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Impact of selected parameters on performance of the Adiabatic Liquid Air Energy Storage system

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Abstract

The paper presents a thermodynamic analysis of a selected hypothetical liquid air energy storage (LAES) system. The adiabatic LAES cycle is a combination of an air liquefaction cycle and a gas turbine power generation cycle without fuel combustion. In such a system, heat of compression is stored and subsequently used during the expansion process in the turbine.

A mathematical model of the adiabatic LAES system was constructed. Balance calculation for a selected configuration of the energy storage system was performed. The influence of pressure in the air liquefaction cycle and the gas turbine power generation cycle on storage energy efficiency was analyzed. The results show that adiabatic liquid air energy storage systems could be very effective systems for storing electrical power, with efficiency levels reaching as high as 57%.

Keywords: energy storage; adiabatic LAES; air liquefaction

1. Introduction

There are many stable and predictable sources generating electrical energy: coal-fired power plants [1, 2], gas turbines [3], combined cycles [4, 5], nuclear power plants [6], ORC systems [7], fuel cells [8–18], piston engines [19–21], Stirling engines [22–27] among others. But there are also unpredictable sources, especially wind turbines and photovoltaics.

For natural reasons, power demand in an energy system is variable in time. There are both short-term daily or weekly variations, and seasonal ones. Sources which considerably affect variations of power supply include in particular wind and solar power plants. In recent years, wind power capacity has been growing fast in Poland. Total capacity installed in wind power plants at the end of 2015 was 5100 MW (Table 1); at the same time total capacity installed in the national power system was almost 40,000 MW. This results in growing difficulties in balancing power supply with demand.

Power supply from wind sources varies considerably. At some points in time, the actual output of wind sources reaches 90% of total installed capacity, but it is not unusual for it to drop to nearly zero [28, 29]. This creates a significant challenge for commercial power plants.

When power demand is low during non-peak hours, operation of renewable sources with an output close to their installed capacity enforces load following operation of base load plants. There are periods, during which the capacity of those plants is reduced below the technical minimum level, which leads to reduced equipment lifetime, lowered generation efficiency and increased emission of pollutants per unit of generated energy.

In this context, the possibility of power storage is becoming a focus area for scientific and industrial communities. Storing electricity makes it possible to absorb some of the variability of intermittent renewable generation.

There are many ways to store energy [30] but not all of them are big enough. Solutions currently used for large scale electricity storage are limited to pumped storage plants and compressed air energy storage (CAES) systems. More information about CAES may be found e.g. in [31–34].

Unfortunately both those technologies have very specific site requirements, which effectively constrain wider application. This kind of restriction does not apply in the case of the liquid air energy storage (LAES) technology discussed in this paper.

LAES consists of a liquefaction module, a module for energy recovery from liquefied air and liquid air storage components. When the system is charging, excess grid electricity is

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Table 1: Capacity installed in wind power plants [MW]; list sorted by 2015 totals [28, 29]

Country	2007	2010	2012	2013	2014	2015
EU	56,614	84,278	106,454	117,384	128,752	no data
China	5,912	44,733	75,564	91,412	114,763	145,104
USA	16,819	40,200	60,007	61,110	65,879	74,772
Germany	22,247	27,214	31,332	34,250	39,165	44,947
India	7,850	13,064	18,421	20,150	22,465	25,088
Spain	15,145	20,676	22,796	22,959	22,987	23,025
UK	2,389	5,203	8,445	10,711	12,440	13,603
Canada	1,846	4,008	6,200	7,823	9,694	11,205
France	2,477	5,660	7,196	8,243	9,285	10,358
Italy	2,726	5,797	8,144	8,558	8,663	8,958
Brazil	247	932	2,508	3,466	5,939	8,715
Sweden	831	2,163	3,745	4,382	5,425	6,025
Poland	276	1,107	2,497	3,390	3,834	5,100
Portugal	2,130	3,702	4,525	4,730	4,914	5,079
Denmark	3,129	3,752	4,162	4,807	4,845	5,063
World total	93,927	197,637	282,482	318,596	369,553	no data

used to liquefy air. This process involves air compression followed by cooling, changing the original gaseous phase into liquid. Liquefied air is then put into storage. Once the grid power demand rises, a pump is used to increase the pressure of the liquid air. The pressurised air is heated, causing it to evaporate. The regasified air is then used to drive power generation turbines.

