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Preliminary exergy analysis of Liquid air energy storage systems integrated with a Pressurized water reactor: A comparative study of Two-phase expansion configurations

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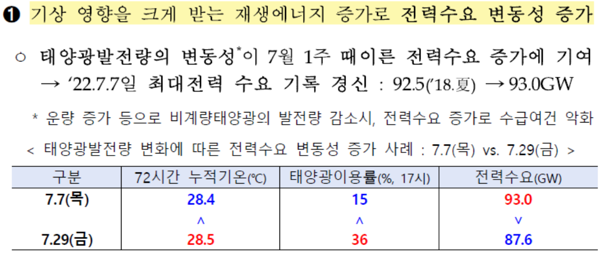
1. Introduction

Various energy policies have been proposed worldwide to reduce carbon emissions. In Korea, for example, the "Renewable Energy 3020 Implementation Plan" aims to increase the share of renewable energy to 30% by 2030 [1]. However, as the proportion of renewables grows, the issue of intermittency arises. The 10th Basic Plan for Long-term Electricity Supply and Demand presents the impact of the increase in renewable energy on power supply and demand [2]. Figure 1 shows one example, illustrating how the increase in renewable energy, which is heavily influenced by weather conditions, leads to increased power demand volatility and provides a case study of this impact. To address this, extensive research has been conducted on pressurized water reactor (PWR) combined with energy storage systems (ESS) [3].



❶ 기상 영향을 크게 받는 재생에너지 증가로 **전력수요 변동성 증가**

○ **태양광발전량의 변동성***이 7월 1주 **때이른 전력수요 증가에 기여**
→ '22.7.7일 **최대전력 수요 기록 경신** : 92.5('18.夏) → 93.0GW

* 운량 증가 등으로 비계량태양광의 발전량 감소시, 전력수요 증가로 수급여건 악화

< 태양광발전량 변화에 따른 전력수요 변동성 증가 사례 : 7.7(목) vs. 7.29(금) >

구분	72시간 누적기온(℃)	태양광이용률(%, 17시)	전력수요(GW)
7.7(목)	**28.4**	**15**	**93.0**
	∧	∧	∨
7.29(금)	**28.5**	**36**	**87.6**

Fig. 1. Some of the impacts of the increase in renewable energy on power supply and demand [2]

Liquid Air Energy Storage (LAES) is a promising ESS technology due to its high energy density, significant power scale, and competitive round-trip efficiency [4, 5]. Previous studies have optimized LAES layouts and operational parameters, primarily focusing on liquid yield and overall thermal performance [6]. While liquid yield is a critical metric for determining discharge flow rates, many conventional analyses rely on first-law thermodynamics, which may not fully account for the specific locations and causes of energy degradation within the system components.

A rigorous evaluation of the liquefaction process is essential, as it involves complex cryogenic expansion stages where irreversibilities occur. Prior research has identified that the thermophysical properties of air and its phase-change behavior are sensitive to operational conditions [7]. However, a comprehensive second-law analysis that quantifies the exergy destruction across different cryogenic expansion configurations integrated with PWR waste heat remains limited. Understanding where exergy is destroyed is important for identifying the sources of thermodynamic inefficiency in LAES plants.

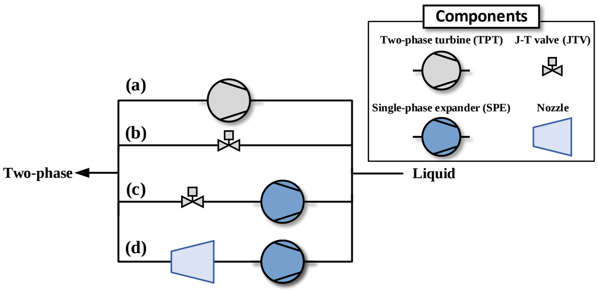


Fig. 2. The layouts of four options for the two-phase expansion process in this study: (a) TPT, (b) JTV, (c) SPE w/ JTV and (d) SPE w/ nozzle

The thermodynamic analysis of various two-phase expansion methods in the Linde liquefaction process for LAES has been documented in previous studies [7, 8]. These methods typically include the two-phase turbine (TPT), Joule-Thomson valve (JTV), and combinations of a single-phase expander (SPE) with either a JTV or a nozzle in Figure 2. However, to provide a more focused and fundamental investigation into the nature of thermodynamic irreversibilities, this study prioritizes a comparative analysis between TPT and JTV.

