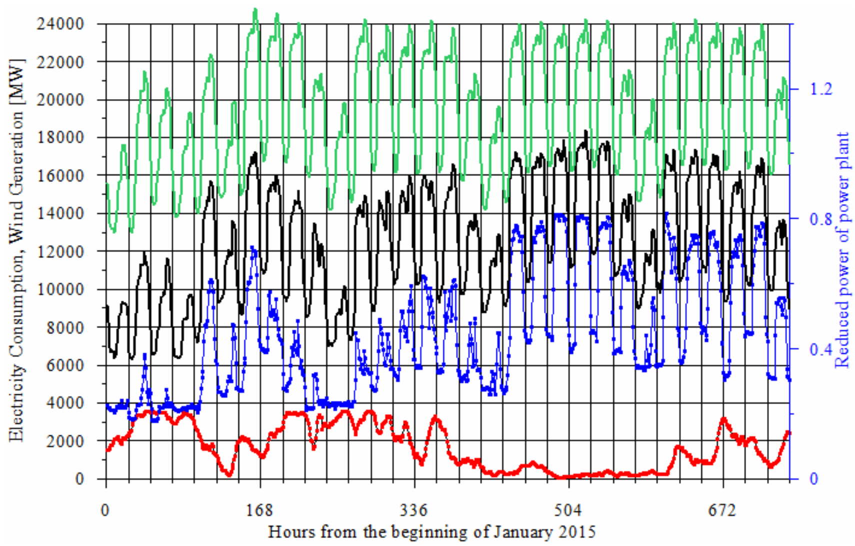

Figure 12: Dynamics of changes in January 2015: wind power plants (bottom line) with changes in demand for electrical energy of KSE (topline), JWCD generation (next topline) and power generation ina a baseload coal-fired power plant (line with points)

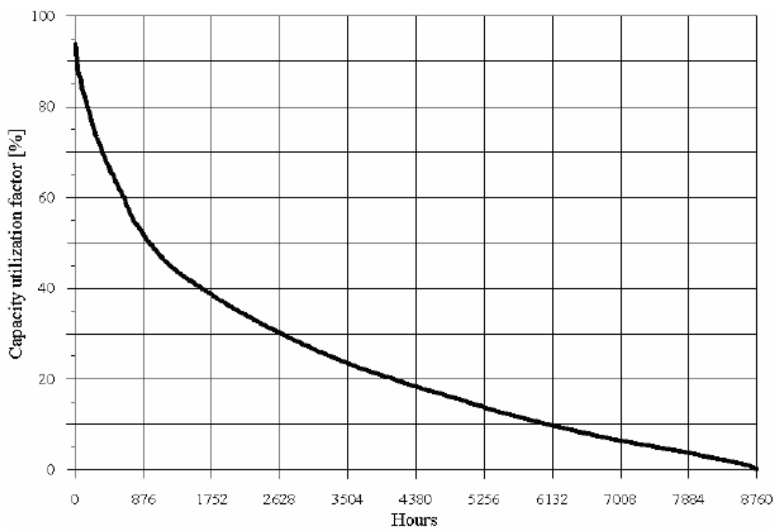

Figure 13: Rate of use of capacity installed in wind power plants in 2013 in Poland, graph structured [54]

