

## EXERGY ANALYSIS OF LIQUID AIR ENERGY STORAGE SYSTEM BASED ON LINDE CYCLE

### ANALIZA EXERGETICĂ A UNUI SISTEM DE STOCARE A ENERGIEI DIN AER LICHID BAZAT PE CICLUL LINDE

Claudia IONITA<sup>1)</sup>; Elena Eugenia VASILESCU\*<sup>1)</sup>; Lucreția POPA<sup>2)</sup>; Horatiu POP<sup>1)</sup>;

Saleh Jassim Saleh ALQAISY\*<sup>1)</sup>; Iulian UTA<sup>1)</sup>

<sup>1)</sup> Faculty of Mechanical Engineering and Mechatronics, University Politehnica of Bucharest / Romania

<sup>2)</sup> INMA Bucharest / Romania

Corresponding author: Vasilescu Elena Eugenia; E-mail: [eev\\_ro@yahoo.com](mailto:eev_ro@yahoo.com);

Alqaisy Saleh Jassim Saleh; [gscs\\_company@yahoo.com](mailto:gscs_company@yahoo.com)

DOI: <https://doi.org/10.35633/inmateh-67-53>

**Keywords:** air liquefaction cycle, storage of liquid air energy, exergy analysis, exergy destruction, performance criteria.

#### ABSTRACT

The paper presents a theoretical analysis from an energetic and exergetic point of view for a liquid air energy storage system (LAES). This paper identifies upper bounds on the energy and exergetic efficiency for this system. The system uses the simple Linde-Hampson liquefaction cycle for the liquefaction subsystem and the direct expansion method without heating above ambient temperature, for the power generation subsystem. It is known that as the temperature decreases, the destruction of mechanical work input increases due to the irreversibility of working processes. As a result, any irreversible process is very important to observe in cryogenic processes. The purpose of this paper is to develop an exergetic analysis which is then used in a procedure to optimize the Linde installation within the liquid air energy storage system when some functional parameters are changed. The analysis aims to find the functional parameters for which the exergetic efficiency of the installation is maximum. For each subsystem of the simple Linde installation an exergetic product and a fuel were defined and, based on their definition, the coefficient of performance of each functional area was calculated as well as the exergy destructions. Finally, the analysis of system components is presented in order to identify the components that have the greatest impact on energy and exergetic efficiency in an ideal environment. The analytical approach presented in this paper can be applied to other LAES configurations to identify the optimal operating points in terms of energy and exergetic efficiency.

#### REZUMAT

Lucrarea prezintă o analiză teoretică din punct de vedere energetic și exergetic pentru un sistem de stocare a energiei din aer lichid (LAES). Această lucrare identifică limitele superioare ale eficienței energetice și exergetice pentru acest sistem. Sistemul utilizează ciclul de lichefiere Linde-Hampson simplu pentru subsistemul de lichefiere și metoda de destindere directă fără încălzire peste temperatura ambiantă, pentru subsistemul de producție de energie. Se știe că pe măsură ce temperatura scade, distrugerea aportului de lucru mecanic crește din cauza ireversibilității proceselor de lucru. Ca urmare, orice proces ireversibil este foarte important de observat în procesele criogenice. Scopul acestei lucrări este de a dezvolta o analiză exergetică care este apoi utilizată într-o procedură de optimizare a instalației Linde în cadrul sistemului de stocare a energiei de aer lichid atunci când sunt modificați unii parametri funcționali. Analiza urmărește găsirea parametrilor funcționali pentru care eficiența exergetică a instalației este maximă. Pentru fiecare subsistem al instalației simple Linde s-a definit un produs exergetic și un combustibil și, pe baza definiției acestora, s-a calculat coeficientul de performanță al fiecărei zone funcționale precum și distrugerile exergetice. În cele din urmă, analiza componentelor sistemului este prezentată cu scopul de a identifica componentele care au cel mai mare impact asupra eficienței energetice și exergetice într-un mediu ideal. Abordarea analitică prezentată în această lucrare poate fi aplicată altor configurații LAES pentru a identifica punctele optime de funcționare din punct de vedere al eficienței energetice și exergetice.