These two components are selected as representative benchmarks for isentropic and isenthalpic expansion processes, respectively. By isolating these core expansion mechanisms, a more fundamental understanding of exergy destruction can be achieved without the added complexity of hybrid configurations. Therefore, the primary objective of this paper is to quantify and compare the exergy destruction characteristics of isentropic and isenthalpic expansion in the LAES liquefaction process from a second-law perspective. Accordingly, this study presents a rigorous thermodynamic analysis of LAES, identifying the fundamental sources of irreversibility associated with these two representative cryogenic expansion types.

2. Thermodynamic modeling

Assumptions used for the modeling are as follows:

(1) The working fluid, air, is treated as a dry and pure fluid.

(2) All tanks have the same temperature and pressure.
(3) There is no pressure drop in the pipelines.
(4) There are no changes in potential and kinetic energies
(5) All points and processes are at equilibrium and under steady-state conditions.

2.1 System description

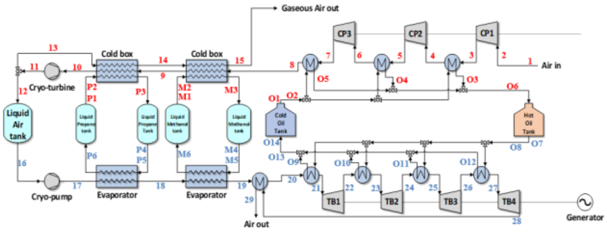


Fig. 3. Layout of LAES in this study

Fig. 3 illustrates the layout of the LAES system analyzed in this study. The charging and discharging processes of the LAES are described as follows:

In the charging process, surplus electricity is utilized to compress and cool ambient air, creating a high-pressure air stream. This air is subsequently liquefied through a cold box, followed by a cryogenic expansion stage. In this study, two distinct two-phase expansion configurations—TPT or JTV—are implemented to investigate their impact on system irreversibility. Following the expansion, only the liquid fraction of the resulting two-phase mixture is separated and stored in a cryogenic tank.

The discharging process is initiated during periods of power shortage. The stored liquid air is pressurized by a pump and passed back through the cold box, where it absorbs heat to transition into high-pressure gaseous air. This high-pressure air is then expanded through a turbine to generate electricity.

2.2 Modeling of components

This paper uses the same modeling of components to be used and explained in the previous study [7, 8]. For turbomachinery, thermodynamic properties of its outlet are obtained to use its isentropic efficiency. For heat exchangers, these properties of both inlet and outlet are calculated to consider pressure drop ratio, energy balance, and minimum pinch temperature. In this paper, the minimum pinch temperature in heat exchangers (HX) is assumed to be 5K.