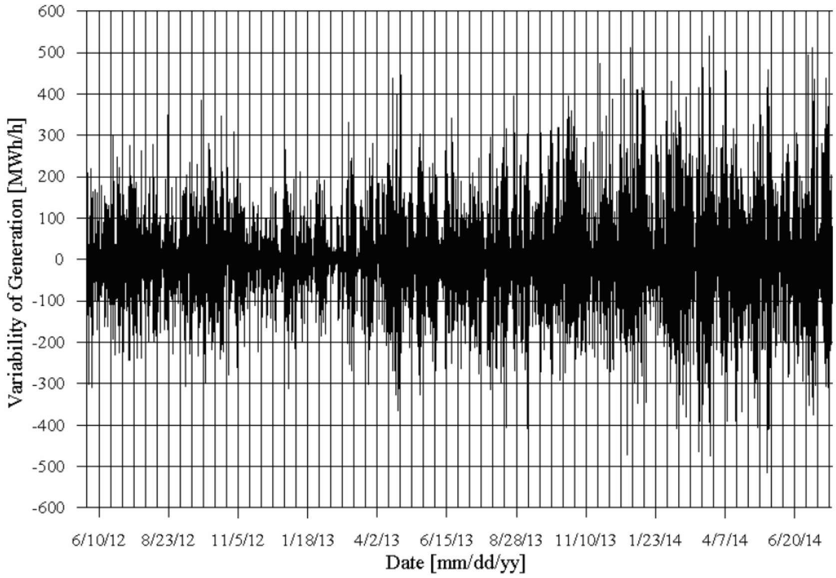

Figure 14: History of dynamics of hourly changes in electrical energy generation from wind power plants, period from 28 May 2012 to 29 July 2014. Made on the basis of data published by KSE Operator

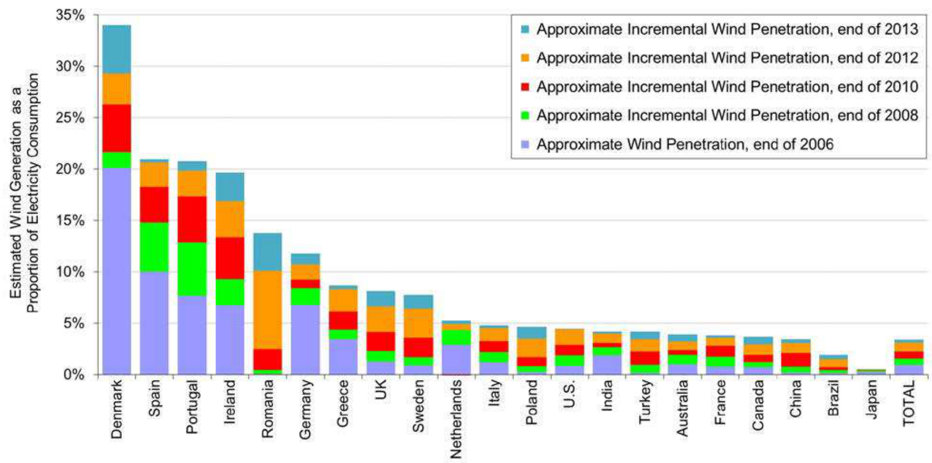

Figure 15: Approximate wind energy penetration in countries with the greatest installed wind power capacity [55]

Pumped-Storage plant to that end would require expensive investment and environmental controversy as regards suitable locations. Practically, the only alternative in terms of installations built on an industrial scale is CAES technology.

In Poland, there are potential locations for compressed air energy storage power plants. Construction of plants may be particularly interesting owing to additional conditions. For some time, due to the rapid growth in demand for power, especially in the northern part of the National Power System,a a threat has existed to the security of electricity supply. As a temporary remedy [57] the construction of peak power source capabilities with emergency operations mode is considered, featuring:

- start up without external power supply,
- achieving the desired power range in a short time (several minutes)
- continuous operation for a few hours a day.

These conditions can met highly if the location for the CAES plant and related facilities is chosen correctly. Gas turbines could provide a fundamental solution to the power deficit problem at peak demand. The advantage of the CAES plant could be the possibility of energy accumulation from renewable sources of electricity. Another advantage is its moderating relation to the realizable power demand for gas (less gas needed) compared to gas turbines. The main difficulties are: finding the right location and potentially long duration of the investment associated with the need to prepare the air tank and completion of delivery of specialist machinery and equipment.

Where there isa a potential for underground storage of air near the locations indicated in Fig. 11, the construction ofa a CAES plant should be considered, provided there are favorable conditions for access to infrastructure, especially electricity and gas networks. The search for underground storage locations for compressed air applies equally to potential sites for storage (sequestration) of carbon dioxide. The most favorable conditions in geological structures can be found in north-western and central Poland. Locations ofa a few old workings (rock salt, natural gas and oil) in the northern part of the country are shown in Fig. 16. Locations indicated in the figure, suitable for sequestration, concern the possibility of storing much larger amounts than is needed for the accumulation of air fora a CAES plant, so the next step would be to search for salt deposits, oil and gas sites that are much smaller than the indicated capacity (a few hundred thousand m^3, corresponding to the storage capacity of air to the order of several tens of million m^3 under normal atmospheric conditions).

