Thermodynamic analysis of a liquid air energy storage system with off-peak electric heat storage and reutilization

X Fan¹,², J Hu¹, W Ji¹,*  L Guo¹,², Z Gao¹,², J Guo¹, L Chen¹, J Wang¹,²

¹ Chinese Academy of Sciences Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, 29 Zhongguancun East Road, Haidian District, Beijing, P. R. China;
² University of Chinese Academy of Sciences, No.19(A) Yuquan Road, Shijingshan District, Beijing, P. R. China;

*Corresponding author: jiwei@mail.ipc.ac.cn

Abstract. As a large-scale energy storage technology, liquid air energy storage (LAES) can effectively improve the stability and quality of power grid. However, the traditional LAES has low cycle efficiency, high initial investment and low economic benefits. In order to improve the system performance, a LAES system based on off-peak electric heat storage and high temperature preheating of turbine inlet air was proposed. The thermodynamic characteristics of the LAES system were analyzed, and the energy analysis, exergy analysis and economic evaluation were carried out. Combined with off-peak electric heat storage, the power generation during the peak time by the LAES system can be significantly increased, and the economy of the LAES system can be effectively improved with the peak-valley electricity price difference, especially in areas where the price difference is obvious. The results will be beneficial for the application and promotion of the LAES technology.

1. Introduction

With the development of energy industry and technological progress, the proportion of renewable energy connected to the grid is increasing. According to the report by REN21 in 2021, renewable energy accounts for 11.2% of global energy consumption [1]. However, the grid connection of renewable energy gradually exposed some problems: renewable energy generation has volatility and uncertainty, renewable energy generation will be affected by the weather environment or day and night cycle, resulting in the load fluctuation of the grid [2]. As an important way to integrate renewable energy into the grid, energy storage system has attracted extensive attention in recent years [3]. At present, the mainstream energy storage technologies include Battery energy storage (BES), Pumped hydro energy storage (PHES), Flywheel energy storage (FES), Compressed air energy storage (CAES) and so on [4-5]. However, the cost of BES is high, and some batteries can cause environmental pollution, PHES and CAES have strict geographical limitations, and the power of FES is low [6]. The cryogenic liquefaction process is introduced into CAES, and the liquefied air is stored in the cryogenic storage tank, namely liquid air energy storage system (LAES). As a large-scale energy storage technology, LAES has no geographical restrictions, low investment cost, high safety factor, long equipment life and is especially suitable for grid connected [7]. So far, LAES is one of the most promising energy storage technologies.

In the past few years, a variety of studies have been carried out on LAES, among which the
thermodynamic and economic analysis of the coupled LAES system is one of the important research directions. However, the efficiency of LAES is low and the profit method is unclear. For this reason, Gao [8-9] et al. conducted thermodynamic analysis and economic analysis on the LAES system coupled with the combined cycle power plant and obtained the power conversion efficiency of 99.39%. System research also shows that the coupled system has better economy.

However, this study underestimated the various irreversible losses under real operating conditions. The heat storage loss of high temperature compression heat is large, and the expansion air cannot be heated to a very high temperature, which limits the improvement of system efficiency. In addition, the economy of LAES is seriously affected by the difference between peak and valley electricity prices. Therefore, a novel LAES system of off-peak electric heat storage is proposed. Heat storage is carried out through electric heating in the low power consumption period and it is used to heat the air before the expander in the discharge process. The compression heat in the charging process is directly used for the user's hot water supply which avoid the irreversible loss of compression heat reuse. Furthermore, the thermodynamic analysis and economic analysis were carried out for this system. The results show that the system makes full use of the off-peak power and the waste heat of compression, and can achieve high efficiency and improve the economy.

