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# Thermodynamic study on the effect of cold and heat recovery on performance of liquid air energy storage

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## HIGHLIGHTS

- Effects of cold and heat recovery on the LAES are disclosed.
- ~18% of the recovered cold is lacking to achieve the maximum liquid air yield.
- 20–45% of the recovered heat is excess, which could be used for power generation.
- The excess heat is used to drive Organic Rankine Cycles with two configurations.
- Round trip efficiency of the LAES could be improved by 17.6%.

## ARTICLE INFO

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## ABSTRACT

Liquid Air Energy Storage (LAES) is one of the most promising large-scale energy storage technologies for intermittent renewable energy. The LAES includes an air liquefaction (charging) process and a power recovery (discharging) process. In the charging process, off-peak electricity is stored in the form of liquid air; meantime, a large amount of compression heat is recovered and stored at over 200 °C for later use in the discharging process to enhance the output power of air turbines. During peak times, liquid air is pumped and heated, and then expands to generate electricity in the discharging process, with cold energy of the liquid air recovered and stored to help liquefying the air in the charging process. It is well known that the recovery and utilization of both the cold and heat energy are crucial to the LAES. However, little attention is paid on the quantity and quality of the cold and heat energy. This paper carries out thermodynamic analyses on the recovered cold and heat energy based on steady-state modelling. It is found that the cold energy has a much more effect on the LAES than the heat energy; the cold energy loss leads to a decrease rate of the round trip efficiency, which is ~7 times of that caused by the heat energy loss. In addition, the recovered cold energy from the liquid air is insufficient to cool the compressed air to the lowest temperature with the shortage of ~18% and liquid air yield does not achieve the maximum in the charging process; external free cold sources would be needed to further increase the liquid air yield, and the round trip efficiency could easily break through 60%. Unlike the cold energy, 20–45% of the stored heat energy is in excess and cannot be efficiently used in the discharging process; we propose to use the excess heat to drive an Organic Rankine Cycle (ORC) for power generation. The ORC is considered to work at two different cold sources: the ambient and the sub-ambient. The sub-ambient cold source is generated through an Absorption Refrigeration Cycle (ARC) by consuming part of the excess heat. The combinations of the LAES and ORC with ambient and sub-ambient cold sources are denoted as LAES-ORC and LAES-ORC-ARC, respectively. Comparisons are made among the LAES, LAES-ORC and the LAES-ORC-ARC. The results show that both the LAES-ORC and LAES-ORC-ARC could achieve a much higher round trip efficiency than the LAES, with the maximum improvement of 17.6% and 13.1% under the studied conditions, respectively. It is concluded that the LAES-ORC has a simpler configuration with a better performance than the LAES-ORC-ARC configuration.

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## 1. Introduction

The past decade has seen an increased penetration of renewable energy and this has promoted the development of energy storage technologies to deal with the intermittency. The world power generation capacity from renewable sources has rapidly risen from 6% in 2007 to 27.7% at the end of 2014 [1]. Energy storage can overcome the intermittent electricity production from renewable sources and contribute to resolve the mismatch between power demand and supply by shifting the peak-load [2]. Among large-scale energy storage technologies, Liquid Air Energy Storage (LAES) has attracted significant attentions due to high energy density, geographical flexibility, and a relatively low capital cost [3,4].

The LAES uses intermittent renewable sources or off-peak electricity to produce liquid air in an air liquefaction (charging) process; in peak times, the liquid air is pumped to high pressure, heated by external heat sources and then expands in air turbines to generate electricity in a power recovery (discharging) process. The principle of LAES was first proposed by University of Newcastle in 1977 with an energy recovery efficiency of 72% [5], and the world's first pilot plant (350 kW/2.5 MWh) was established and tested by Highview Power Storage in collaboration with University of Leeds from 2009 to 2012. It was relocated at University of Birmingham for further testing and academic research in 2013 [6]. Right now, a pre-commercial scale LAES (5 MW/15 MWh) is under construction by Highview Power Storage in Manchester, UK [7].