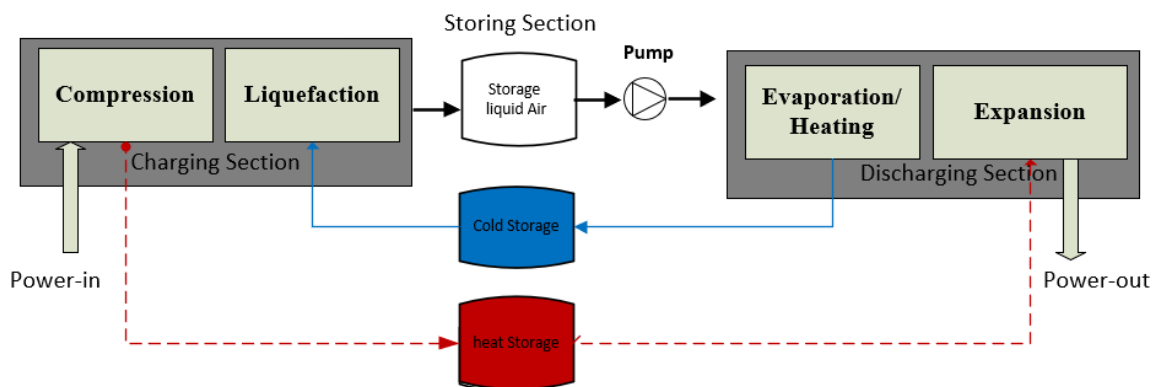
<sup>1)</sup> Claudia Ionita, Lecturer Ph.D. Eng.; Elena Eugenia Vasilescu, Assoc.Prof. Ph.D. Eng.; Horatiu Pop, Assoc.Prof. Ph.D. Eng.; Saleh Jassim Saleh Alqaisy, PhD.Stud.; Iulian Uta, Ph.D.Eng.

## INTRODUCTION

The current trend is towards the use of renewable energy sources which are very important in solving the environmental challenge of fossil fuel depletion and global warming. As a result, energy storage technologies have been developed. Liquid air energy storage (LAES) is a relatively new technology that has the potential to increase the use of renewable energy resources in the power grid. This technology is interesting because it is not geographically constrained, it is economical and safe for the environment. An additional advantage is that the energy is stored in liquid form, which means that the storage volumes are significantly smaller than those required to store energy in compressed air, even 700 times smaller (She *et al.*, 2017).

Air has been recently regarded as a Cryogenic Energy Storage (CES) medium, whereby air is liquefied at around  $-195\text{ }^{\circ}\text{C}$  and stored in insulated tanks (Antonelli *et al.*, 2016). At off-peak times, energy produced by renewable sources is fed to an air liquefaction unit, while, when electrical energy is needed, the liquid air could be pumped, heated and expanded into turbines to generate power (Brett and Barnett, 2014). This technology is called Liquid Air Energy Storage (LAES).

Cryogenic energy storage (CES) is a large-scale energy storage technology that stores electricity in the form of liquefied gas at cryogenic temperatures. The CES system has three sub-processes, namely, charging or liquefaction, storage, discharging or power cycle. The liquid air energy storage (a basic stand-alone configuration) can be divided into a charging section for the air liquefaction process; storage section and a discharging section for power recovery process; waste heat and cold recycle sections to thermally couple charge and discharge sections operating asynchronously. Every part is composed of several sub-systems as shown in Fig.1.



**Fig. 1 – Illustration of cryogenic energy storage steps of operation (charge, storage, discharge), Heat and cold recovery and storage**

Consequently, as a result of increased interest, LAES has become an area of focus for both academic circles and industry. Some of the research work has focused on reviewing LAES systems but most of it is based on thermodynamic and economic analyzes focusing on different LAES configurations and liquefaction systems.

From the first category, a paper is noticed, where a useful and comprehensive review of LAES systems was carried out and it was concluded that there is a clear disconnect between what has been proven in the literature and what has been demonstrated in practice and therefore further analysis should be carried out (O'Callaghan and Donnellan, 2021). The same conclusion was also reached by other researchers, namely that, so far, too few reviews have been carried out on LAES systems and a methodology has been proposed to evaluate the economic viability of energy storage in liquid air (Lin *et al.*, 2019).