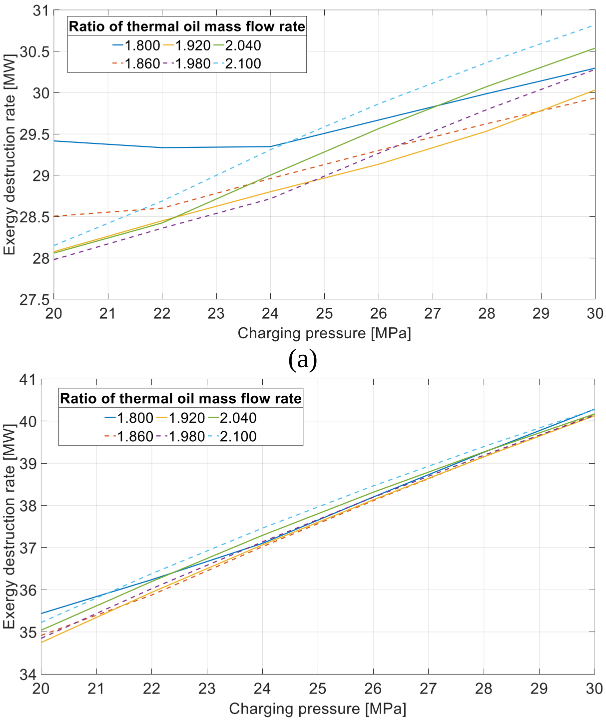
2.3 Parameters & Variables

Table I: Parameters and variables of LAES

Fixed values for cycle design	
Parameters	Values
Compressor efficiency	85%
Turbine efficiency	90%
Cryo-expander efficiency	80%
Cryo-pump efficiency	80%
Pressure drop	3%
Pinch of HX	5K
Minimum propane temperature	93K
Maximum propane temperature	214K
Minimum methanol temperature	214K
Maximum methanol temperature	288K
Temperature of Ambient Air	298.15K
Pressure of Ambient Air	101kPa
Mass flow rate of air (Total)	100kg/sec
Optimization variables	
Variables	Ranges
System maximum pressure	20-30MPa
Ratio of thermal oil mass flow rate	1.8-2.1

Table I presents the design conditions and variables used in this study, and the results are obtained based on these conditions.

3. Results and Discussions



(a)

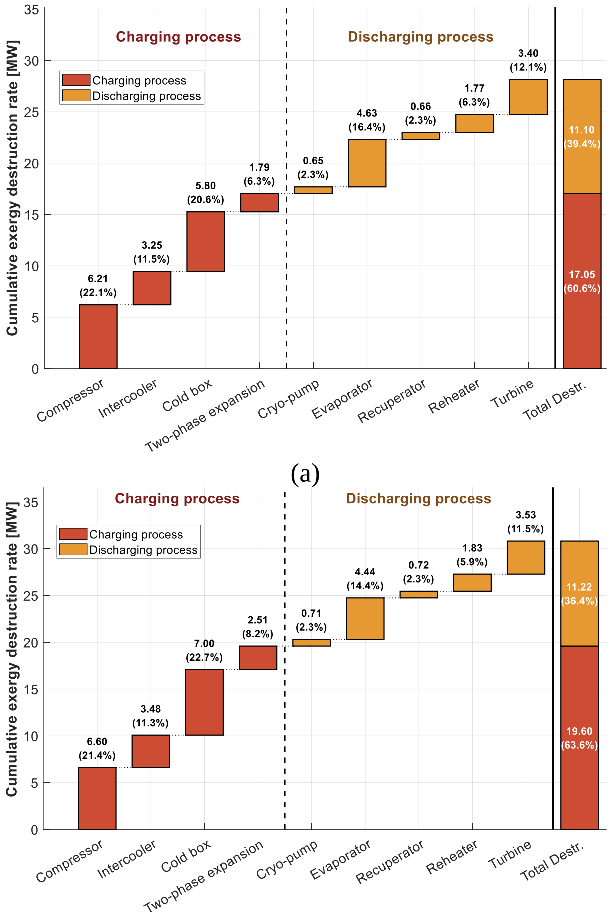
(b)

Fig. 4. Total exergy destruction rate trend of LAEs with (a) TPT and (b) JTV

Figures 4 (a), and (b) present the total exergy destruction rates for the four investigated configurations: TPT and JTV. In general, a consistent increase in the total exergy destruction rate is observed as the charging pressure increases across all systems.

These results are found to be in close agreement with the trends identified in previous studies regarding RTE [7, 8]. The observed correlation suggests that the exergy destruction rate serves as a critical indicator of overall system performance. When comparing the different configurations, it is identified that the TPT exhibits the lowest exergy destruction rates. In contrast, the JTV configuration is characterized by a significantly higher exergy destruction rate and demonstrates the greater sensitivity to changes in charging pressure than the TPT.

To further investigate these characteristics, the exergy destruction ratios of individual components within each configuration are compared to identify the specific sources of thermodynamic irreversibility.