During the air evaporation process, the heat supply medium is cooled to a low temperature. In order to improve the efficiency of the system, the cooling power contained in it must be stored for later use in the liquefaction process.

In addition to cold storage, an adiabatic facility also needs storage for heat generated during air compression. This heat is later used in the LAES discharging cycle. In order to improve utilization of stored heat, it is necessary to split the gas turbine (and therefore the expansion process) into several parts. Heat exchangers supplied with the stored heat should be installed between each two turbine parts, and also before the first turbine.

LAES technology has not achieved general use. At this time, there is only one research LAES facility with a power of 350 kW and storage capacity of 2.5 MWh, built in the UK in 2011 [35]. This plant performs poorly due to its simplified configuration: round trip efficiency barely reaches 8% [35].

Nevertheless, LAES technology is currently subject to intense research in many scientific facilities all around the world. In recent publications authors have proposed various solutions for energy storage systems based on liquefaction.

The paper [36] presents a concept and thermodynamic performance analysis for an adiabatic LAES system. The calculated efficiency of the proposed solution is 49%.

Publications [37] and [38] present a hybrid solution combining features of CAES and LAES. In the authors' opinion, this solution is cheaper than LAES or CAES (when using artificial compressed air reservoirs). Preliminary analysis [37] yielded a calculated efficiency value of 53%, although further investigation [38] demonstrated that it would be lower – 42%.

A comparison of energy storage systems based on various liquefied agents (air, nitrogen and carbon dioxide) with the CAES system is presented in [39]. In the authors' opinion, systems based on liquefied gases have potential for large scale energy storage.

The study [40] presents an analysis of energy storage systems based on compressed air and liquid air for different shares of liquid air (from 0 to 100%).

An energy storage system based on a closed circuit of liquefied CO_2 is presented in [41]. This system contains two liquid CO_2 tanks (high and low pressure). During the charging process, the high pressure tank is filled, and the low pressure tank is emptied; while discharging the process is reversed. The calculated efficiency of this system is 56.64%.

The study [42] compares different cryogenic energy storage systems in terms of their capability to cooperate with distributed sources. In the authors' opinion the best air liquefaction solution is the Claude cycle (involving a turbine and a Joule-Thomson valve), not the Linde-Hampson cycle (with a Joule-Thomson valve only).

An interesting configuration is presented in [43]. This solution utilizes a Rankine cycle with air as a working agent. This system may operate non-stop, continuously liquefying air, which is subsequently pumped, heated and expanded in a turbine. This system is also equipped with a cryogenic liquid air tank, which provides energy storage. The calculated efficiency of the system is from 20 to 50%.

This paper presents a selected hypothetical adiabatic LAES system and its thermodynamic analysis. The Adiabatic LAES cycle is a combination of an air liquefaction cycle and a gas turbine power generation cycle without fuel combustion. In such a system, the heat of compression is stored and subsequently used during the expansion process in the turbine.

The influence of pressure in the air liquefaction cycle and the gas turbine power generation cycle on the storage energy efficiency was analyzed.

2. The object of discussion—the analyzed system

The object of thermodynamic analysis was a LAES system schematically presented in Fig. 1. In the system under consideration, fresh air is compressed in a three-stage intercooled compressor together with the air circulated in the liquefaction system.