Another research paper also offers a review of the present development of LAES technology, both from the scientific and from the technical points of view (Damakt *et al.*, 2020).

In 2015, researchers evaluated the performance of the various LAES systems. They evaluated the Linde-Hampson liquefaction cycle and proposed the Claude and Collins cycles as alternatives, the conclusion being that the Claude cycle is the best alternative (Abdo *et al.*, 2015).

In another paper (Vecchi *et al.*, 2021) made a review of the latest generation technology where he describes 54 installations and technical-economic data are presented. He came to the conclusion that a large group of literature addresses this topic, but few studies in the literature have tried to rationalize, leaving some key areas unaddressed, such as the integration of LAES.

A series of studies have been carried out regarding the use of Linde-Hampson liquefaction cycles in liquid air energy storage systems. Thus, the author of a research paper found that the specific consumption of the Linde cycle decreased with increasing pressure up to an optimal pressure of 25MPa. After this threshold, any increase in the liquid air flow did not cancel the increase in the specific consumption of the compressor. Two-stage compression resulted in lower specific consumption than the single-stage compression configuration at all the tested pressures (Borri *et al.*, 2021).

Other researchers conclude that in all the liquefaction cycles, the design of heat exchangers is crucial for achieving the optimal liquefaction performance since the temperature difference during the operation should be reduced as much as possible (Popov *et al.*, 2019). It was further found that higher charge pressures resulted in lower cold exergy recovery, showing that there is a trade-off between liquid air production and cold exergy recovery (Krawczyke *et al.*, 2015). In another paper the authors analyse energy storage with a liquid air Rankine cycle and report that 43% of the energy can be recovered from liquid air (Ameel *et al.*, 2013).

In a new research paper, the authors present an exergetic analysis of the Adiabatic Liquid Air Energy Storage (A-LAES) system based on the Linde-Hampson cycle. The exergetic analysis was performed for four cases with different parameters, especially the air discharge pressure at the turbine inlet (20, 40, 100, 150 bar). The analysis results show that the highest exergy destruction can be observed in the air evaporator and the Joule–Thompson valve. In the case of the air evaporator, the exergy destruction is the highest for the lowest discharge pressure, i.e. 20 bar, and reaches over 118 MWh/cycle. It decreases with increasing discharge pressure to about 24 MWh/cycle for 150 bar, which is caused by a decrease in the heat of vaporization of the air. In the case of the Joule–Thompson valve, the changes are reversed. The highest exergy destruction is observed for the highest discharge pressure considered (150 bar) and amounts to more than 183 MWh/cycle. It decreases as the pressure drops to 57.5 MWh/cycle for 20 bar. The other components of the system do not show exergy destruction greater than about 50 MWh/cycle for all of the considered pressures (Szablowski *et al.*, 2021).

## MATERIALS AND METHODS

### System description

Energy and exergy analysis are applied to assess the performance of the LAES system. It is worthy to mention that Engineering Equation Solver (EES) software is used for simulation of the proposed system. The liquid air energy storage system analyzed in this paper investigates the liquefaction subsystem based on the simple Linde-Hampson cycle and the energy generation subsystem with the direct expansion method. Figure 2 shows the entire LAES system.

