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A compact liquid air energy storage using pressurized cold recovery with enhanced energy density for cogeneration

Chen Wang[1], Xiaosong Zhang[1*], Lu Xue[2], Xiaohui She[3*]

1 School of Energy & Environment, Southeast University, Nanjing 210096, China

2 Xinglu air separation Ltd., Suzhou 215131, China

2 School of Chemical Engineering, University of Birmingham, Birmingham B15 2TT, UK

ABSTRACT

Liquid air energy storage (LAES) is promising for decarbonizing the power network. Fluids are popular as both cold recovery and storage media with the benefits of no additional heat exchangers and straightforward control strategy. Methanol and propane are required to work together as single fluid is not able to work in such a wide temperature range of 85-300 K. This leads to a four-tank configuration, making the cold storage bulky and complex. To address this issue, this paper investigates various fluids and it is found that their temperature range could be extended when they are under pressure (i.e., pressurized fluids). This makes it possible to recover and store the cold energy from liquid air by single pressurized fluid with a two-tank configuration. Therefore, a compact LAES configuration is proposed with pressurized propane (1 MPa) as an example for cold recovery and storage. A new concept of cold storage density is discussed for the first time to show how much cold energy is stored per unit. The Simulation results show that the proposed LAES system increases the volumetric cold storage density by ~52%, saves the capital cost of cold storage by 37%, and shortens the simple payback period of the system by 1.13-67.72%, compared with the traditional LAES system with fluids-based cold storage. This study will provide a feasible way to simplify the LAES system and improve the economic benefits.

Keywords: liquid air energy storage; thermo-economic; thermal energy storage; cold storage; power plants

1. INTRODUCTION

To combat climate changes, the demand of renewable energy sources still increased in 2020 despite the pandemic, and consumption of fossil energy sources decreased. Renewables accounted for 90% of global power capacity expansion between 2021 and 2022 [1]. However, renewables are intermittent, and their power generation when connected to electric networks will threaten the stability and security of grid [2, 3]. Energy storage is a good solution to decouple the energy supply and demand, making sure a stable power output. Among various kinds of energy storage technologies, liquid air energy storage (LAES) becomes popular in recent decades, owing to its significant advantages including no geographical constraints, long operational lifetime, high energy storage density, low levelised cost of storage, etc. [4]. The first concept of the LAES was proposed for peak-shaving of power networks by Smith [5] in 1977. Then, the first pilot plant (350kW/2.5MWh) in the world was built by the Highview Power Storage and University of Leeds in 2012 [6]. In April 2018, Highview Power constructed a pre-commercial LAES plant (5 MW/15 MWh) based on the pilot plant in Bury, UK [7]. Recently, Highview Power planned to establish the UK's first (50 MW/250 MWh) and the US's first (50 MW/400 MWh at a minimum) commercial LAES plants [8].

Packed bed energy storage is a mature and widespread thermal energy storage technology, generally employing phase change materials [9, 10] and pebbles/rocks [11, 12] as the heat storage materials. Pebbles/rocks are more promising for industrial applications due to their low capital costs and good chemical stability. Therefore, using pebbles/rocks for cold storage is employed in many LAES studies [13-16]. As early as 2000, Chino and Araki [13] sent liquid air to a combustor of a natural-gas turbine in peak hours, while the liquid air was produced in off-peak hours. It achieved a round trip efficiency of over 70% with pebbles for cold recovery. Morgan et al. [14] tested the above-mentioned LAES pilot plant with quartzite as the cold storage material and external heat from CHP plants. Its round trip efficiency was predicted to be ~60%. Sciacovelli et al. [15] developed and validated a dynamic model of the LAES system with packed bed for cold storage, achieving a round trip efficiency of ~50%. Generally, the packed bed for cold storage has significant thermoclines especially after several cyclic operations and the cold energy cannot be extracted totally from the beds. The footprints and axial dispersion also cause unavoidable energy loss. It was reported that the packed bed cold storage will cause dynamic performance to the LAES system and result in a lower round trip efficiency compared to common fluid-based cold storage (methanol/propane).