Outside of northern Poland there are: the Legnica-Głogów Copper Area, copper rich Monoklina Przedsudecka, and large deposits of rock salt. There isa a possibility of leaching salt caverns with the following characteristics:

- cylindrical shape, diameter of 64 m and height of 120 m,
- geometric volume of 350,000 m^3,
- maximum pressure in chamber 200 bar,
- minimum pressure in chamber 40 bar.

Table 3: Estimated investment costs ofa a CAES plant [59]

Cost type	Rock reservoir	Salt cavern	Aquifer
Power plant without storage, $/kW	440	430	410
Cavern, $/kWh	30	1	8
Storage time, h	10	10	10
Total costs, $/kW	740	440	490

Those dimensions are close to that achievable at Huntorf power station [42]. Caverns could be used to store gas, petroleum liquid fuels and other materials suitable for storage, including air. Development would, however, requirea a long preparation period.

1.3. Key features of the CAES plant

The core technology ofa a plant with air stored underground is well-known and proven. Gas turbines for CAES plants are based on adaptations of standard energy solutions (expanded with additional elements). Compressor systems are based on the axial compressor, which has been tried and tested in power plants, supplemented with units proven in many years of work in other industries (high-pressure centrifugal compressor for air).

In most papers on energy storage, CAES technology is recognized as practically the only technically feasible alternative for large power plants to water pumped storage. The starting time for pumped storage turbine work is in the order of 1 to 15 minutes. CAES power plant start-up time to full power is about two to three times faster than the average time of starting a gas turbine unit and closes in the range of up to about 10 minutes.

Estimates data (based on figures from 2000) presented in Table 3shows that expected CAES plant construction costs would be noticeably higher than fora a conventional gas turbine plant, but significantly lower (at least twice) than for hydro peak plants. CAES plant costs given in Table 3 can be considered similar to expected national conditions for potential locations of underground tanks for the storage of useful air, for example, in Lower Silesia or Kujaw. Polish coastal areas could be particularly attractive for CAES plant—to co-operate with planned offshore wind farms. A method for optimizing a CAES system connected toa a load center is presented in [60]. This method is suitable for CAES sizing in systems with high wind power penetration.

In the open literature there are two methods employed in the practice of the air storage in underground tanks: at constant pressure and at constant volume. Alternative terms for these two methods are dry storage and wet storage, or—compressed air storage with compensation and without compensation. Ina a constant volume cavern, the operation takes place within a specified range of working pressures.

Figure 16: CO_2 sequestration possibilities, the section in northern Poland [58]. Symbols associated with storage capacity: ◇ salt mines, △ old gas fields, △ old oil and gas

Upper pressure is determined by the geological conditions, mainly airtightness during operation (defined as acceptable loss of air). The lower pressure limit is determined by the operating conditions of machines through the tank power plant. Based on the volume of the tank and pressure ranges it is possible to determine the amount of air stored.

2. Thermodynamic analysis of CAES performance

To compare different variants of CAES plants, energy conversion efficiency can be used, which is defined as:

$$\eta_{CAES\,c} = \frac{E_{elg}}{E_{elc} + Q_f} \tag{1}$$

where: E_{elg}—energy provided by the CAES plant to the grid, E_{elc}—energy delivered to the CAES plant in the form of electricity to drive the compressor, Q_f—flow of chemical energy contained in the fuel supplied.
Using the size of the energy (not power) is essential in the analysis of energy conversion quality by CAES in connection with differing: time to take and return energy to the grid and of input and output power. Time-varying parameters of the process, including the efficiency of the compressor depending on the air pressure in the reservoir (compression), the flow through the turbine inlet pressure dependent (if variable). With the conditions in the cavern and a method for carrying out the process (throttling parameters, lubricants, surge limitation, etc.) the time characteristics of charging and discharging of the tank are obtained. To determine these characteristics, a suitable dynamic model of the plant is needed.

$$\eta_{CAES\,s} = \frac{E_{elg}}{\frac{E_{elc}}{\eta_{elR}\,\eta_{tr}} + Q_f} \tag{2}$$

where: η_{elR}—the efficiency of electricity generation in the reference power system, η_{tr}—efficiency of the transmission of electricity to CAES plant.

It is not always helpful to use the described relationship (1) of the efficiency definition. Two different types of energy are added: (i) electricity taken from the network, and (ii) the chemical energy of fuel. From this point of view it would be more appropriate to use the relation (2), which takes into account the efficiency of generation of electricity taken from the network for compression. This method seeks to assess the energy consumption of the fuel for the purpose of generation (total) of electricity from the CAES plant.

