CHEMICAL ENGINEERING TRANSACTIONS
VOL. 81, 2020
A publication of AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Petar S. Varbanov, Qiuwang Wang, Min Zeng, Panos Seferlis, Ting Ma, Jiří J. Klemeš

**ISBN** 978-88-95608-79-2; **ISSN** 2283-9216
DOI: 10.3303/CET2081010

# Multi-component Fluid Cycles in Liquid Air Energy Storage

Zhongxuan Liu, Donghoi Kim, Truls Gundersen*

Department of Energy and Process Engineering, Norwegian University of Science and Technology, Kolbjoern Hejes v. 1A,
NO-7491 Trondheim, Norway
truls.gundersen@ntnu.no

With the penetration of renewable energy sources into the energy market, an emerging problem is the energy stability during energy supply and delivery. Energy storage technologies have the ability to overcome the intermittent nature of energy sources (such as wind and solar energy) and respond to unexpected situations like power failure. Liquid air energy storage (LAES) achieves good round-trip efficiencies by using hot and cold energy storages for heat transfer between the charging and discharging operations. In this work, the LAES technology has been studied and multi-component fluid cycles (MCFCs) are considered for the first time to replace the previously suggested single-component fluids in the cold thermal energy storage cycles to increase the performance of the cold cycles. Two case studies related to single MCFC and dual MCFC are simulated, optimized and compared. The optimal composition for the multi-component fluids is determined by using a particle swarm optimization (PSO) method. The objective function is to maximize the round-trip efficiency of the process. The results indicate that the LAES process with dual MCFC is superior to the case with single MCFC in terms of liquid yield (95.1 % vs. 87.1 %), exergy efficiency (86.1 % vs. 82.4 % for charging and 85.5 % vs. 78.5 % for discharging) and round-trip efficiency (61.8 % vs. 53.9 %).

## 1. Introduction

Over the past 5-10 years, the share of renewables in global power generation has accelerated recently. The global growth was 14 % in 2018, compared to 8.4 % in 2017 and 4.6 % in 2012 (British Petroleum, 2019). Among new renewable energies, the most frequently used for power generation are solar and wind energy. However, the intermittent nature of these energy forms leads to a mismatch between the renewable power supply and the demand from the grid. A large amount of renewable power is wasted rather than utilized by end users in the energy network. Energy storage technologies could be the interface between renewable energy and the grid to balance the unpredictable power supply and demand (Rozali et al., 2013).

Another promising application for energy storage technologies is in distributed energy systems (DES), where energy conversion units are situated close to energy consumers within a small-scale system, compared to the traditional centralized fossil fuel-based system. The advantages of adopting such systems are mainly flexibility and locality. The flexibility is related to their ability to utilize various energy storage technologies and energy sources and provide different forms of energy depending on demands. The locality is related to the use of available local sources and networks (Alanne and Saari, 2006). The DES represents a new trend for energy systems where energy storage technologies are crucial, since they can guarantee the transition from traditional centralized to decentralized energy systems where renewable energy can be used without limitation.

Among various energy storage technologies, liquid air energy storage (LAES), which can also be called cryogenic energy storage (CES), has outstanding performance compared to other technologies. The excess energy is stored in liquid air, which has a higher energy density than the water that is the working fluid in pumped hydroelectric energy storage (PHES) and the air that is the working fluid in compressed air energy storage (CAES). The volume of storage tanks is considerably reduced, and the application of LAES avoids the geographical requirements of PHES and CAES. The LAES could be integrated with other energy conversion processes, and the storage system will benefit from the ideas of existing gas liquefaction processes and air separation units.

Paper Received: 31/03/2020; Revised: 24/04/2020; Accepted: 25/04/2020
Please cite this article as: Liu Z., Kim D., Gundersen T., 2020, Multi-component Fluid Cycles in Liquid Air Energy Storage, Chemical Engineering Transactions, 81, 55-60 DOI:10.3303/CET2081010