Liquids for cold storage can avoid above-mentioned defects in packed bed cold storage. However, it is a challenge to cover a temperature span of ~200 K from liquid air temperature to ambient air temperature. Few single liquid can keep its liquid state within such a huge temperature range. Thus, a combination of methanol (high temperature range) and propane (low temperature range) are widely employed to store and utilize the cold exergy from liquid air [17-21]. The thermodynamic performance of the standalone LAES system was first evaluated by Guizzi et al. [17] with methanol/propane and thermal oil as cold and heat storage materials, respectively, which showed a round trip efficiency of ~55%. To enhance the thermodynamic performance of LAES, She et al. [18] pointed out that ~40% of compression heat was excess in the standalone LAES system. This inspired a great deal of LAES researchers to study the utilization and allocation of compression heat, including additional electricity generation [19, 20], cooling/heating [21, 22], and regeneration of air purification unit [23].

The knowledge gaps for cold storage in the LAES system is indicated in the above literature review: (1) cold storage with packed bed is cost-effective, but there is a large temperature gradient inside the packed bed, leading to exergy destruction and a lower round trip efficiency; (2) cold storage with fluids is promising to overcome the drawbacks of packed bed, while it requires two fluids to work together due to the wide temperature range of 85-300 K, causing the cold storage bulky and complex with a low cold storage density; (3) cold storage with single fluid has a huge potential to improve energy storage density and simplify the system, while seldom research has been found in the literature.

To address the above issues, this paper first investigates several working fluids as cold storage media with different pressures. It is found that working fluids have an increased temperature range of liquid states with a higher pressure. Thus, single propane at 1 MPa is enough to fully recover and store the cold energy in the novel LAES system. A novel LAES system is then proposed with pressurized propane as cold recovery and storage medium. Techno-economic analyses are conducted on the novel LAES system for combined heat and power generation.

2. SYSTEM DESCRIPTION

Fig. 1 shows the specific flow diagram of the proposed LAES system. The main feature of the proposed LAES system is that the cold energy from discharging cycle is stored for use in the charging cycle only by one kind of cold storage fluid (ie., pressurized propane).

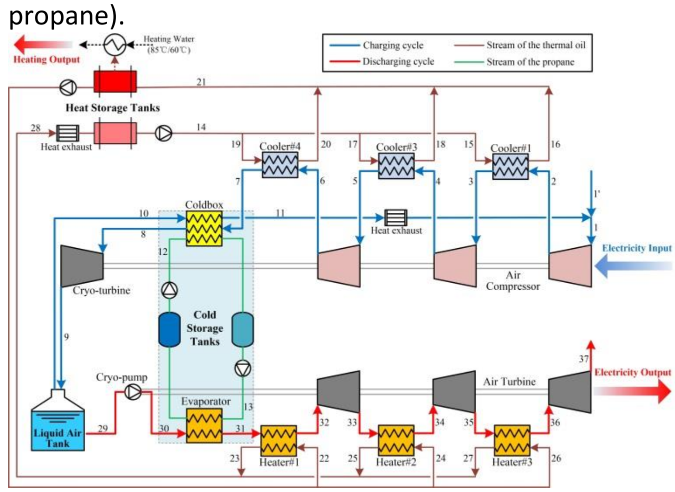


Fig. 1. The simplified block diagram (a) and specific flow diagram (b) of the proposed LAES system.

At off-peak time (8 hours), the charging cycle operates to make liquid air. Purified air (point 1) with return air is first compressed to a high pressure (point 7) by a 3-stage compressor with inter-cooling, where the compression heat is recovered by thermal oil and stored in a heat storage tank; the compressed air is deeply cooled down by the cold storage fluid from a cold storage tank; finally, the liquid air is produced through the cryo-turbine and stored in the liquid air tank.

At peak time (8 hours), the discharging cycle operates to generate power. The liquid air (point 29) out of the storage tank is pumped to a high pressure (point 30), and releases cold exergy via a evaporator which is recovered by the cold storage fluid; the cold storage fluid is then stored in a cold storage tank to use in the charging cycle; the gasified air (point 31) is furtherly heated by the hot oil from a heat storage tank, and expands in the air turbine for electricity generation.