2. System description

Figure 1 shows the schematic diagram of the proposed LAES system with off-peak electric heat storage. The system consists of five units, including the compression unit, cold storage unit, expansion unit, hot water supply unit and off-peak electric heat storage unit. The components of the compression unit and the hot water supply unit include compressors (COM1-COM3), inter-coolers (IC1-IC3) and a preheater (PH3) while expansion unit and off-peak heat storage unit are composed of air turbine (ATB1-ATB4), inter-heaters (IH1-IH3), an electric heater (EH), a high-temperature water tank (HWT), a low-temperature water tank (LWT) and preheaters (PH1-PH2). The cold storage unit adopts solid phase cold storage, and the components include air-coolers (AC1-AC2), air expander (AE), liquid air tank (LAT), liquid air pump (LAP), air heaters (AH1-AH2) and packed beds (BED1-BED2).

During energy storage process, the off-peak electric drive COMs compressed air, IC cools the air at the outlet of COMs. Then, the air enters the cold storage unit after multi-stage compression. After being cooled by AC1 and AC2, the air is liquefied through the AE and stored in LAT while the heat is stored in BEDs. In addition, the pressurized water collects the compression heat of the air in the ICs and transfers the heat in the PH3, applying the heat to the user's hot water supply. At the same time, the off-peak electric also drives EH to heat the pressurized water, and the electric energy is stored in the form of heat energy for the subsequent energy release process.

During energy release process, air is output from the LAT, pressurized by the LAP and reheated through the AH1,AH2 and PH1, while the cold energy of the air is stored in the packed bed. The air is then heated by the pressurized water in PH2 and IHs and expanded in the ATB, driving motors to generate electricity and providing a steady electrical supply.
3. Thermodynamic analysis model

To simplify the analysis of the proposed novel LAES system, some reasonable assumptions were adopted as follows:

a) The operating state of the system is steady.
b) The pressure drop loss in pipes and exchangers is ignored.
c) The pressure drop loss and heat loss in the LAT are ignored.
d) Each stage of compression and expansion is adiabatic.

3.1. Energy analysis model

In the charging process, the compression work at i-th stage of the system is as follows:

\[ W_{c,i} = m_c w_{c,i} = m_c (h_{c,i}^{\text{out}} - h_{c,i}^{\text{in}}) \]  

(1)

where \( w_{c,i} \) is the specific work of i-th stage compression, \( m_c \) is the air flow rate in the compression process, \( h_{c,i}^{\text{in}} \) and \( h_{c,i}^{\text{out}} \) represent the inlet and outlet specific enthalpy of air at the i-th stage compressor, respectively.

The specific enthalpy of air at the outlet of the i-th stage compressor is shown in the following formula:

\[ h_{c,i}^{\text{out}} = h_{c,i}^{\text{in}} + \left[ h(p = p_{c,i}^{\text{out}}, s = s_{c,i}^{\text{in}}) - h_{c,i}^{\text{in}} \right] / \eta_{\text{COM}} \]  

(2)

where \( \eta_{\text{COM}} \) is the adiabatic efficiency of the compressor.

In the discharge process, the output work of the i-th stage expander is as follows:

\[ W_{e,i} = m_e w_{e,i} = m_e (h_{e,i}^{\text{in}} - h_{e,i}^{\text{out}}) \]  

(3)

where \( w_{e,i} \) is the expansion specific work of i-th stage; \( m_e \) is the air flow rate of the expansion unit; \( h_{e,i}^{\text{in}} \) and \( h_{e,i}^{\text{out}} \) are the inlet and outlet specific enthalpy of i-th stage expander, respectively.

The specific enthalpy at the outlet of the i-th stage expander is as follows:
\[ h_{\text{out},i} = h_{\text{in},i} + \eta_{\text{ATB}}[h_{\text{in},i} - h(p = p_{\text{in},i}, s = s_{\text{in},i})] \]  

(4)

where \( \eta_{\text{ATB}} \) is the adiabatic efficiency of the expander.

The input work of the EH is as follows:

\[ W_{\text{EH}} = m_o(h_{\text{in}} - h_{\text{in}})/\eta_{\text{EH}} \]  

(5)

where \( m_o \) is the flow rate of the hot water through EH, \( \eta_{\text{EH}} \) is the electric heating efficiency of EH, \( h_{\text{in}} \) and \( h_{\text{out}} \) are the specific enthalpy of the heat storage medium at the inlet and outlet of EH, respectively.