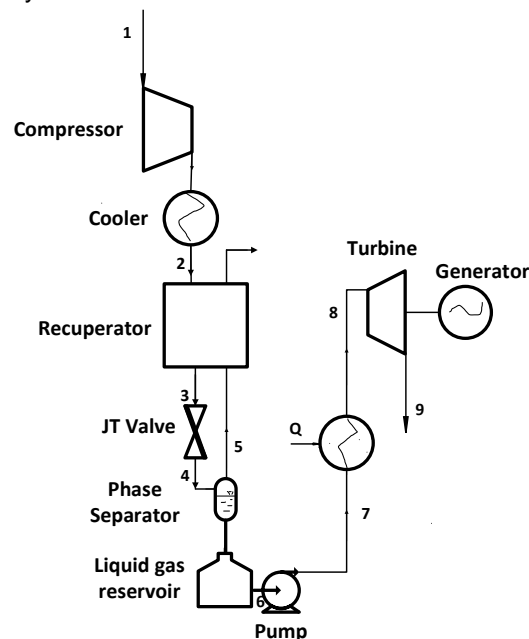
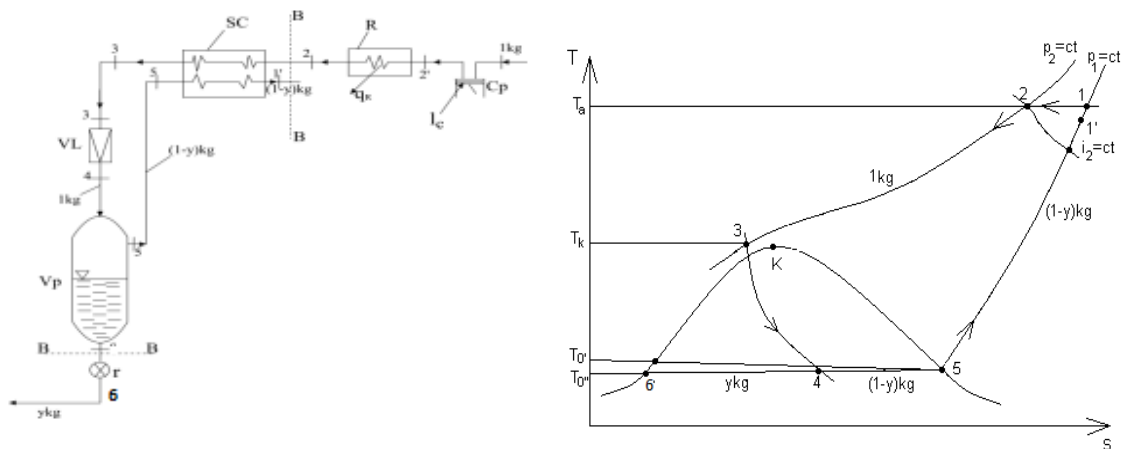


Fig. 2 - The schematic of the plant with simple Linde-Hampson cycle and direct expansion

### 1.1. Liquefaction Subsystem

The liquefaction unit is a Linde liquefaction system with a throttling and is the key part of the system because the energy release unit has a simple configuration.

The installation includes: the multi-stage air compressor, the final cooler, which reduces the air temperature to its initial value, the countercurrent heat exchanger where the isobaric cooling of the air is carried out due to the cold vapors produced in the evaporator, the throttling valve where takes place the decrease in air pressure from  $p_2$  to the working pressure in the vaporizer  $p_1$  takes place, corresponding to the saturation temperature,  $t_0$  and the vaporizer in which the air brought to the state of wet vapors at the pressure  $p_1$ , vaporizes and separates into liquid air and cold vapors.