3. MATHMATICAL MODEL

3.1 The power components

The specific enthalpy change from inlet stream to outlet stream in the compressor, turbine and pump can be expressed as:

$$he_{out} - he_{in} = \frac{P_{in} v_{in}}{\frac{k-1}{k}\eta_{iso}} \cdot \left[\left(\frac{P_{out}}{P_{in}} \right)^{(k-1)/k} - 1 \right] \qquad (1)$$

3.2 Thermodynamic performance indexes

The cold storage density is proposed to show how much cold energy is stored per unit volume or mass. It is defined as the stored cold exergy from liquid air evaporation divided by the required mass or volume of storage materials. The gravimetric (GCSD) and volumetric (VCSD) cold storage densities in the LAES system are calculated by:

$$w_{GCSD} = \frac{m_{13} \cdot he_{13} - m_{12} \cdot he_{12}}{m_{cold\ storage}} \qquad (2)$$

$$w_{VCSD} = \frac{m_{13} \cdot he_{13} - m_{12} \cdot he_{12}}{V_{cold\ storage}} \qquad (3)$$

Round trip efficiency is a key index for the performance evaluation of the LAES system, and is defined as the ratio of the total power generated in the discharging cycle during peak time to the total power input consumed in the charging cycle during off-peak time:

$$\eta_{RTE,LAES} = \frac{W_{PO,dis} \cdot t_{peak}}{W_{PI,ch} \cdot t_{off-peak}} \qquad (3)$$

As there is excess compression heat stored in the heat storage tank, it is suggested to use the excess compression heat for domestic heating with hot water supply (85/60 ℃). A combined heat and power (CHP) efficiency of the LAES system is defined as the sum of heating capacity and net power generation at peak time divided by the net power consumption at off-peak time:

$$\eta_{CHP,LAES} = \frac{W_{PO,dis} \cdot t_{peak} + (m_{21} \cdot t_{off-peak} - m_{28} \cdot t_{peak})(he_{21} - he_{oil,65℃})}{W_{PI,ch} \cdot t_{off-peak}} \qquad (4)$$

3.3 Economic analysis

An economic analysis is conducted to show the systemic economic benefits. The simple payback period (SPP), is defined as the capital cost divided by the annual savings.

$$\mathrm{SPP} = \frac{\text{Capital cost}}{\text{Savings/year}} \qquad (5)$$

4. RESULTS AND DISCUSSION

The mathematical model of the proposed LAES system is developed in Matlab R2020a. Table 1 shows the default working parameters. From the simulation based on basic assumption, it shows that the CHP efficiency is 79% and exergy efficiency is 56.5%. Compared to the baseline LAES, the proposed LAES has a lower round trip efficiency of 45.7%, which is mainly due to the more exergy destruction in the cold box with a exergy efficiency of 67.2%.

Table 1 Simulation parameters of the proposed LAES.

Parameters	Value
Ambient pressure	0.1 MPa
Ambient temperature	293 K
Charging pressure P_{ch}	9 MPa
Discharging pressure P_{dis}	12 MPa
Initial thermal oil temperature	293 K
Liquid air temperature	78.82 K

4.1 Selection of fluid-based cold storage media

This study attempts to use one kind of liquid instead of the original combination of methanol and propane. Some common fluids are selected and compared. From Fig. 2, it can be observed that an increasing pressure from 0.1 MPa to 1.2 MPa leads to a longer liquid temperature range. Among propane, ethane, propylene and R218, liquid propane with a pressure of 1 MPa are able to cover the long refrigeration range from ambient temperature to near liquid air temperature.