In order to avoid having to add together two different types of energy (electricity to chemical), CAES plant efficiency can also be defined as:

$$\eta_{CAES\,f} = \frac{E_{e\lg} - E_{elc}}{Q_f} \tag{3}$$

treating the process of the CAES plant as a form of power generation based on fuel supplied. This defined the fuel efficiency for generation of electricity generated (net) by the plant. It is to be noted that the equation (3) can givea a negative result (if E_{elc}>E_{elg}) and an infinity high (if Q_f=0).

There is another way to determine the efficiency of the CAES plant, as given for example in [61]. The net efficiency of electric energy storage is defined as the amount of electricity delivered to the grid in relation to the energy supplied in the natural gas:

$$\eta_s = \frac{1 - (HR \cdot \eta_{gas})}{ER_{net}} \tag{4}$$

where: HR—heat rate of the gas turbine only, η_{gas}—efficiency of conversion of chemical energy into electricity, ER_{net}—the net value of energy supplied to the energy received.

The result obtained based on the equation (4) is sometimes compared with the efficiency of pumped storage. Evidently, it is not straightforward to make this comparison.

Fig. **??** containsa a Sankey diagram showing the main flows of energy during charging and discharging processes. It also shows the efficiencies of the whole cycle in accordance with the definitions given previously.
The process of charging and discharging the cavern can be analyzed using the mass balance and energy balance of the working medium (transformed into a balance of enthalpy):

$$\frac{dm}{dt} = \frac{d(\rho \cdot V)}{dt} = m_\alpha - m_\omega \tag{5}$$

$$\frac{dH}{dt} = \frac{d(\rho \cdot V \cdot h)}{dt} = m_\alpha h_\alpha - m_\omega h_\omega + V\frac{dp}{dt} + Q \tag{6}$$

where: m —mass flow, h —specific enthalpy, H—total enthalpy, p—pressure, Q—heat exchanged, ρ—density, V—volume, t—time; indexes: α, ω—inlets and outlets, respectively.

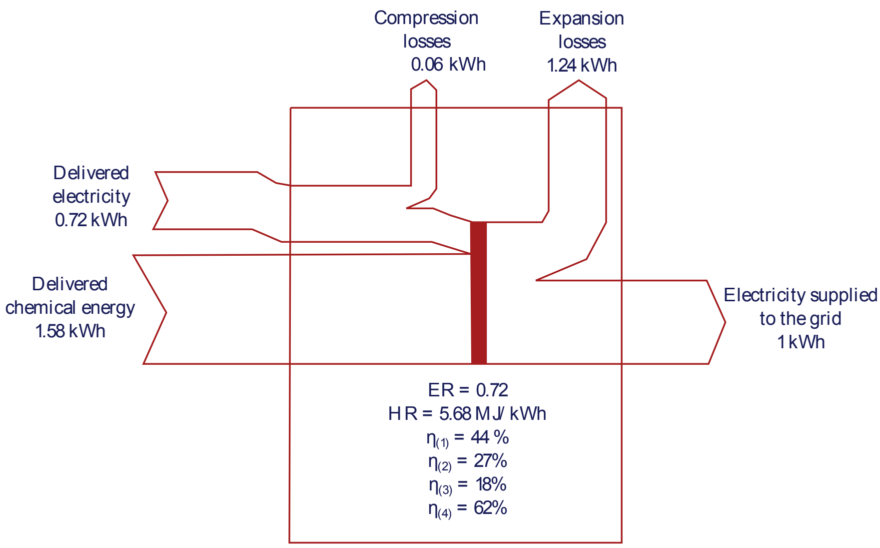

Figure 17: Sankey diagram showing the main flows of energy during charging and discharging processes. It also shows the efficiencies of the whole cycle in accordance with the definitions

Equations (5) and (6) in long written form are sometimes developed on the basis of an assumption (not always explicit) of an ideal gas model for the medium. This is a far-reaching simplification in light of the high pressures and large differences in pressure in the process. Specific heat at room temperature under a pressure range of from 1 to 100 bar changes by about 18%. Equations (5) and (6) are analyzed separately for the charging and discharging of the tank. The work (energy input) required to compress the working medium of the compressor in the loading tank should be determined. The work obtainable in the expansion turbine can be determined in similar fashion. The analysis should take into account the compression inter-stage and final cooling processes and and the work produced by the turbine.