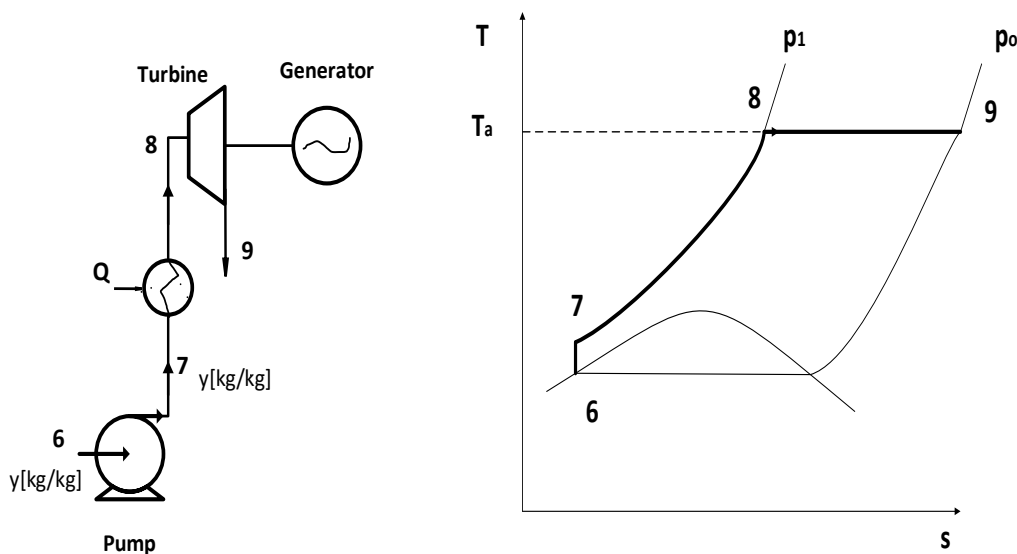


**Fig. 3- Simple Linde-Hampson cycle**

a) Flow chart b) cycles in the T-s diagram

1.2. Direct Expansion of liquid air (Work extraction process)

The simplest way to recover the energy stored in the liquefied air is to perform the direct expansion cycle (figure 4). At first, the liquid air is pumped to high pressure (process 6-7), then it is heated using ambient or, if available, waste heat (7-8). Finally, the air is expanded in turbine (processes 8-9) driving an AC generator.



**Fig. 4 - Work extraction process**

a) Flow chart b) cycles in the T-s diagram

The pump is assumed to be isentropic and for the turbine one case is looked into: isothermal reversible expansion. No reheating is used.

**Mathematical model**

As previously stated, this paper investigates the upper bounds of an ideal LAES system. Therefore, all components are ideal components, the compressor compresses the fluid isothermally, the pump compresses the fluid isentropically, the heat exchangers are 100% efficient, the turbine expands the fluid isothermally, and there are no losses in the lines. Each subsystem is analyzed individually and then as a complete system.

The system is analyzed both from energetic and exergetic points of view.

### 2.1. Energy analysis

For the liquefaction subsystem, the plant has the following operating conditions:

- aspiration pressure in the compressor  $p_1=1$  bar
- aspirated air temperature  $t_1=15^\circ\text{C}$
- pressure at the end of the compression: 120 bar;
- cold losses due to incomplete heat recovery:  $q_n=5$  kJ/kg
- cold losses due to heat flow from outside:  $q_i=5$  kJ/kg
- isothermal efficiency of the compressor:  $\eta_m=0.8$

Fraction  $y$  of obtained liquefied gas is determined by writing the thermal balance on the B-B outline:

$$y = \frac{h_1 - h_2 - q_n - q_i}{h_1 - h_6 - q_i} \quad (1)$$

The actual cooling power of the cycle:

$$q_{0,r} = y \cdot q_0 = y \cdot (h_1 - h_6) \quad (2)$$

The specific mechanical work consumed by the compressor:

$$w_c = \frac{1}{\eta_{iz} \cdot \eta_m} \cdot R \cdot T \cdot \ln \left( \frac{p_2}{p_1} \right) \quad (3)$$

Refrigeration efficiency of the installation:

$$\varepsilon_f = \frac{q_{0,r}}{|w_c|} \quad (4)$$

Specific energy consumption for producing one kg of liquid air:

$$K = \frac{|w_c|}{y} \quad [\text{kWh/kg}_{\text{liquid}}] \quad (5)$$

Following the thermal calculation, the results presented in Table 1 were obtained.

**Table 1**

The energy characteristics of the liquefaction system	
Energy characteristics	Simple Linde-Hampson cycle
Liquefaction coefficient $y$ [kg of liquid/kg of compressed gas]	0.04719
Specific cooling power $q_{0,r}$ [kJ/kg of compressed gas]	19.38
Mechanical work consumed by the compressor $w_c$ [kJ/kg of compressed gas]	666.9
Refrigerating efficiency of the plant	0.04844
Specific energy consumption $K$ [kWh/kg of liquid]	3.925

For the Direct Expansion of liquid air subsystem:

Specific work of turbine can be calculated as follows:

$$w_T = \eta_{iz} \cdot R \cdot T_8 \cdot \ln \left( \frac{p_8}{p_9} \right) \quad (6)$$

Specific pump work can be determined in similar way:

$$w_P = h_7 - h_6 \quad (7)$$

The network output is difference between work of the turbine and the pump work:

$$w_{net} = w_T - w_P \quad (8)$$

### 2.2. Exergy analysis

Exergy analysis is based on the Second Law of thermodynamics.