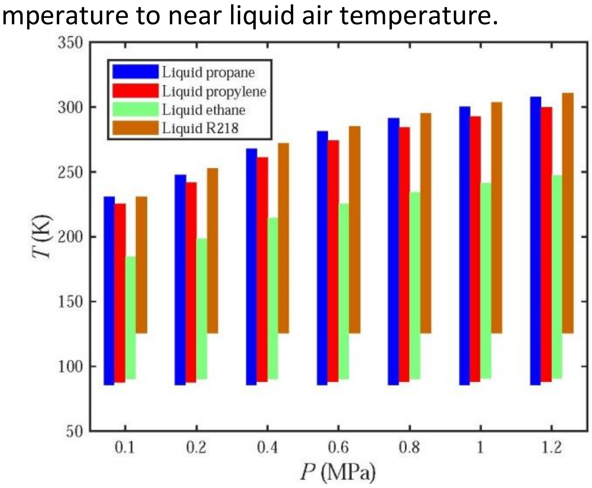
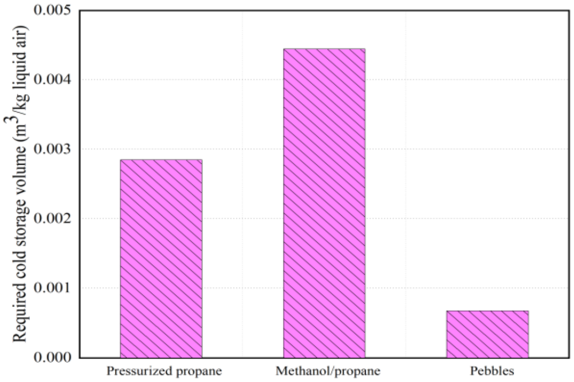


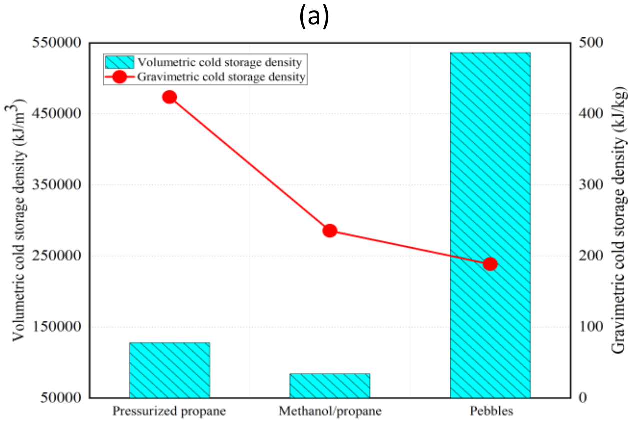
Fig. 2. The temperature ranges of charging/discharging air and cold storage fluids.

4.2 Cold storage density

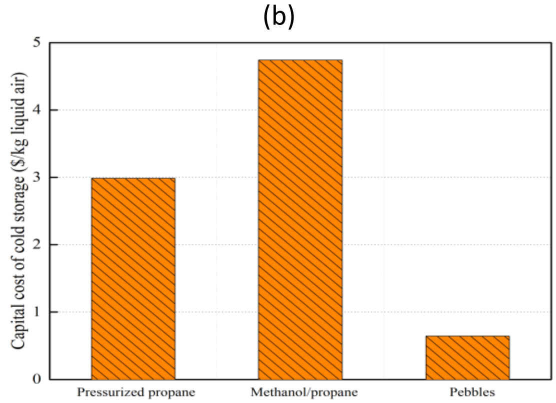
Methanol/propane and pebbles are two most popular cold storage media for the LAES system. Thus, the pressurized propane for cold storage is compared with them in terms of storage volume, energy storage density and capital cost.



(a)



(b)



(c)

Fig. 3. Cold storage volume (a), cold storage density (b) and capital cost of cold storage (c) with pressurized propane, ambient-pressure methanol/propane and pebbles as cold storage media, respectively.

Fig. 3(a) shows that using pressurized propane for cold recovery results in a cold storage volume of 2.85×10^{-3} m^3 per unit mass of liquid air, which is 64.19% of methanol/propane and finally makes the system more compact. The specific cold storage volume of pebbles is smaller than that of liquids, which is mainly because of its high bulk density. This leads to the maximum volumetric cold storage density of 536.45 MJ/m^3, while the volumetric cold storage densities of pressurized propane and methanol/propane are 127.77 MJ/m^3 and 84.02 MJ/m^3, respectively (as shown in Fig. 3(b)). Pressurized propane has the highest gravimetric cold storage density of 423.61 kJ/kg, reflecting effective cold storage and recovery of the proposed LAES system. Moreover, Fig. 3(c) indicates that the capital cost of cold storage with pressurized propane is 2.99 $/kg liquid air, which is 37% lower than that of methanol/propane. Pebbles has the lowest cold storage capital cost of 0.65 $/kg liquid air, because of its high specific heat capacity and cheap price.