The round-trip efficiency is the most important parameter for evaluating energy storage technologies, which reveals the potential effective energy that can be recovered from such technologies. So far, the largest existing scale for the LAES is a pilot plant that was built in the UK (Highview Power, 2019) with 15 MWh (54 GJ) storage capacity and a round-trip efficiency of 60 %. Guizzi et al. (2015) studied an LAES process with storage of the heat from adiabatic compression and the cold thermal energy from regasification. A round-trip efficiency of 54.4 % was obtained with reasonable design parameters. Ameel et al. (2013) proposed a process using a Rankine Cycle to expand liquid air with a round-trip efficiency for the overall system of 43 %. Morgan et al. (2015) tried to improve the efficiency of the process by adding a Claude cycle in the low-temperature heat exchanger, and the round-trip efficiency was improved to 57 %. Li et al. (2014) integrated the LAES process with a nuclear power plant (NPP) to utilize the excess heat in the NPP, which further increased the temperature of air and a round-trip efficiency of 70 % could be reached. Antonelli et al. (2017) considered and compared different cases: a standalone LAES, an LAES integrated with additional combustion heat, and an LAES integrated both with additional combustion heat and an Organic Rankine Cycle (ORC) or a Brayton Cycle. The highest round-trip efficiency of 90 % was obtained in the last case (Brayton Cycle). Lee et al. (2017) studied the integration of an LAES with liquefied natural gas (LNG). The air was liquified by the cold thermal energy of the LNG regasification, and the electricity came from the expansion of natural gas and air. Good performance for the charging and discharging processes is achieved, and the corresponding values for the exergy efficiencies are 94.2 % and 61.1 %. Lee and You (2019) performed a similar study, where cold energy from LNG regasification is used to support air liquefaction in the LAES. In this case, direct expansion was used for the LNG to produce power, and an ORC with a multi-component working fluid was used to produce additional power. The overall exergy efficiency of the process was 70.31 %. Peng et al. (2018) found that about 20-45 % of the compression heat in the LAES could not be used in the discharging process, and an ORC and an ORC-Absorption Refrigeration Cycle (ARC) were proposed to make the most of this heat. The results showed that the LAES-ORC process has a higher round-trip efficiency with a simpler layout than the LAES-ORC-ARC.

Most of the publications try to improve the performance of the LAES by integrating with additional waste thermal energy sources (both hot and cold). However, for a standalone LAES process as described by Guizzi et al. (2015), it can be observed that the round-trip efficiency of the process has increased a lot due to the hot and cold thermal energy storages. In the hot storage cycle, thermal oil is chosen as the working fluid to transfer the compression heat in the charging process to the expansion part in the discharging process. The temperature difference between the air and the thermal oil is evenly distributed within the temperature range of the heat exchanger, since no phase change takes place. The situation is, however, different for the cold thermal energy storage cycles, consisting of two pure fluid cycles using methanol and propane. The cold storage cycles are used to collect the cold duty of the regasification of liquid air in the discharging process and release it to the liquefaction part in the charging process. Because of the phase change of air, the operating pressure for liquefying air is generally larger than the critical pressure of air (37.8 bar), so that a smooth liquefaction curve is obtained at lower temperatures. This makes it easier to find a working fluid to match with the liquefaction curve of air. The performance of the methanol cycle and propane cycle is acceptable (they are both in liquid form, so only sensible heat is used), but still contributes large exergy losses in the process related to the irreversibilities caused by large temperature differences in the heat exchangers. In order to increase the efficiency of the process, other cold cycles or fluids should be considered. Among a large number of proposals, multi-component fluid cycles (MCFCs) can be a promising alternative. The MCFC is superior to single-component fluid cycles because it is able to provide a wider range of temperature profiles, and a better match between the hot and cold composite curves is obtained. The performance of the LAES will be improved due to the reduction of exergy losses in the cold box. In this work, multi-component fluid cycles are used for the first time to transfer the cold thermal energy of regasification to the liquefaction of air. A particle swarm optimization (PSO) method is adopted to find the optimal composition of the multi-component fluids. Two case studies related to a single MCFC and dual MCFC applied in the LAES process are simulated, optimized and compared in Section 5.

## 2. Process description

The process flow diagram of the liquid air energy storage process is shown in Figure 1. The LAES process has three distinct parts: charging process, storage, and discharging process. In the charging process, air is first compressed in stages, then air passes through heat exchangers in the cold box, before being expanded to atmospheric pressure by a cryo-turbine that is used to generate refrigeration capacity and power. Essentially, the charging process is a liquefaction process, where excess energy is utilized to liquefy air. Energy (or power) is stored in the form of liquid air. In the storage part, liquid air is stored in cryogenic tanks at nearly atmospheric pressure. In the discharging process, liquid air is pumped to high pressure before being evaporated by transferring heat to the fluids of the cold thermal energy storages. High-pressure air is then sent to a series of expanders to generate electricity. In order to obtain a higher round-trip efficiency, the heat of compression is used to heat the inlet air of the expanders and produce more electricity.

