

Numerical Analysis of Packed-Bed Cold Thermal Energy Storage Performance in Liquid Air Energy Storage Operation

Seok Jun Oh, Jeong Ik Lee*

Nuclear Quantum Engineering department, KAIST, Yuseong-gu, Daejeon, 34141

*Corresponding author: jeongiklee@kaist.ac.kr

***Keywords :** Liquid air energy storage, Packed bed, cold energy storage.

1. Introduction

Liquid air energy storage (LAES) has attracted increasing attention as a promising large-scale and long-duration energy storage technology for future low-carbon power systems. The increasing penetration of variable renewable energy requires additional operational flexibility to maintain grid stability, while nuclear power plants, which have traditionally been operated as baseload units, are also expected to contribute to flexible operation [1].

However, direct load-following operation of nuclear power plants can be limited by economic, operational, and safety-related considerations. Therefore, coupling nuclear power plants with energy storage systems has been proposed as an effective approach to improve grid-side flexibility while maintaining stable reactor operation. In this context, LAES is an attractive option because it is not strongly constrained by geographical conditions, unlike pumped hydro energy storage, and can provide large-scale storage without relying on critical battery materials. Recent reviews have also identified LAES as a scalable and site-flexible storage technology with high energy density, while emphasizing its potential role in future decarbonized energy systems. [2]

Despite these advantages, the relatively low round-trip efficiency remains one of the major challenges of LAES. Recent studies have reported that standalone LAES systems typically show round-trip efficiencies of approximately 50–60%, while further improvement requires effective recovery and utilization of both compression heat and cryogenic cold energy. In particular, cold thermal energy storage (CTES) is a key component because the cold exergy released during liquid air regasification can be recovered and reused for air pre-cooling during the subsequent liquefaction process. Tafone et al. emphasized that CTES performance strongly affects the round-trip efficiency of LAES, and that cold storage losses can have a significantly larger impact on system efficiency than heat losses. [3]

Therefore, this study aims to numerically investigate how the performance of the cold storage unit affects LAES operation. In particular, the effects of CTES outlet temperature and cold storage round-trip efficiency on liquid air yield, liquefaction performance, and overall

system operation are analyzed using a simplified system-level model.

2. LAES numerical analysis model

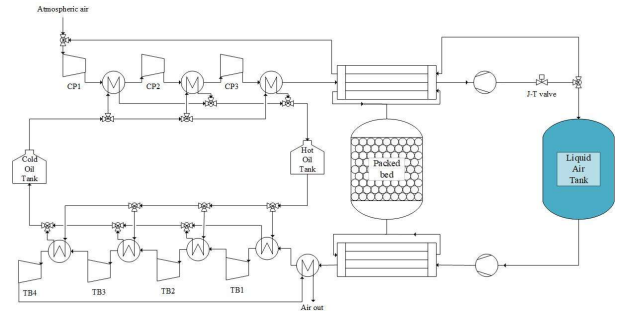


Figure 1. LAES with packed bed schematic diagram

Figure 1 shows the schematic layout of the liquid air energy storage system considered in this study. The system consists of a charging process, a liquid air storage section, and a discharging process. The charging process includes three-stage air compression, intercooling, cryogenic heat exchange, cold energy storage, and liquefaction. The discharging process consists of cryogenic pumping, reheating, multi-stage turbine stage, and power generation.

In the present model, the compression and expansion sections are connected to thermal oil tanks, which are used to recover and supply compression heat during system operation. The cold energy storage section is represented by a single packed-bed storage unit. During discharge, the cold energy released from liquid air evaporation is stored in the packed bed.

During the subsequent charging process, the stored cold energy is reused to pre-cool the compressed air before liquefaction. The proposed system includes three compressors and four turbines, while the heat exchangers and packed bed are modeled as isobaric components in order to focus on the influence of cold storage performance.