For stationary regimes of operation, the exergy balance equation is given by the relation:

$$0 = \sum \left( 1 - \frac{T_0}{T_i} \right) \dot{Q}_i - \dot{W} - (\dot{E}x_{out} - \dot{E}x_{in}) - I \quad (9)$$

where:

$T_0$  is the reference temperature in exergetic analysis, usually ambient temperature, [K];

$S$  system entropy, [J/K];

$\tau$  time, [s];

$\dot{Q}_i$  [W] the heat flows exchanged by the system at the temperature level of the outer sources  $T_i$  [K]

$\dot{W}$  mechanical power produced or consumed, [W];

$\dot{E}x_{in}$  si  $\dot{E}x_{out}$  are the exergy flows carried by thermal agents (the working fluids circulating in the system), [W].

According to Guy-Stodola theorem, the exergy destruction rate is computed by:

$$I = T_0 \cdot \dot{S}_{gen} \quad (10)$$

where  $I$  [W] is the exergy destruction rate.

Typical irreversible processes in installations (heat transfer at finite temperature difference, flow with friction and pressure loss, throttling, mixing) lead to a high rate of entropy generation, directly proportional to the destruction of exergy in each device and in the system as a whole. In conclusion, the exergy destruction rate in a device or in a plant is the best indicator of the operating efficiency. In general, the flow of exergy destroyed in a device can be calculated using the formula:

$$I = \sum \dot{E}x_{in} - \sum \dot{E}x_{out} \quad (11)$$

and the exergy efficiency is:

$$\eta_{ex} = \frac{\sum \dot{E}x_{out}}{\sum \dot{E}x_{in}} = 1 - \frac{I}{\sum \dot{E}x_{in}} \quad (12)$$

The exergetic flow is defined as:

$$ex = h - h_0 - T_0 (s - s_0) \quad (13)$$

The dead state temperature for the exergetic analysis is considered to be equal to that of the ambient environment which is equal to the temperature  $t_0=15^\circ\text{C}$  and  $p_0=1.01325$  bar.

In thermodynamics, the exergy destruction represents a major inefficiency and a quantity to be minimized when the overall system efficiency should be maximized (*Tsatsaronis et al., 2011*)

The analysis will present the calculation of the exergy destruction rate  $I$ , for each component and the system.

The analysis is performed with the software program Engineering Equation Solver (EES).

### 2.3. Performance criteria

The overall system efficiency is the ratio of work output to inputs:

$$\eta_{sys} = \frac{w_T}{\frac{w_C}{y} + w_P} [-] \quad (14)$$

The exergetic efficiency for the entire LAES system is defined as:

$$\eta_{ex\_sys} = \frac{w_{input} - i_{totw\_input}}{w_{input}} [-] \quad (15)$$

$$w_{input} = w_C + y \cdot w_P \quad (16)$$

The liquefaction efficiency ( $\eta_l$ ) is the ratio of exergy contained in liquid air and the energy needed to liquefy it.

$$\eta_l = \frac{y \cdot e_{xl}}{w_c} [-] \quad (17)$$

Recovery efficiency ( $\eta_r$ ) is the ratio of network produced in air expansion and the available exergy of liquid cryogen:

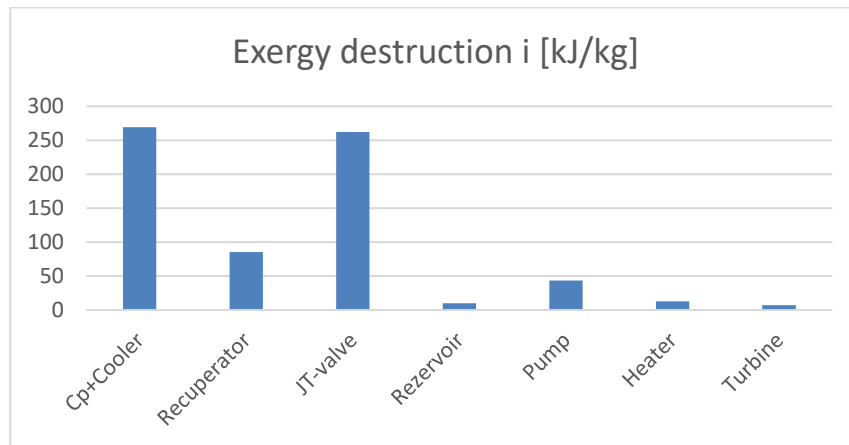
$$\eta_r = \frac{w_{net}}{e_{xl}} [-] \tag{18}$$