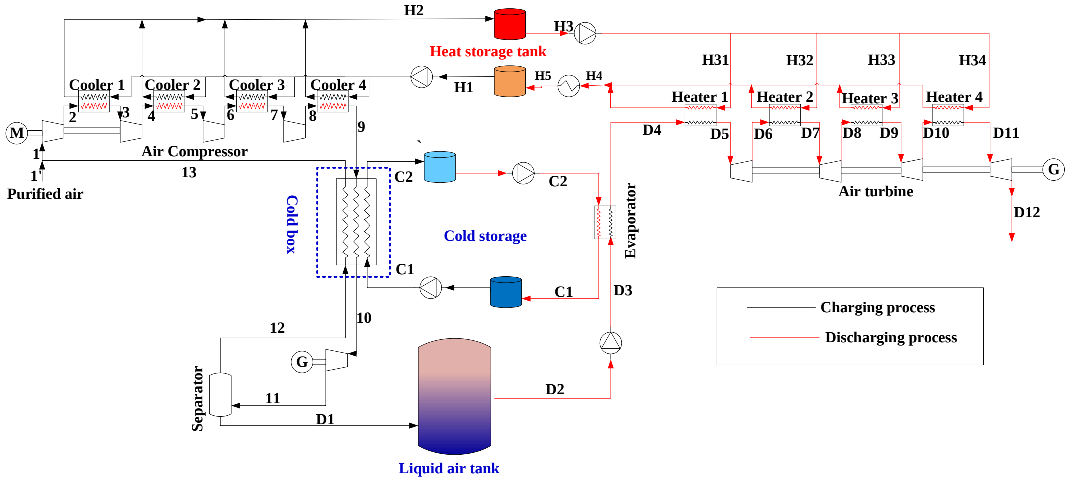

*Figure 1: Flow diagram for the liquid air energy storage process*

Thermal oil is chosen as the working fluid in the hot storage cycle. The cold thermal energy of regasification is stored in cold fluids and will be released to the liquefaction part to increase the efficiency of the overall system. In this work, fluids consisting of certain components (nitrogen, methane, ethane, propane and n-butane) are selected for the cold storage cycles. Although somewhat arbitrarily, the components are selected to cover the temperature ranges of air liquefaction and regasification. The isobaric heat capacities of these five components are similar to the heat capacity of air for relevant pressure conditions. Since the cold storage fluids must remain in liquid form throughout, boiling and freezing points of components have also been considered in the selection process.

## 3. Methodology

### 3.1 Process modeling

The LAES process was modeled in Aspen HYSYS (Aspen Technology, 2017). The Peng-Robinson equation of state has been used to obtain relevant physical properties. The air feed contains 78.82 mole%, nitrogen, 21.14 mole% oxygen and 0.04 mole% argon, with a mass flow rate of 2,000 kg/h at 20 °C and atmospheric pressure. The air is compressed in a 4-stage compressor with intercoolers where the air is cooled down to 30 °C. The high-pressure air is then further liquefied by the fluids of the cycles in the cold storage. In this work, two cases related to single MCFC and dual MCFC are studied. The results of the case studies will be described in more detail in Section 5. Some assumptions are made in case studies:

- Pressure drops and heat losses in heat exchangers, storage tanks and the flash tank are neglected.
- The LNG module in Aspen HYSYS has been used to model all heat exchangers.
- All storage tanks are at atmospheric pressure.
- Isentropic efficiencies of 85 % for compressors and 90 % for expanders are assumed, while the cryo-turbine has an assumed efficiency of 75 %.

### 3.2 Process evaluation

Certain key performance indicators are used to evaluate the LAES process. These are liquid yield, round-trip efficiency and exergy efficiency. Liquid yield is defined in Eq(1).

$$\eta_{LA} = \frac{m_{liq}}{m_{comp}} \tag{1}$$

$m_{liq}$ and $m_{comp}$ denote the mass flow rate of liquid air and the total mass flow rate of air entering the compressors. Once the liquid yield is known, the recirculation ratio could be obtained as well. A higher liquid yield is preferred, which means that less compression work is needed because less air is compressed twice.

The round-trip efficiency can be expressed by Eq(2).

$$\eta_{RT} = \frac{W_{out}}{W_{in}} = \frac{m_{liq} w_T}{m_{comp} w_C} = \eta_{LA} \cdot \frac{w_T}{w_C} \tag{2}$$