(a)

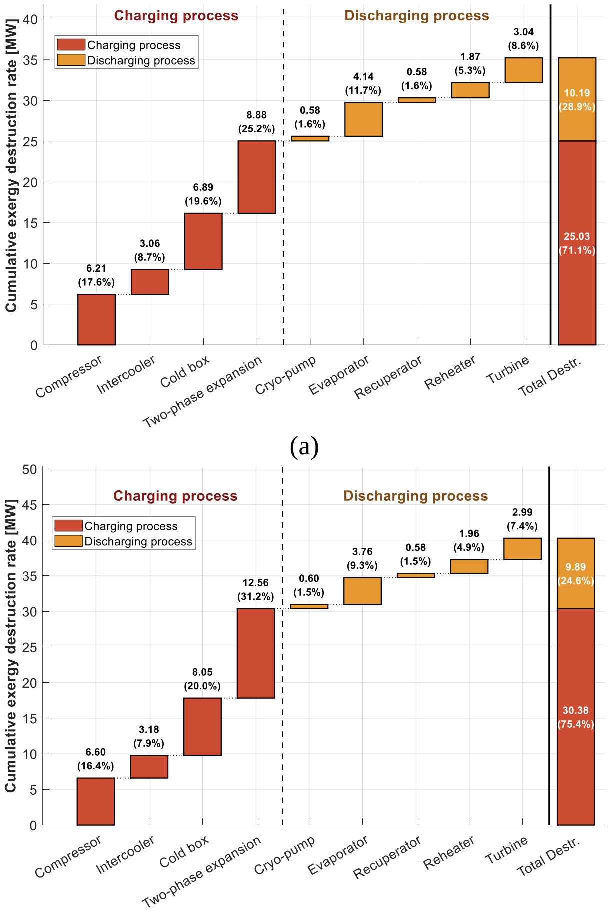
(b)

Fig. 5. Comparison of exergy destruction rates by component for the LAES with TPT at (a) 20 MPa and (b) 30 MPa charging pressures (Ratio of thermal oil mass flow rate: 2.1)

Figures 5 (a) and (b) present the exergy destruction rates by component for the LAES system with TPT at charging pressures of 20 MPa and 30 MPa, respectively. In general, it is observed that the compressors, cold box, evaporator, and turbines constitute the primary portions of the total exergy destruction, while the two-phase expansion stage accounts for a relatively smaller fraction.

As the charging pressure increases, a corresponding rise in the exergy destruction rates is identified due to the higher pressure ratios. Notably, the charging process is found to be significantly more sensitive to pressure variations than the discharging process, with the increase in exergy destruction in the charging phase exceeding that of the discharging phase by more than twenty times. Within the charging process, the cold box exhibits the largest absolute change in exergy destruction, while the two-phase expansion stage demonstrates the highest rate of increase.

The significant trend in the cold box is attributed to the fact that the variation in exergy destruction on the cold side becomes more pronounced than on the hot side as the charging pressure rises. Furthermore, although an increase in exergy destruction within turbomachinery is expected with higher charging pressures, the two-phase expansion stage shows a greater increment and a higher growth rate compared to the compressors. This indicates that the expansion process in the two-phase region is more sensitive to pressure changes than the compression of superheated vapor, highlighting the thermodynamic complexity of phase-change expansion.



(a)

(b)

Fig. 6. Comparison of exergy destruction rates by component for the LAES with JTV at (a) 20 MPa and (b) 30 MPa charging pressures (Ratio of thermal oil mass flow rate: 2.1)

Figures 6 (a) and (b) illustrate the exergy destruction rates by component for the LAES system with a JTV at charging pressures of 20 MPa and 30 MPa, respectively. Unlike the previously discussed TPT configuration, the JTV system is characterized by a different hierarchy of irreversibility, where the two-phase expansion stage exhibits the highest exergy destruction rate, followed by the cold box and the compressors. This indicates that the choice of two-phase expansion method significantly shifts the dominant sources of exergy destruction, thereby determining the overall thermodynamic performance of the system.

A distinct trend is observed regarding the influence of charging pressure on each process. As the charging pressure increases, the exergy destruction rates in the charging process rise substantially, whereas a slight decrease is identified in the discharging process. This phenomenon is consistent with findings from previous studies, which reported that an increase in charging pressure for the JTV configuration leads to a reduction in both liquid yield and RTE [7, 8]. The resulting decrease in mass flow rate and pressure ratio during the discharging phase subsequently leads to the observed marginal reduction in exergy destruction within that stage.