The output power of hot water supply can be expressed as the following formula:

\[ W_{\text{HW}} = m_w(h_{\text{out}} - h_{\text{in}})/\eta_{\text{HW}} \]  

(6)

where \( m_w \) is the flow rate of the hot water through PH3, \( \eta_{\text{HW}} \) is the hot water supply efficiency of PH3, \( h_{\text{in}} \) and \( h_{\text{out}} \) are the specific enthalpy of the hot water at the inlet and outlet of PH3, respectively.

The energy storage efficiency (ESE) of the novel LAES system is as follows:

\[ \text{ESE} = (W_{\text{ATB}} + W_{\text{HW}} - W_{\text{LAP}})/(W_{\text{COM}} + W_{\text{EH}} - W_{\text{AE}}) \]  

(7)

where, \( W_{\text{ATB}} \) and \( W_{\text{COM}} \) are expansion and compression work of the system, \( W_{\text{LAP}} \) and \( W_{\text{AE}} \) are the power of LAP and AE.

### 3.2 Exergy analysis model

According to the second law of thermodynamics, exergy efficiency is the ratio of exergy output to exergy input of the system. Therefore, the exergy efficiency of the system can be summarized as follows:

\[ \eta_{\text{ex}} = (W_{\text{ATB}} + E_{\text{xH}} - W_{\text{LAP}})/(W_{\text{COM}} + W_{\text{EH}} - W_{\text{AE}}) \]  

(8)

where \( E_{\text{xH}} \) is the exergy output of hot water during the discharging process.

The exergy of a specific stream can be expressed as:

\[ E_{\text{xI}} = m_i[(h_i - h_0) - T_0(s_i - s_0)] \]  

(9)

where \( h \) and \( s \) represent the enthalpy and entropy of stream \( i \), \( T_0 \) is the ambient temperature and \( m_i \) represent the flow rate of stream \( i \).

### 3.3 Economic analysis model

In the economic analysis of LAES, investment payback period (IPP) and total profit are two key indicators.

The IPP represents the number of years for the system to recover the initial investment and can be expressed by the following formula:

\[ \text{IPP} = \frac{\text{IIC}}{\Sigma \text{Profit} - \Sigma \text{Cost}} \]  

(10)

where, \( \text{IIC} \) is the initial investment cost, \( \Sigma \text{Cost} \) and \( \Sigma \text{Profit} \) are the annual operating cost and the annual profit, which can be expressed by the following formula:

\[ \Sigma \text{Cost} = C_M + C_E \]  

(11)

\[ \Sigma \text{Profit} = PR_E + PR_W \]  

(12)

where \( C_M \) and \( C_E \) are maintenance cost and power cost each year, \( PR_E \) and \( PR_W \) are power profit and hot water profit each year.

### 4. Results and discussions

The energy analysis and economic analysis of the proposed novel LAES system were carried out. The
influence of some key working parameters on the system performance and economic index was studied.

4.1 Thermodynamic and economic simulation results
In an appropriate working environment, this section obtains the simulation results of the novel LAES system, including efficiency, economy and other indicators. Among them, the operating conditions of the system are shown in Table 1, and the simulation results are shown in Table 2. When the heat storage temperature is 600K, the system can obtain the $ESE$ of 84.23% and the $\eta_{ex}$ of 47.94%. When the peak and valley electricity price difference is 0.9 $\$/kwh, the $IPP$ of the system is 6.12 years, and the $Total\ profit$ of 30 working years is 72,251 k$.