2.1. Pump

$$h_{out} = h_{in} + \frac{(h_{isen} - h_{in})}{\eta_{Pump}} \quad (1)$$

$$W_p = \dot{m}_p (h_{out} - h_{in}) \quad (2)$$

η_{Pump} : Pump efficiency W_p : Pump work
 h : Fluid enthalpy $\dot{m}$: Mass flow rate
 h_{isen} : Isentropic enthalpy

The cryogenic pump is used to increase the pressure of the stored liquid air before the discharging process. The pump outlet state is calculated using the isentropic outlet enthalpy and the pump efficiency based on equations (1)~(2).

2.2. Heat exchanger

$$T_{cold-ou} = T_{cold-in} + \frac{Q}{C_{cold}} \quad (3)$$

$$T_{hot-o} = T_{hot-i} - \frac{Q}{C_{hot}} \quad (4)$$

$$C_i = \dot{m}_i * c_{p_i} \quad (5)$$

$$Q = \eta_{HX} * \min(C_{hot}, C_{cold}) * (T_{hot-in} - T_{cold-in}) \quad (6)$$

η_{HX} : Heat exchanger efficiency C : Heat capacity
 c_p : Specific heat T : Temperature
 Q : Exchanged heat

The heat exchangers are modeled using the effectiveness method. Pressure drops in the heat exchangers are neglected, and each heat exchanger is assumed to operate under steady-state conditions. In the charging process, the cryogenic heat exchanger has one hot channel and two cold channels. The hot stream corresponds to the compressed air to be pre-cooled, while the two cold streams represent the cold energy supplied from the cold storage side. The heat capacity rates of the hot and cold streams are defined by equations (3)~(6).

2.3. Compressor

$$h_{out} = h_{in} + \frac{(h_{isen} - h_{in})}{\eta_{Comp}} \quad (7)$$

$$W_c = \dot{m}_c(h_{out} - h_{in}) \quad (8)$$

η_{Comp} : Compressor efficiency W_c : Compressor work

The compressor model is based on an adiabatic compression process with prescribed isentropic efficiency by equations (7)~(8). For each compressor stage, the outlet pressure is specified by pre-defined pressure ratio value and enthalpy is calculated based on isentropic compression model.

2.4. Turbine

$$h_{out} = h_{in} - (h_{in} - h_{isen}) * \eta_{Turbine} \quad (9)$$

$$W_T = \dot{m}_t(h_{in} - h_{out}) \quad (10)$$

$\eta_{Turbine}$: Turbine efficiency W_T : Turbine work

The turbine stages convert the thermal and pressure energy of the expanded air into power during the

discharging process. Similar to the compressor model, each turbine is calculated using the isentropic outlet state and the turbine efficiency (Eqs. (9)~(10)). The isentropic outlet enthalpy is obtained at the turbine outlet pressure while keeping the inlet entropy constant.