Within the charging process, the two-phase expansion stage demonstrates both the largest absolute exergy destruction and the highest growth rate as the pressure increases. This behavior is attributed to the fact that the isenthalpic expansion process in a JTV incurs a rapid surge in entropy generation as the inlet charging pressure rises, which in turn causes a significant escalation in exergy destruction. These component-level characteristics provide a fundamental explanation for the overall system trends previously identified in Figure 4(b).

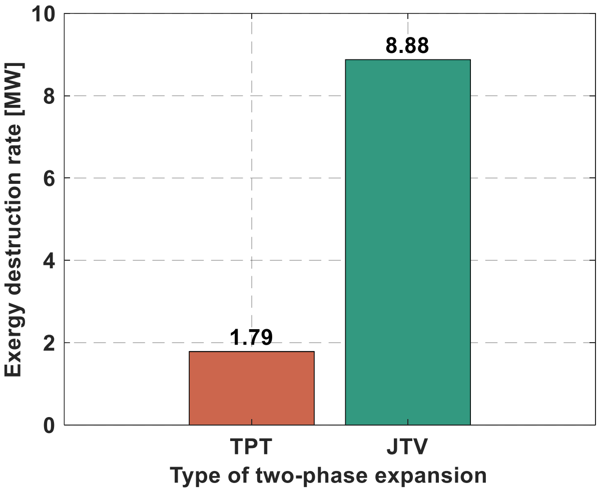


Fig. 7. Comparison of exergy destruction rates specifically for the two-phase expansion processes (Red: TPT, Green: JTV) at a charging pressure of 20 MPa and a thermal oil mass flow rate ratio of 2.1.

Figure 7 compares the exergy destruction rates specifically associated with the two-phase expansion process for the TPT and JTV configurations, at a charging pressure of 20 MPa and a thermal oil mass flow rate ratio of 2.1. In this representation, the red bar indicates the exergy destruction within the TPT, representing an isentropic expansion process, while the green bar represents the exergy destruction in the JTV, which follows an isenthalpic process.

It is clearly observed that the JTV configuration exhibits a significantly higher exergy destruction rate, reaching a magnitude approximately five times greater than that of the TPT. This substantial difference identified between the TPT and the JTV during the two-phase expansion stage highlights the inherent inefficiencies of the throttling process. Overall, these results confirm that the isenthalpic expansion process in the JTV incurs significantly higher exergy destruction than the isentropic process in the TPT, as the thermodynamic irreversibility is shown to be particularly pronounced within the two-phase region.

4. Summary and Future works

This study investigated the thermodynamic irreversibility and exergy destruction characteristics of a LAES system integrated with a PWR, focusing on two representative two-phase expansion configurations: the TPT (isentropic) and the JTV (isenthalpic). The analysis demonstrated that total exergy destruction rates increase with higher charging pressures across both systems. Between the investigated cases, the TPT configuration exhibited significantly lower exergy destruction, showing close agreement with the trends identified in RTE performance. In contrast, the JTV configuration was found to be the most inefficient, primarily due to the rapid surge in entropy generation inherent in isenthalpic expansion, particularly within the two-phase region. Furthermore, it was identified that the exergy destruction within the cold box and evaporator is highly sensitive to the thermal oil mass flow rate ratio, which significantly influences the saturation temperature and liquid yield growth rates.

Based on these findings, further research is proposed to conduct an exergy-economic analysis to evaluate the cost-effectiveness of the proposed high-performance expansion layouts. Additionally, more comprehensive investigations are necessitated regarding nozzle efficiency and non-equilibrium flashing phenomena. Since rapid expansion in cryogenic nozzles often involves metastable states and delayed nucleation that deviate from ideal equilibrium assumptions, the development of a non-equilibrium model for two-phase air expansion, such as the Delayed Equilibrium Model (DEM), is required to achieve more accurate performance predictions for future LAES optimizations.

Acknowledgement

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