4.3 Effects of charging pressure

The charging pressure can affect the thermodynamic performance of the proposed LAES system. Fig. 4 shows that the liquid yield increases from 48.2% to 69.2% and round trip efficiency grows from 44% to 51.1%, when the charging pressure increases from 7 to 17 MPa. This is because that the specific heat capacity of air generally decreases at low-temperature range (~110-200 K) with a higher charging pressure, and is hence easier to be liquefied. Through sensitive analysis, the proposed LAES system achieves a maximum exergy efficiency of 60%, as the charging pressure reaches its highest value of 17 MPa. Differently, the CHP efficiency decreases when charging pressure rises. This is mainly caused by the decreased proportion of compression heat for heating.

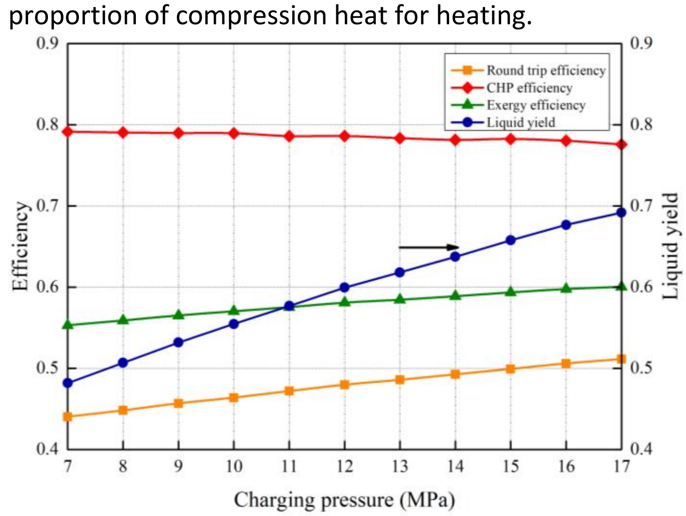
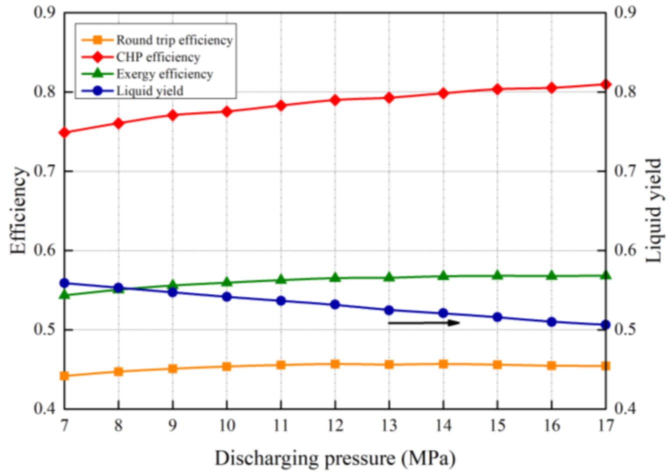


Fig. 4. Effects of the charging pressure on the proposed LAES (discharging pressure at 12 MPa).

4.4 Effects of the discharging pressure

The discharging pressure can also affect the performance of the proposed LAES system. Fig. 5 shows that an increase in the discharging pressure from 7 to 17 MPa results in a decrease in the liquid yield from 55.9% to 50.6% and an increase in the exergy efficiency from 54.3% to 56.8%. The CHP efficiency also increases from 74.9% to 81%, which is mainly due to the proportion changes of compression heat. Moreover, the round trip efficiency increases first as the discharging pressure increases from 7 MPa, reaches a maximum of at a discharging pressure of 12 MPa, and decreases little since then. It can be concluded that the discharging pressure has little impact on the efficiencies of the LAES system, compared to the charging pressure.



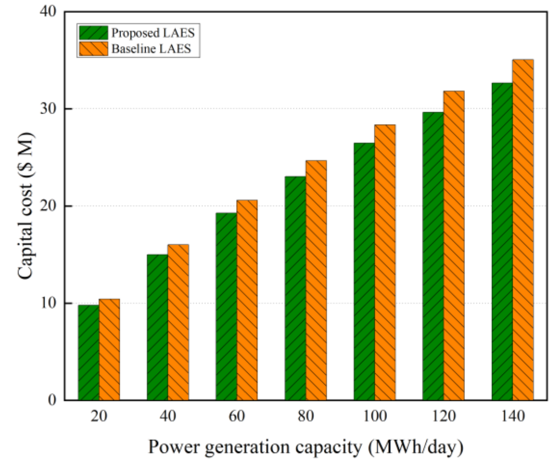
(b)

Fig. 5. Effects of the discharging pressure on the proposed LAES (charging pressure at 9 MPa).