3. Numerical analysis result

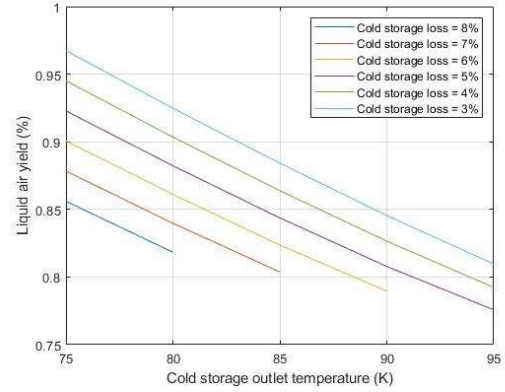


Figure 2. Liquid air yield on charging cycle analysis

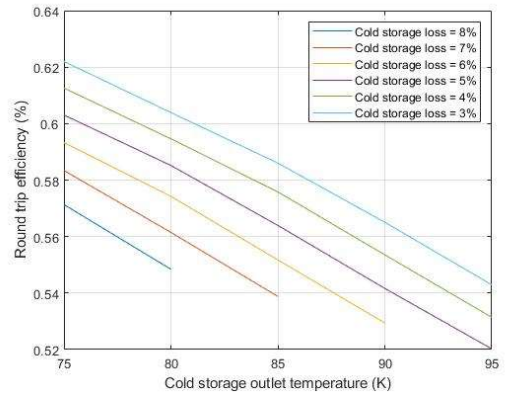


Figure 3. Round trip efficiency of whole LAES system

Figures 2 and 3 show the effects of the packed-bed cold storage outlet temperature on the liquid air yield and the round-trip efficiency of the LAES system. In this analysis, the packed-bed outlet temperature is represented by the inlet temperature of the cold channel in the charging-side heat exchanger. The inlet temperature was varied from 75 K to 95 K, and the cold storage loss ratio was changed from 3% to 8% in order to evaluate the sensitivity of the system performance to the degradation of packed bed during storage period.

As shown in Fig. 2, the liquid air yield decreases as the cold-channel inlet temperature increases. This is because a higher cold-side inlet temperature reduces the pre-cooling performance of the compressed air before liquefaction. As a result, the air entering the expansion and separation process has a higher enthalpy, which directly lowers the liquid fraction after expansion. The cold storage loss ratio also has a negative effect on the liquid yield. When the loss ratio increases, the amount of

useful cold energy delivered from the packed bed decreases, and the liquefaction process becomes less efficient.

Under the most favorable condition considered in this study, where the cold-channel inlet temperature is 75 K and the cold storage loss ratio is 3%, the liquid air yield reaches 96.74%. However, when the packed-bed outlet temperature and cold storage loss become less favorable, the yield decreases to 77.57%. This result indicates that the thermal condition of the packed-bed cold storage has a direct influence on the liquefaction performance of the LAES system.

Figure 3 shows a similar trend for the round-trip efficiency. Since the liquid air yield determines the amount of stored liquid air and the available discharge-side mass flow rate, a decrease in yield leads to a reduction in the recoverable power output during discharge. In addition, a larger cold storage loss increases the effective energy penalty of the charging process because less recovered cold energy is available for air pre-cooling. Therefore, the round-trip efficiency decreases as the packed-bed outlet temperature and the cold storage loss ratio increase.

For the best operating condition, the system round-trip efficiency is calculated to be 62.19%. In contrast, under the least favorable condition in the present analysis, the round-trip efficiency decreases to 52.02%. The difference between these two cases demonstrates that the packed-bed cold storage is not a secondary component in LAES operation, but a key factor that affects both liquefaction performance and overall system efficiency. These results also suggest that maintaining a low packed-bed outlet temperature and minimizing cold storage loss are essential for improving the performance of LAES systems.

Table 1. Liquid air yield on charging cycle with different cold storage operation pressure

Operation pressure (MPa)	10MPa	20MPa	30MPa
75K	0.9654	0.9655	0.9655
80K	0.9227	0.9228	0.9228
85K	0.8822	0.8822	0.8822
(Cold storage outlet temperature)			

Table 2. Round trip efficiency of LAES with different cold storage operation pressure

Operation pressure (MPa)	10MPa	20MPa	30MPa
75K	0.6208	0.6211	0.6212
80K	0.6028	0.6030	0.6031
85K	0.5850	0.5852	0.5852
(Cold storage outlet temperature)			

Tables 1 and 2 present the effects of the cold storage operation pressure on the liquid air yield and round-trip

efficiency. In this case, the operation pressure of the cold storage side was varied from 10 MPa to 30 MPa. Three packed-bed outlet temperature conditions, 75 K, 80 K, and 85 K, were considered to compare the pressure effect under different cold energy storage temperatures.

As shown in Table 1, increasing the cold storage operation pressure slightly improves the liquid air yield. This tendency can be attributed to the thermodynamic state of the cold stream and its influence on the heat exchange process. At higher pressure, it slightly increases heat capacity of air flowing through heat exchanger that can marginally improve the cold energy transfer and pre-cooling condition. However, the magnitude of this improvement is very small compared with the effect of the packed-bed outlet temperature shown in Fig. 2. Across the investigated pressure range, the increase in liquid air yield remains within approximately 0.1%.