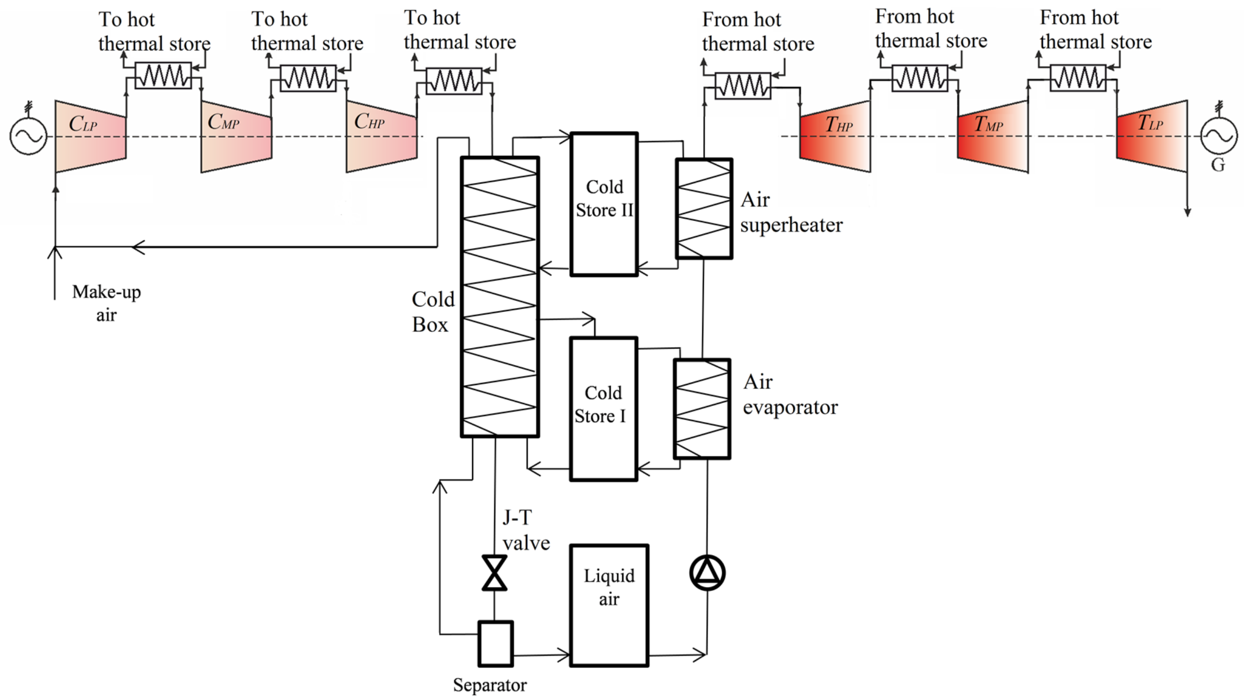

Figure 1: Diagram of the analyzed LAES system

Then it flows into a multi-flow heat exchanger (Cold Box), where it cools down and liquefies. After this exchanger it flows into a Joule-Thomson (J-T) valve, where it expands isentalpically. As a result, the air cools down further. Cooled air under low pressure is then directed into a separator, to separate the liquid and gaseous phases. Liquid air at a temperature below -190°C is directed into a tank. The gaseous phase of the cold air is directed through the multi-flow heat exchanger (Cold Box) back to the start of the liquefaction system. According to the presented diagram (Fig. 1), the multi-stream heat exchanger is also supplied by two flows from the cold storage.

The ability to store cold from the air evaporation system and use this cold in the liquefaction process is an essential feature required to achieve high energy storage efficiency in this technology. In the available publications, primary solutions considered for LAES system cold storage were beds of solid minerals (sand, gravel) [35]. In this paper, a different type of cold storage is proposed for a LAES system based on liquids. The concept involves using two vessels – “cold” and “hot” – which jointly form a cold store. When the cold store is cold, i.e. energy storage has been discharged, the medium from the “hot” tank flows into the “cold” tank through the air heater in the discharging section. Likewise, cold storage discharging, i.e. energy storage charging, involves flow of the medium from “cold” storage to the multi-flow heat exchanger where it heats up, and its accumulation in the “hot” vessel.

A two-stage cold storage system operating according to this principle has been proposed for the analyzed LAES system. The cold carriers are:

- in the first stage refrigerant R290, i.e. liquid propane;
- in the second stage liquid methanol.

It is assumed that the temperatures in the cold vessels would be respectively:

- -185°C for R290;
- -60°C for methanol.

The temperatures in hot vessels would be:

- -60°C for R290;
- 25°C for methanol.

When the energy storage is discharged, a pump is used to increase the pressure of the liquid air from the storage tank. The air is then evaporated and preheated. The heat needed for this process is supplied from the first stage of the cold storage, with refrigerant R290, which lowers its temperature from -60°C (hot vessel temperature) to -185°C (cold vessel). The regasified air then flows into the second heater, where its temperature increases to approximately 20°C. The heat of that process is used in the second stage of cold storage, lowering the temperature of the methanol from 25°C (hot vessel temperature) to -60°C (cold vessel temperature). As a result of the whole process described above, the air temperature rises from some -190°C to 21°C. Warm regasified air under high pressure is directed into a heat exchanger, where its temperature is further increased using stored heat from compressor intercoolers. The air is then fed into the high-pressure turbine. More heat is supplied to the air before further stages of expansion.