3. Simulations of the charging and discharging processes

This section presents the assumptions and the results obtained from the model calculations ofa a CAES plant (simulation of the combustion chamber by introducing air for heating purposes).

The aim of this calculation is not to givea a presentation of a real system—based on the actual characteristics of the devices—but only a qualitative and quantitative analysis of the idea of energy storage in the form of compressed air. The results of technical implementation of the system willrely largely on the characteristics of the devices. The special nature of the work of the whole system and custom parameters (eg. very high static pressure) requires the use of equipment that is specially constructed for this purpose. Hence the performance and operating parameters from some devices are not reflected in others. In order to illustrate the potential of one way of storing energy in the form of compressed air, an idealized case—constant polytropic efficiency of turbines and compressors—is presented. In practice, deviations from the performance shown here are expected.

The performance characteristics, including efficiency as defined by the formulas (2), (3), ofa a CAES plant for different variants of operating parameters can be found in [62], and ina a slightly different arrangement in [22].

The basic assumptions for the calculation:

1. air tank capacity (caverns): 300,000 m^3—a system with constant volume,
2. heat loss to the surrounding air and were found to be negligible,
3. polytropic compressor efficiency: 75%
4. compressor power: 60 MW
5. polytropic turbine efficiency: 75%
6. nominal air flow through the turbine: 400 kg/s,
7. turbine air outlet pressure: 1 bar,
8. model of the working medium: real gas (Peng Robinson).

Separate components created in the used software [63] are dynamic models of the compressor unit and air turbine with the cavern. The turbine deign point parameters are:

1. inlet pressure 40 bar,
2. discharge pressure 1 bar,
3. air flow rate 400 kg/s.

The calculation results shown below are for the following selected cases:

1. charging the cavern with pressure from 1 bar (50°C) to 70 bar ina a system equipped with inter-stage and final coolers (50°C/50°C)
2. discharge from 70 bar (50°C) to 1 bar and air is warmed up to a high temperature (1,100°C) with air throttling to 40 bar prior to the turbine.