The storage efficiency ( $\eta_s$ ) is the ratio of work of cryogen expansion and work of liquefaction:

$$\eta_s = \frac{y \cdot w_{net}}{w_c} = \eta_l \cdot \eta_r [-] \tag{19}$$

**RESULTS**

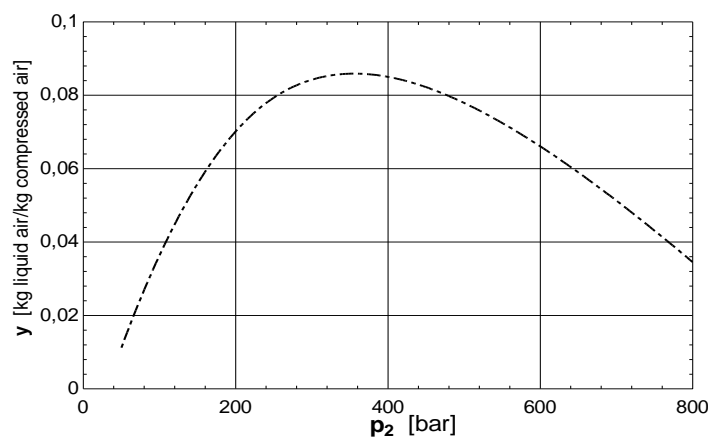
Destructions of exergy on the components of the adiabatic LAES system are shown in Figure 5.



**Fig. 5 - Exergy analysis of LAES system**

The greatest destruction of exergy for this case occurs at the J-T valve and then at the Compressor and cooler. Exergy destructions of the other elements of the system are small. Low pressure in the charging system means that the share of throttling in total exergy destruction is not dominant. On the other hand, at low pressure in the discharge system, the temperature differences in the heater are high, which causes large exergy destruction.

Fig. 6 shows the yield mass rate variation with compressor pressure, up to 280 bar the yield mass rate begins to decrease.



**Fig. 6 - Variation of liquefaction mass ratio with the compressor pressure**

The highest liquefaction efficiency can be achieved for air above 8% as fig.7. The liquefaction efficiency maximum of Joule-Thomson cycle is obtained for large compressor discharge pressure ( $p_2$ ) values – around 300 bar for air.

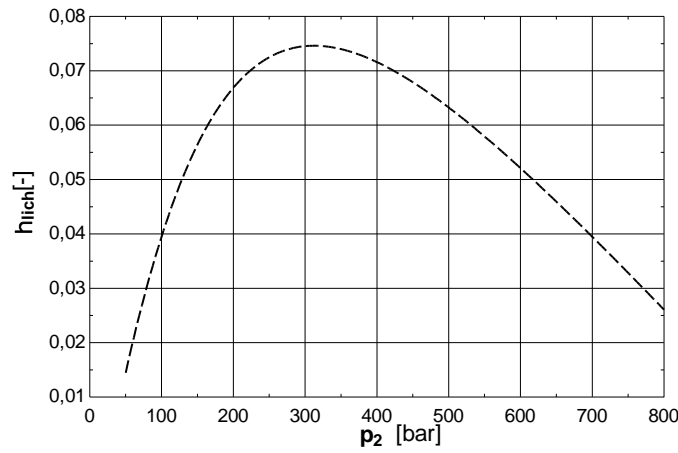


Fig. 7 - Liquefaction efficiencies of air in considered LAES system

Figure 8 presents the recovery efficiency value of air for different pressure at the turbine pressures. It can be found that the recovery efficiency values exhibit the maximum for a certain pressure at the inlet to the turbine. For air this maximum is around 10 MPa. It is also worth noticing that there is no large increase in recovery efficiency for turbine inlet pressures above 10 MPa.