Table 2 shows the corresponding variation in the round-trip efficiency. Similar to the yield trend, the round-trip efficiency increases slightly as the cold storage operation pressure rises. Nevertheless, the improvement is also limited to less than approximately 0.1% under the present modeling assumptions. This indicates that the operation pressure of the cold storage side has only a minor influence on the overall system performance compared with the cold storage outlet temperature and cold storage loss ratio.

The results in Tables 1 and 2 suggest that increasing the cold storage operation pressure can provide a small thermodynamic benefit, but the effect is not significant in the present system configuration. Therefore, from a system-level perspective, improving the temperature quality of the recovered cold energy and reducing cold storage losses are more effective strategies than increasing the cold storage pressure.

4. Summary and Conclusions

In this study, a simplified system-level model was developed to investigate the influence of cold thermal energy storage performance on liquid air energy storage operation. The motivation of this work is based on the fact that cold energy recovery and reutilization are essential for improving the performance of LAES systems. Since the liquefaction process strongly depends on the pre-cooling condition of the compressed air, the performance of the cold storage unit can directly affect the liquid air yield and, consequently, the overall round-trip efficiency of the system.

The numerical results showed that the outlet temperature of the packed-bed cold storage has a significant effect on LAES performance. When the inlet temperature of the cold channel in the charging-side heat exchanger increased, the pre-cooling performance of the compressed air decreased, resulting in a lower liquid air

yield. In addition, an increase in the cold storage loss ratio reduced the amount of usable cold energy supplied to the charging process. Under the most favorable condition considered in this study, the liquid air yield and round-trip efficiency were calculated to be 96.74% and 62.19%, respectively. However, as the cold storage condition deteriorated, the liquid air yield and round-trip efficiency decreased to 77.57% and 52.02%, respectively.

The effect of cold storage operation pressure was also analyzed. Although increasing the operation pressure from 10 MPa to 30MPa slightly improved the liquid air yield and round-trip efficiency, the magnitude of improvement was less than approximately 0.1%. This indicates that, under the present modeling assumptions, the outlet temperature and loss characteristics of the packed-bed cold storage are much more influential than the cold storage operation pressure.

These results demonstrate that even relatively small changes in cold storage performance can strongly influence LAES operation. In particular, degradation of cold storage performance directly affects the charging cycle by reducing the liquid air yield, which subsequently changes the available discharge-side mass flow rate and the overall system efficiency. Therefore, maintaining a low loss ratio and providing a stable low-temperature outlet are important requirements for cold storage systems in LAES applications.

As a future study, a more detailed analysis of packed-bed cold storage will be conducted by considering non-uniform packed-bed structures. In particular, particle-size-graded or material-graded packed beds will be investigated as potential approaches for improving outlet temperature stability, reducing thermal degradation, and enhancing the applicability of packed-bed cold storage to stable LAES operation.

REFERENCES

- [1] International Atomic Energy Agency, *Non-baseload Operation in Nuclear Power Plants: Load Following and Frequency Control Modes of Flexible Operation*, IAEA Nuclear Energy Series No. NP-T-3.23, Vienna, 2018.
- [2] X. She, H. Wang, T. Zhang, Y. Li, X. Zhao, Y. Ding, and C. Wang, "Liquid air energy storage – A critical review," *Renewable and Sustainable Energy Reviews*, vol. 208, Article 114986, 2025. doi: 10.1016/j.rser.2024.114986.
- [3] A. Tafone, E. Borri, L. F. Cabeza, O. O'Callaghan, P. Donnellan, A. Mashayekh, R. Kothari, F. Haglind, D. Li, L. Xu, Y. Ding, Y. Li, L. Yang, A. Romagnoli, A. Dzido, and P. Krawczyk, "Progress and prospects of cold thermal energy storage for liquid air energy storage systems – A critical review," *Renewable and Sustainable*

Energy Reviews, vol. 230, Article 116672, 2026. doi: 10.1016/j.rser.2025.116672.