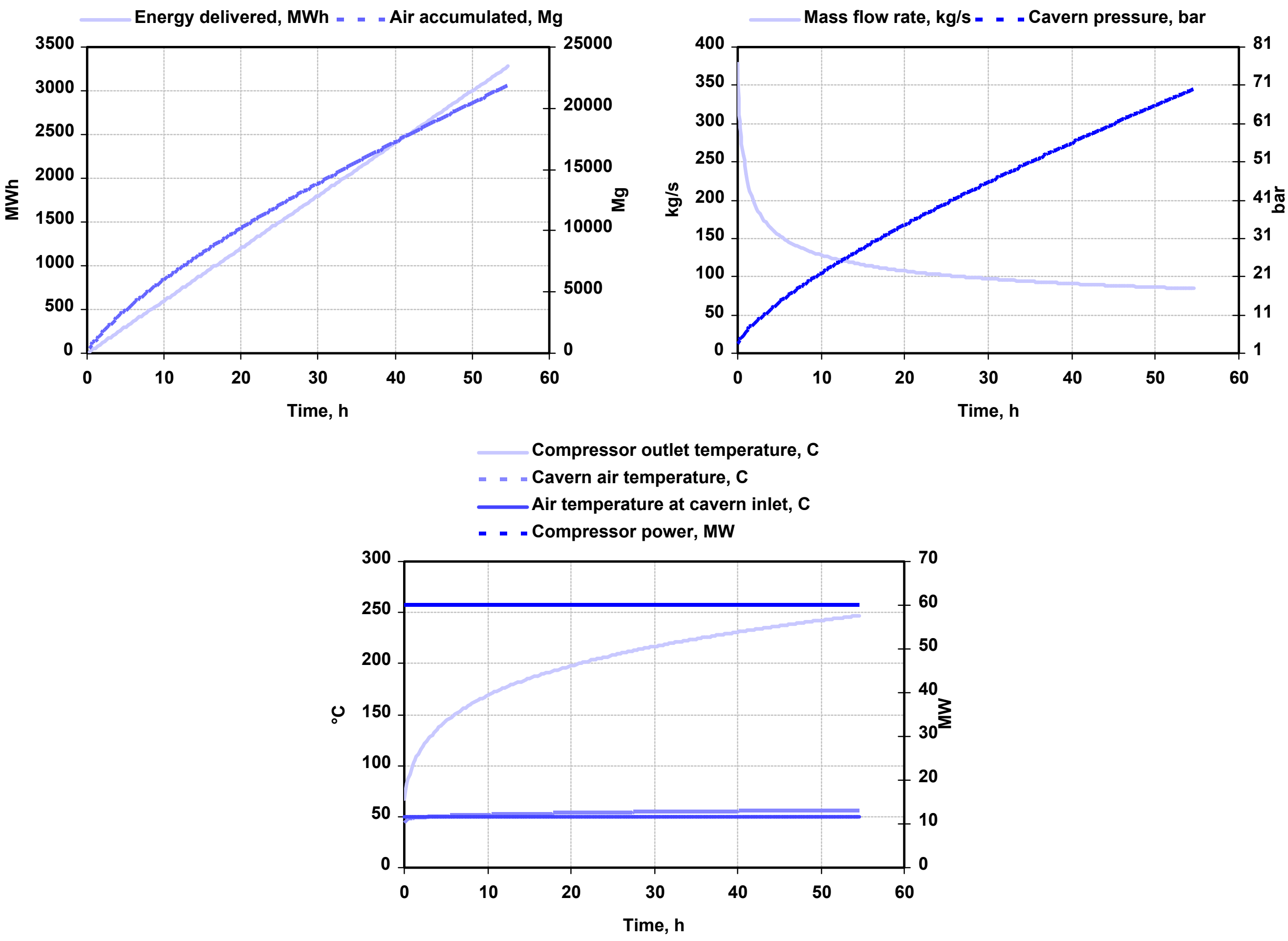

Figure 18: The main parameters of the charging process from 1 to 70 bar

Real operation ofa a CAES plant is carried out in a narrower pressure range than considered here (see Fig. 18). Lower pressure is chosen so that the plant had an air reserve fora a possible emergency run. For example, the Huntorf plant is operated in the pressure range 43...70 bar. Exceptionally,a a reduction in operating conditions to 20 bar is allowed. An analysis of the effect on CAES plant performance of selecting lower pressure is performed in [62].

The power generated by the turbine set, at the indicated assumptions, is 320 MW. It is possible to obtain it for nearly seven hours, then to lower it so that one half of the maximum value may be achieved for a further 5 hours. The pressure at the inlet of the turbine is kept constant at 40 bar until the cavern pressure is higher. In the next stage of the expansion process before the turbine, the pressure decreases with the decrease in the cavern. The energy generated by the turbine discharge is achieved by both the flow of air from the cavern and combustion of NG (Fig. 19).

4. Conclusions

The introduction of emissions trading, primarily as regards carbon dioxide, has increased the price attractiveness of electricity from renewable sources. A significant drawback of wind and solar renewables is the irregularity of the supply of electricity. A CAES plant hooked up to renewable energy sources could go some way to eliminating this disadvantage. In the case of a purely adiabatic method, no greenhouse gas emissions would be made at all. The energy produced becomes available in a controlled manner at periods of peak demand. With the additional use of organic fuel combustion (eg natural gas),a a renewable power system cooperating witha a CAES plant enjoys much lower emissions than gas-fired plants alone. The goal of zero emissions could be obtained by using biofuels to power the turbine. Concepts of this sort are currently under consideration.

If extra power is obtained by utilizing biofuels, attention must be paid to the possible (total, partial) loss of green certificates of energy produced from the CAES plant. This would severely impact the selling price obtainable. The authors did not analyze this important factor in detail, and it may even be decisive for the profitability of any investment.

The CAES power plant is characterized by favorable properties in the partial load range. This is a significant advantage over the classical gas turbine power plant. There are very rapid changes in the load of the turbine: several dozen percent per minute. These properties predispose compressed air based plants to work in peak periods, as rapid reserves available for network regulation and reactive power compensation.

Poland has potential locations for compressed air storage power plants, for example in salt caverns. Construction of plants of this type may be of particular interest in light of the major investments in wind energy, both current and planned , especially in the north of the country.