Commercial uptake of the LAES is affected by the low round trip efficiency in many applications of the technology. Therefore, significant efforts have been made to improve the round trip efficiency [8–25]. Guizzi et al. [9] studied the effect of isentropic efficiencies of turbines, pressure losses and pinch-point temperatures of heat exchangers on the performance of the LAES. Morgan et al. [10,11] studied the air liquefaction process of the LAES by adding a Claude cycle in a cold box, and obtained an efficiency of 57%. Abdo et al. [12] compared the Linde-Hampson cycle, Claude cycle and the Collins cycle for the cryogenic energy storage system. The results showed that the systems presented similar talents on power output while the Claude cycle behaved better on cost-benefit. Sciacovelli et al. [13] investigated a direct-contact cold store using pebbles and rocks as cryogenic energy storage media to improve the efficiency of cold recovery. Peng et al. [14,15] used packed-beds to store heat generated during air compression and analyzed the thermodynamic performance of the LAES; the results showed that a round trip efficiency of 50–60% could be achieved. Borri et al. [17] analyzed the configuration of a small-scale air liquefaction cycle for LAES applications in a microgrid; the results demonstrated a maximum 25% of performance improvement with operating pressure in the range of 38–45 bar. Kantharaj [18,19] proposed a hybrid energy storage system involving compressed air and liquid air; the round trip efficiency of the hybrid system could reach 53%. Hamdy et al. [21] improved the cryogenic energy storage system by utilizing the cold from liquid air evaporation to drive an indirect Rankine cycle. This additional cycle increased the specific power output of the discharging process by up to 25%, and reached a round trip efficiency of 40%. It has been claimed that the performance of the LAES could be improved through integration with waste heat and cold sources from industries. Li et al. [22] proposed the integration of the LAES with nuclear power generation and found a higher round trip efficiency of 70% could be achieved. Antonelli et al. [23] compared LAES with and without fuel combustion and found that the LAES with the use of heat coming from fuel combustion could achieve a round trip efficiency over 80%. Krawczyk et al. [24] studied the LAES with fuel combustion as heat sources and showed that the LAES obtained a higher round trip efficiency than compressed air energy storage. Lee et al. [25] integrated the cryogenic energy storage system with a liquified natural gas (LNG) regasification process: the air was liquified by adequate cold energy from the LNG regasification process and the heated natural gas drove multi-turbines to generated additional work to decrease the consumption of the air compressors. The results presented a significantly high exergy efficiency of 94.2% and 61.1% for the air storage process and the air release process respectively.

It is well-known that the round trip efficiency of the LAES can be significantly improved by recovering the compression heat in the charging process and cold energy from liquid air in the discharging process. However, little attention is paid on the effect of quantity and quality of the cold and heat energy on the LAES. This paper aims to bridge the gap by performing a sensitivity analysis on the effect of cold and heat energy on the LAES. It is found that the cold energy has a much more effect on the LAES than the heat energy; the cold energy loss leads to a decrease rate of the round trip efficiency, which is ~7 times of that caused by the heat energy loss. In addition, the recovered cold energy from liquid air is insufficient to achieve the maximum liquid air yield in the charging process, and the difference is ~18%, indicating that external cold sources could significantly increase the round trip efficiency. Unlike the cold energy, ~20–45% of the compression heat cannot be used efficiently in the discharging process, which could be used to increase the round trip efficiency of the LAES. We propose the use of the excess heat to drive an Organic Rankine Cycle (ORC) for power generation. Two configurations of LAES-ORC and LAES-ORC-ARC are considered. In the LAES-ORC configuration, the working fluid in the ORC is cooled by the ambient, while in the LAES-ORC-ARC configuration, it is cooled by a low-temperature cold source obtained through an Absorption Refrigeration Cycle (ARC) using part of the excess heat. Thermodynamic analyses are performed on the two configurations, and comparisons are made among the LAES, LAES-ORC and the LAES-ORC-ARC with different charging and discharging parameters.

## 2. The integration of Liquid Air Energy Storage with Organic Rankine Cycle

### 2.1. System description

The basic principle of the LAES is shown in Fig. 1, which consists of a charging cycle and a discharging cycle. The charging cycle runs at off-peak times: the purified air is compressed to a high pressure through multistage compression with compression heat recovered and stored with thermal oil; the compressed air is then cooled in a cold box by recycling air and cold fluids (propane and methanol) containing cold recovered from liquid air in the discharging cycle; finally, liquid air is obtained through air expansion in a cryo-turbine and stored in a liquid air tank at approximately 77 K. The discharging cycle works at peak times: the liquid air flowing from the tank is pumped to a high pressure, and then releases cold energy to the cold fluids (propane and methanol) in two evaporators, which are later used to cool the compressed air in the charging cycle; the air is then heated by the hot thermal oil containing heat recovered in the charging cycle before entering air turbines to generate electricity.

Our analyses found that the amount of cold energy recovered in the discharging cycle is not enough to fully cool the compressed air in the charging cycle (see details in Section 3.1.3), whereas the compression heat generated in the charging cycle is in excess and cannot be used efficiently in the discharging cycle (see details in Section 3.1.4). To make full use of the excess heat for generating power, two configurations are considered. The first configuration, denoted as LAES-ORC, is shown in Fig. 2; all the excess heat is used to heat the working medium in the Organic Rankine Cycle (ORC), which is then cooled down by ambient cooling water at 293 K. The second configuration, denoted as LAES-ORC-ARC, is shown in Fig. 3; the excess heat is split into two streams: one is to heat the working medium in the ORC, and the other drives Absorption Refrigeration Cycles (ARC), with $NH_3$-$H_2O$ as the working medium, to generate low-temperature cold sources for cooling the working medium in the ORC. Here, several ARCs in serial are