| Table 1. Operating parameters of the LAES system. |
|----------------------------------|-----------------|
| Term                             | Value           |
| Compression pressure             | kPa             |
| Expansion pressure               | kPa             |
| Compression stage                | %               |
| Expansion stage                  | %               |
| Ambient pressure                 | kPa             |
| Ambient temperature              | K               |
| Heat storage temperature         | K               |
| Heat storage pressure            | kPa             |
| Peak electricity                 | $/kwh$          |
| Valley electricity               | $/kwh$          |
| Operating life                   | years           |
| Adiabatic efficiency of COMs     | %               |
| Adiabatic efficiency of ATBs     | %               |
| Adiabatic efficiency of AE       | %               |
| Adiabatic efficiency of LAP      | %               |
| Adiabatic efficiency of PH3      | %               |
| Adiabatic efficiency of EH       | %               |
| Mass flow rate                   | kg/s            |

| Table 2. Simulation results of the LAES system. |
|----------------------------------|-----------------|
| Term                             | Value           |
| Power of compressors             | kW              |
| Power of air turbines            | kW              |
| Power of hot water supply        | kW              |
| Power of electric heating        | kW              |
| Flow rate of EH                  | kg/s            |
| $ESE$                            | %               |
| $\eta_{ex}$                      | %               |
| $IPP$                            | years           |
| $Total\ profit$                  | k$              |

4.2. Parametric sensitivity analysis
Figure 2 shows the influence of heat storage temperature on the efficiency and economy of proposed novel LAES system. With the increase of heat storage temperature, both $ESE$ and exergy efficiency increase, while $IPP$ decreases. This is because with the increase of heat storage temperature, greater proportion of the heat can be utilized, and the system also makes greater use of the difference between peak and valley electricity prices, increasing the profit of the system. When the heat storage
temperature is 700 K, the $ESE$ and $\eta_{ex}$ of the system can reach 84.28% and 50.75% while the $IPP$ can be reduced to 5.28 years.

Figure 2. Effect of heat storage temperature on $ESE$, $\eta_{ex}$ and $IPP$.

Figure 3 shows the influence of ambient temperature on $ESE$, $\eta_{ex}$ and $IPP$ of the LAES system. As the ambient temperature increases, $ESE$ increases and $\eta_{ex}$ decreases. This is because the higher the ambient temperature is, more compression heat will be generated, and the power of hot water supply increases, but the available energy decreases. In addition, the $IPP$ decreases as the ambient temperature increases, because the higher ambient temperature allows the system to generate more hot water supply and achieve higher profits. When the ambient temperature is 313 K, the system can obtain the $ESE$ of 85.43% and the $IPP$ can be reduced to 5.53 years.

Figure 3. Effect of ambient temperature on $ESE$, $\eta_{ex}$ and $IPP$.

Figure 4 shows the effect of peak electricity price on $IPP$ and $Total profit$ of the system while $C_d$ refers to the price of electricity at peak times. With the increase of peak electricity price, that is, the difference between peak and valley electricity price, the $IPP$ of the system decreases inversely and the $Total profit$ increases directly. It can be seen that the peak-valley electricity price difference is the most important factor affecting the economy of the system. If the peak-valley electricity price is 0.19 $, the $IPP$ of the system can be reduced to 3.40 years, and the $Total profit$ in the 30-year operation period can
reach 144780 k$.

Figure 4. Effect of peak electricity price on IPP and Total profit.

5. Conclusions
In order to improve the economy of energy storage system, a novel LAES system with off-peak electric heat storage was proposed and analyzed. The novel LAES system can make full use of the off-peak electricity price for heat storage which is used to heat the air at the inlet of the expander in the discharging process, with high energy utilization efficiency and good economy. The results show that both the heat storage temperature and the ambient temperature have significant effects on the system efficiency. The maximum ESE of the system can reach 85.43% when the ambient temperature is 313K, the maximum $\eta_{ex}$ of the system can reach 50.75% when the heat storage temperature is 700K. In addition, the difference between peak and valley electricity prices is the most important factor affecting the economy of the system. When the peak and valley electricity prices are 0.19 $ and 0.03 $ respectively, the IPP of the system can be greatly reduced to 3.40 years.

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