Table 2: Air composition assumed for calculations

Component	%-wt
Oxygen	23.052
Nitrogen	74.99
Carbon dioxide	0.046
Argon	1.276
Water vapour	0.636

It was assumed that the heat storage (not shown in the diagram above—Fig. 1) would be configured analogically to the cold storage, i.e. there would be a liquid medium, thermal oil, and two vessels—"hot" and "cold". It was also assumed that the storage would have three sections, with each section serving its own intercooler and air heater.

Heat storage would be charged at the same time as the whole energy storage system. The medium from the “cold” storage would be heated in compressor intercoolers to 200–270°C, and then stored in the “hot” vessel. Heat storage would be discharged with the whole energy storage system. At that time the thermal oil from the “hot” vessel would be used to heat the air before individual expansion stages.

3. Modelling method and scope of investigated parameters

Models of individual components of the analyzed system, as well as the model of the whole system were built using the commercial Aspen HYSYS software package [44]. The model of the working medium relied on the Peng-Robinson equation of state [45]:

$$p = \frac{RT}{v-b} - \frac{a(T)}{v(v+b)+b(v-b)}, \tag{1}$$

where: p—pressure, R—gas constant, T—absolute temperature, v—molar volume, a—attraction parameter, b—van der Waals covolume.
The assumed composition of air at the inlet of the liquefaction system is presented in Table 2. Air parameters were assumed according to ISO conditions, i.e. temperature of 15°C, pressure 1.013 bar. It was assumed that the charging time to discharging time ratio would be 2. The capacity of the liquefaction system was assumed at 150 kg/s (540 Mg/h). The internal efficiency of compressors was assumed at 89%. The compressed air temperature after the last cooler was assumed to be 20°C.

The results presented in this paper concern the influence of pressure in the system for recovering stored energy (i.e. turbine first stage inlet pressure) on energy storage efficiency and achievable electrical output at the assumed pressure in the air liquefaction system (i.e. pressure at the inlet to the J-T valve). The scope of the analysis included first stage inlet pressure values from 20 to 150 bar (20 bar, 40 bar, 100 bar, 150 bar).

The influence of pressure in the charging system on the specific energy consumption in the air liquefaction process was analyzed in [46]. As demonstrated (Fig. 2), the optimal

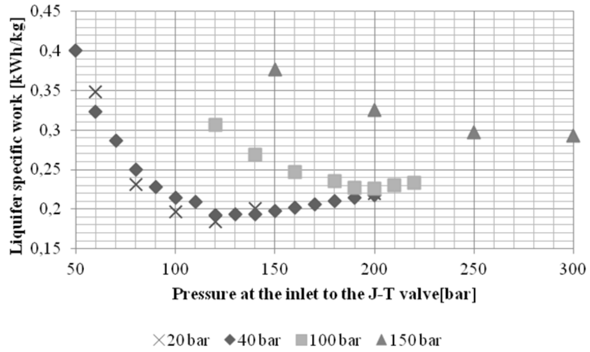

Figure 2: Specific energy demand of the air liquefaction process as a function of pressure at the J-T valve inlet for different turbine inlet pressures

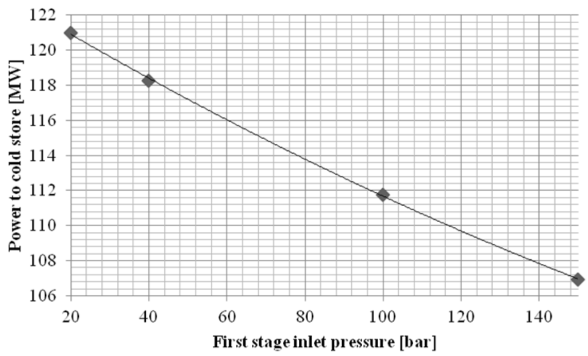

Figure 3: Power to cold store in a function of turbine first stage inlet pressure