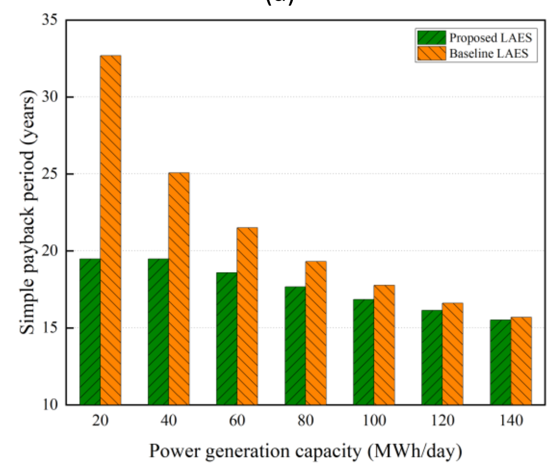
4.5 *Economic analysis*

Economy analysis is carried out to show the economic benefits of the proposed and baseline LAES systems. Two LAES plants based on the proposed and baseline system configuration are considered to operate in Beijing, China. The lifetime of the plants is assumed to be 30 years with an annual operation time of 300 days. The electricity rate is $153.18/MWh at peak hours (8 h) and $50/MWh at off-peak hours (8h). The heating price in Beijing is selected as $55.8/MWh. In the LAES systems, it is noted that power generation capacity is proportionate to the air liquefaction and storage capacities.

From Fig. 6(a), the capital cost of the proposed LAES system is $ 0.6-2.6M lower than that of the baseline LAES system. A larger power generation capacity results in a higher capital cost. Nevertheless, the simple payback period declines with the increase of the capacity as the annual savings increases more significantly (see Fig. 6(b)). This revealed that increasing the LAES capacity can make better economy. Moreover, the proposed LAES system achieves a short payback period of 15.5-19.5 years when the power generation capacity increases from 20 MWh/day to 140 MWh/day, which is lower than the baseline LAES system especially at lower capacities.



(a)



(b)

Fig. 6. The capital cost (a) and simple payback period (b) of the proposed and baseline LAES system with different capacities.

5. *CONCLUSIONS*

Liquid air energy storage (LAES) is a promising and popular large-scale energy storage technology, including the charging cycle (air liquefaction) and discharging cycle (power generation). Cold recovery and storage from liquid air are crucial for improving the LAES performance. The fluids-based cold storage is popular with the combination of two kinds of fluids (baseline system). However, it makes the cold storage bulky and complex. To address this issue, a novel configuration of LAES is proposed with single pressurized fluid for cold recovery and storage. Techno-economic analysis is carried out with various working parameters. The proposed LAES system is compared with the baseline LAES system in terms of thermodynamic and economic indexes. The key findings are as follows:

- The pressurized propane at 1 MPa is able to fully recover the cold exergy at 85-300 K in the proposed LAES system. This increases the volumetric cold storage density by ~52% and reduces the capital cost of cold storage by 37%, compared with the baseline LAES system with fluids-based cold storage.

- With the benefits of enhanced cold storage density, the proposed LAES system has a system energy storage density of 9.16 kWh/m^3, which is 16.69% higher than the baseline LAES system. Besides, the capital cost of the proposed LAES system is 6-7% lower than the baseline LAES system.
- The proposed novel LAES system has a high combined heat and power (CHP) efficiency of 74.9-81%, an electrical round trip efficiency of 44-51.1% and an exergy efficiency of 54.3-60%, which is promising for commercial application.
- With the power generation capacity increasing from 20 to 140 MWh/day, the simple payback period of the proposed LAES system decreases from 19.5 to 15.5 years, which is lower than that of the baseline LAES system (32.7-15.7 years). Thus, the proposed LAES is more economical than the baseline LAES.

ACKNOWLEDGEMENT

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