The energy efficiency of power plants of this type cannot be compared with conventional pumped storage power plants based on water reservoirs, where the compressibility of water is incomparably smaller than the compressibility of air. Most of the energy collected in the valley of the night is brought into the environment through the inter-coolers compressors. Electricity produced at the peak comes mainly from the chemical energy contained in natural gas (see Fig. 17). The solution to this issue is the subject of many studies focused mainly on the development of suitable additional thermal energy storage, which is used to heat the air before it enters the turbine. The storage facility would be charged from behind the cooling air compressors.

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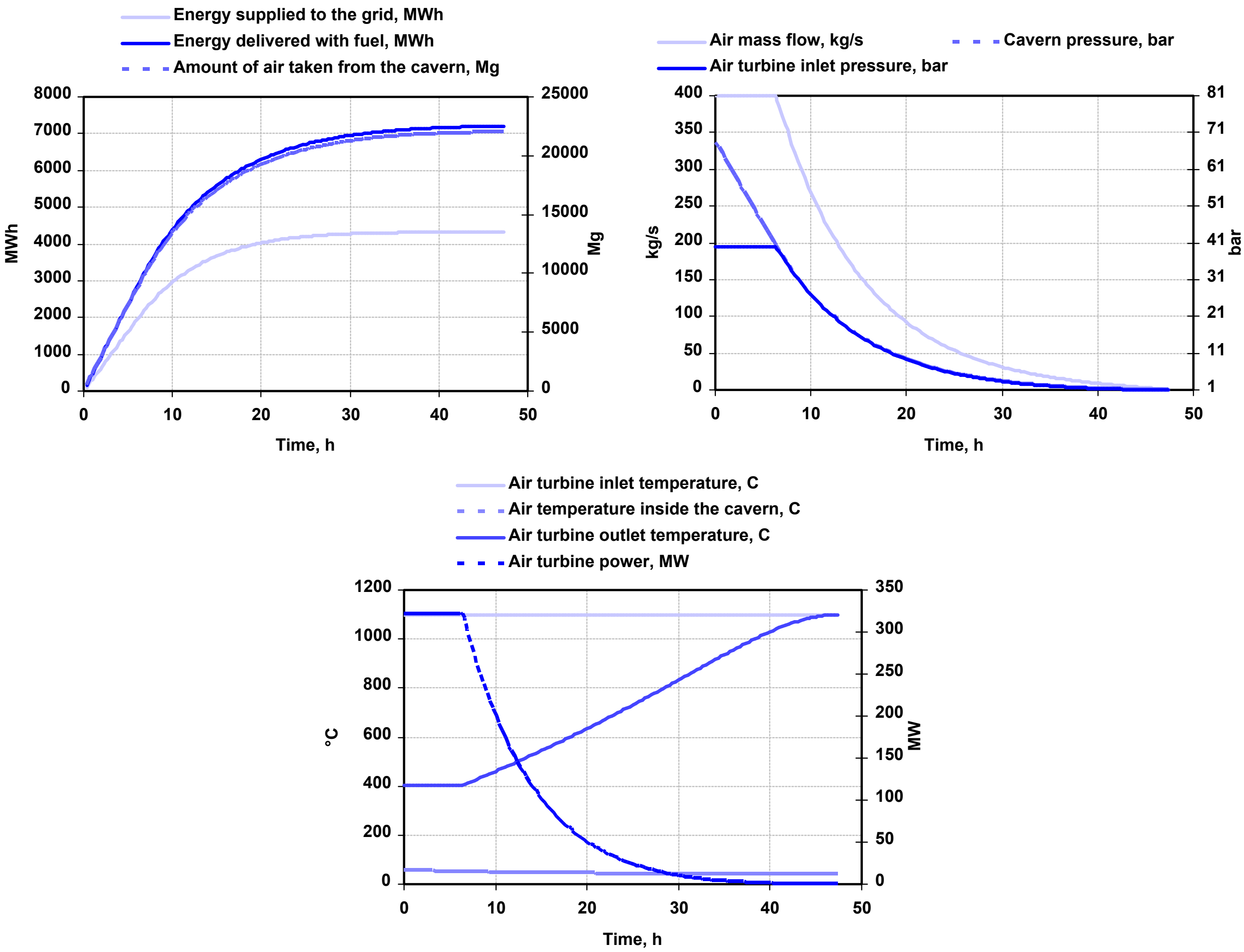

Figure 19: The main parameters of the discharging process from 70 to 1 bar with heating air to 1,100°C at turbine inlet

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