pressure in the air liquefaction system (i.e. pressure at the J-T valve inlet) depends on the pressure in the discharge system (i.e. first stage inlet pressure).
This is due to the fact that the air pressure in the storage discharge system (i.e. first stage inlet pressure) is significant not only for energy recovery. It also affects the air liquefaction cycle, limiting the amount of cold which may be reclaimed from the regasification process. The higher the first stage inlet pressure, the smaller amount of cold may be recovered for the air liquefaction plant. For the analyzed system this value is from some 107 to 121 MW, depending on the turbine inlet pressure value (Fig. 3). The total energy in cold delivered to storage in a single liquefaction cycle was from 430 MWh to 485 MWh.
In the performed calculations, for each analyzed value of pressure in the storage discharge system (i.e. first stage inlet pressure), an optimal (in terms of specific energy consump-

Table 3: Energy parameters of the air liquefaction plant within the investigated LAES system as a function of turbine inlet air pressure

Turbine first stage inlet pressure, bar	Best pressure at the inlet to the J-T valve, bar	Lowest liquifer specific work, kWh/kg	Total power of compresor, MW
20	120	0.184	99
40	120	0.193	104
100	200	0.22	118
150	300	0.283	152

Table 4: Heat power and the temperature of the heat carrier in the compressor cooling system as functions of air pressure in the storage charging and discharging systems

Pressure at the inlet to the J-T valve, bar	Turbine first stage inlet pressure, bar	The total thermal power of the intercoolers, MW	Temperature range, °C	The amount of heat per charging cycle, MWh
120	20	113.6	180–220	908
120	40	129.1	190–220	1032
200	100	163	225–240	1304
300	150	185.2	245–270	1480

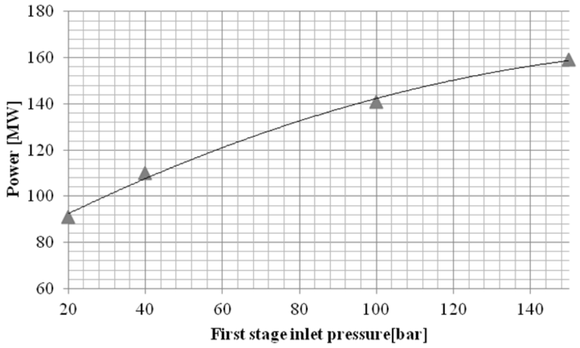

Figure 4: Output power generated by discharging the storage as a function of turbine inlet air pressure

tion) charge system pressure (i.e. J-T valve inlet pressure) was determined as per chart (Fig. 2). Relevant data is presented in Table 3.

When analyzing the chart (Fig. 3) and data given in Table 3 it may also be noted that as the air pressure in the storage discharge system increases, so does the specific energy consumption of the air liquefaction process within the storage charging system.

4. Results

The results of the simulations revealed that for different values of air pressure in the liquefaction system, different heating power is generated in the compressor intercooling system. Also, the temperature of heat storing medium grows along with the pressure in this system (Table 4). Heat losses from the storage to the environment were neglected during the analysis.

Both the amount of heat and the heat carrier temperature have significant impact on performance of the analyzed system during its discharging. The higher the heat carrier temperature, the higher the achievable air temperature before individual expansion stages. Calculations have demonstrated that it is not possible to utilize all heat recovered from compressor cooling in the storage discharge system. Some of the low temperature heat must be dispersed in the environment.

The higher the pressure in the discharge system (i.e first stage inlet pressure), the higher the optimal pressure in the charge system (i.e. pressure at the inlet to the J-T valve),

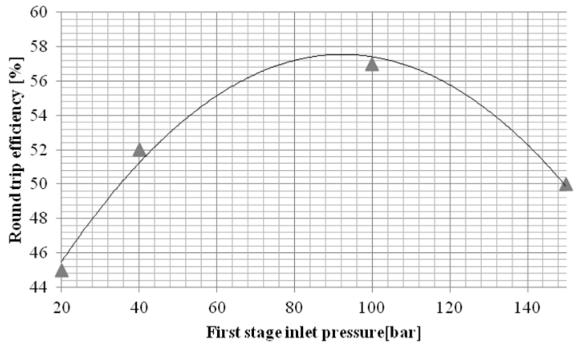

Figure 5: Round trip efficiency of the investigated LAES system as a function of turbine inlet air pressure

which also means a higher recoverable amount of heat (and at higher temperature level) from compressor cooling. The result is higher output power generated by discharging the energy storage in the case of higher air pressure in the system (Fig. 4).