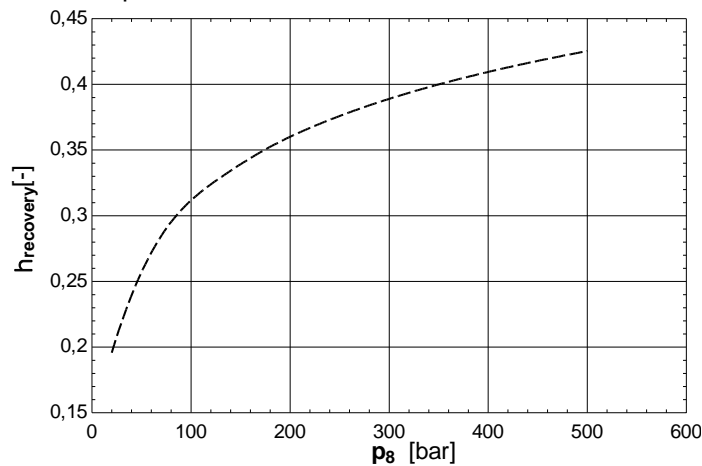


Fig. 8 - Recovery efficiencies of air in considered LAES system

The storage efficiency (fig.9) was obtained for work of liquefaction ( $w$ ) equal to minimal Joule-Thomson liquefaction work (maximal liquefaction efficiency – figure 7). The highest storage efficiency (up to 3,5%) can be achieved for air. Efficiency values are very low in the analysed system. Both liquefaction and gas expansion cycles used for air are the most basic ones, and therefore, their liquefaction and recovery efficiencies are low. Further research should focus on more complex and more efficient liquefaction and cryogen expansion cycles.

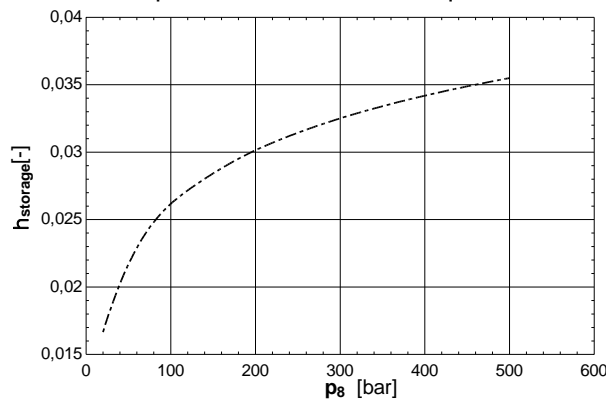


Fig. 9 - Storage efficiencies of air in considered LAES system

**CONCLUSIONS**

Energy storage by liquefaction of air seems to be an interesting option in a world based on renewable energy production. In this paper, an energetic and exergetic analysis of an ideal combined liquid air energy storage and expansion system with a Linde cycle with a lamination was performed. The optimum pressure



range in condition 2 was 20 to 50 MPa where there was maximum liquefaction yield. From the technical point of view, the simple Linde-Hampson cycle plant is the simplest, but it has the lowest indicators.

Thermodynamic analysis shows that the performance of the ideal cycle is not high. If liquefied air is stored, energy can only be recovered with a maximum efficiency of 50% in a direct expansion cycle.

The presented cryogenic energy storage system is basic and its efficiency is very low. The single-throttling Linde liquefaction cycle used in the analyzed air-liquid storage system has low efficiency and requires high pressures. In more complex systems, this liquefaction cycle can be replaced by one that uses a retainer instead of a rolling valve, the Claude cycle for example can provide a much higher liquefaction yield and therefore higher liquefaction efficiency. Also, the direct liquid air expansion cycle used in the analysis can be replaced by a more complex one with higher efficiency. However, the main disadvantage of a direct expansion cycle is that the thermal exergy of the cryogen (liquid air) is destroyed in the heater (process 5-6). There are few solutions for this problem. The cold from the expansion cycle can be stored and used in a liquefaction cycle to increase its efficiency. Additional cycles such as the organic Rankine cycle or the Brayton cycle can be incorporated using cryogen as a low temperature heat source. The efficiency of the direct expansion cycle can also be increased by adding more turbine stages or by increasing the T8 temperature using available waste heat sources (heat of compression from the liquefaction cycle or waste heat available in thermal plants or industrial processes).

In further research it is necessary to determine the best way to use the thermal exergy of liquid air.

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