Calculated generated electrical output of the storage was from 90 MW to 160 MW, depending on the analyzed case. This is therefore power comparable to that consumed by the compressor when the storage is charged. However it needs to be remembered that the charging cycle is twice as long as thedischarging cycle.

Efficiency is a key performance indicator of any energy converting system. For energy storage systems it describes the ratio of recoverable energy to the energy put into the storage (round trip efficiency). In the case of an adiabatic system which does not use any additional external energy sources such as fuel chemical energy, defining storage efficiency is relatively simple. It may be expressed by the equation 2:

$$\eta = \frac{W_T - W_P}{W_C} \tag{2}$$

where: W_T—turbine work [MWh], W_P—pump work [MWh], W_C—compressor work [MWh].

Naturally, work consumed by the pump depends on the pressure in the storage discharge system (i.e. first stage inlet pressure) and varies from 1 MW for the pressure of 20 bar to 6.9 MW for the pressure of 150 bar.

The results of the simulations show that round trip efficiency of energy storage in the investigated system varies from 45% to 57% depending on the analyzed case. The lowest efficiency was obtained for the turbine inlet air pressure of 20 bar. Then, as the pressure grows, so does storage efficiency, which achieves a maximum value for pressure of approximately 100 bar. Then above that value, efficiency starts to drop, and for the turbine inlet pressure of 150 bar it is already clearly reduced (Fig. 5).

The increase in turbine inlet pressure increases output power which may be generated by the system, but at the same time it reduces the amount of cold which may be transferred into the liquefaction plant. This in turn increases energy consumption by the air liquefaction process within the storage charging system. Then, the higher the pressure in that system (i.e. pressure at the inlet to the J-T valve), the higher the amount of heat which may be recovered from compressor cooling.

The calculations performed demonstrated that the optimal operating parameters for the analyzed system, which enable maximum efficiency, are:

- turbine first stage inlet pressure –100 bar;
- pressure at the inlet to the J-T valve – 200 bar;

For those parameters, round trip storage efficiency is 57%.

5. Conclusions

A significant disadvantage of wind and solar power generation is its intermittency, which depends on changeable local weather conditions. The introduction of feasible system-scale energy storage systems might considerably reduce the impact of intermittency. In such a case, the generated energy could become available in a controlled manner during peak load hours.

Nevertheless, the discussed technology is still at the stage of intense research in many scientific facilities all around the world. Its clear advantage is the capability of large scale energy accumulation, combined with the absence of siting constraints typical for pumped storage or CAES technologies.

The results of the calculations performed demonstrate that the operating parameters assumed for the LAES cycle may significantly impact its performance. Of particular importance here are: the pressure in the charging system (pressure at the inlet to the J-T valve) and the pressure in the discharging system (turbine first stage inlet pressure).

Changes of pressure in the discharging system change the amount of cold which may be recovered (from the air regasification process) and stored. This in turn affects the optimal pressure of the liquefaction plant, i.e., the pressure at which energy consumption of the liquefaction process is minimized. The pressure before the J-T valve on the other hand affects the amount of heat which may be recovered from compressor cooling. It also affects the temperature of the coolant after the intercoolers.

Thus the analyzed LAES system features multiple internal interdependencies in the part responsible for charging.

The goal of the simulations was to investigate the impact of analyzed pressure levels on the output and efficiency of the considered LAES cycle. Maximum round trip efficiency of 57% was achieved for the turbine inlet pressure in the energy recovery system of 90–100 bar. Both increase and reduction of pressure in reference to that value considerably reduce system efficiency.

The calculated efficiency obtained is lower than the value which may be achieved in pumped storage plants. Nevertheless, it is still high when compared to other competing technologies.

Clear advantages of LAES technologies include: no siting restrictions, wide range of achievable power ratings and energy storage capacities and utilization of proven components.

LAES therefore presents an attractive storage technology for balancing a future low carbon power network.

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