$W_{out}$ and $W_{in}$ are the work generated by expanders in the discharging process and the work consumed by compressors in the charging process. $w_C$ and $w_T$ represent the specific work of compressors and expanders.
Thermodynamic performance of the LAES process can also be evaluated by using exergy efficiency. Exergy measures the quality of different energy forms such as work and heat in a consistent way. The exergy of material streams consists of physical (or thermo-mechanical) exergy and chemical exergy. Physical exergy is the maximum work generated when the process stream is taken from its initial temperature and pressure to environment conditions by ideal processes. Chemical exergy is the maximum work generated when the stream is taken to a state with the same composition as its natural surroundings, again by ideal processes. Since no chemical reactions are involved in the LAES process, chemical exergy can be neglected in this work.
In this work, exergy efficiency is measured by the exergy transfer effectiveness (ETE). The ETE is defined by identifying the exergy sinks (produced exergy) and exergy sources (consumed exergy) in the process. The ETE was proposed by Marmolejo-Correa and Gundersen (2015) and further developed by Kim and Gundersen (2018) for chemical exergy. The exergy efficiency can then be expressed by using the definition of the ETE as shown in Eq(3).

$$E = ETE = \frac{\sum Exergy\ Sinks}{\sum Exergy\ Sources} \tag{3}$$

The charging process and the discharging process may not work at the same time. As a consequence, the exergy efficiencies of these processes are analyzed separately to reveal the exergy transfer within the process. Otherwise, the exergy efficiency of the total LAES process is close to the round-trip efficiency due to the relatively small physical exergy of exhaust air and air feed. The exergy efficiency of the charging process $E_{ch}$ is given by Eq(4).

$$E_{ch} = \frac{\sum Exergy\ Sinks}{\sum Exergy\ Sources} = \frac{W_{t,ch} + E_{liq} + E_h}{W_{c,ch} + E_c + E_{fa}} \tag{4}$$

$W_{t,ch}$ and $W_{c,ch}$ are the power that is generated by the cryo-turbine and consumed by compressors in the charging process. $E_{liq}$, $E_h$, $E_c$ and $E_{fa}$ represent the physical exergy of the liquid air, the thermal oil (working fluid in the hot storage cycle), the multi-component fluid (working fluid in the cold storage cycle) and the air feed. The exergy of streams was determined by means of a Visual Basic code in the Aspen HYSYS flowsheet simulation (Abdollahi-Demneh et al., 2011) based on the methodology proposed by Kotas (2012). Similar to Eq(4) for the charging process, the exergy of the discharging process $E_{dc}$ is calculated by Eq(5).

$$E_{dc} = \frac{\sum Exergy\ Sinks}{\sum Exergy\ Sources} = \frac{W_{t,dc} + E_c + E_{ea}}{E_{liq} + W_{p,dc} + E_h} \tag{5}$$

$W_{t,dc}$ and $W_{p,dc}$ are the power that is produced by expanders and consumed by the pump in the discharging process. $E_{ea}$ is the physical exergy of the exhaust air from the last stage expander.

### 3.3 Process optimization

The objective of the optimization is to increase the efficiency of the LAES technology to make it more competitive when it is compared to other technologies. In this work, particle swarm optimization is used, and the objective function is the round-trip efficiency. The pressure ratios and inlet temperatures for compressors and expanders as well as the operating temperatures and pressures of multi-component fluids are selected as decision variables. The molar flow rates for the components of the multi-component fluids are also considered as variables. Minimum temperature differences of 10 K are applied in intercoolers and reheaters, while 1 K is used for low-temperature exchangers (the cold box and the evaporator). This value is commonly adopted in cryogenic processes (Higginbotham et al., 2011). Other constraints are related to the fact that the multi-component fluids should always be liquid during heat transfer, so the vapor fractions of the fluids are fixed to be zero.

## 4. Case studies

### 4.1 Case study 1: Single multi-component fluid cycle

A single multi-component fluid cycle is used to replace the previously suggested methanol cycle and propane cycle, which transfer the cold duty from regasification of liquid air to the liquefaction part. In this case, the initial assumption for the composition of the single MCFC is: 3.16 mole% nitrogen, 9.16 mole% methane, 7.66 mole% ethane and 80.02 mole% propane. The other variables mentioned in Section 3.3 are determined to meet the constraints.

### 4.2 Case study 2: Dual multi-component fluid cycle

Two multi-component fluid cycles are adopted in the LAES process. The compositions of the two cycles are different and different from the composition of the single MCFC in case study 1. The initial composition for the first cycle is: 3.85 mole% methane, 3.85 mole% ethane, 51.85 mole% propane and 40.45 mole% n-butane. The second cycle consists of nitrogen, methane, ethane and propane, with initial composition 7.22 mole%, 6.74 mole%,17.39 mole% and 68.65 mole%.

## 5. Results and Discussion

In both case studies, Particle Swarm Optimization (PSO) has been used to optimize the round-trip efficiency, which is used as the Key Performance Indicator for the LAES technology. Table 1 shows round-trip efficiency, liquid yield and exergy efficiency for the two case studies together with values for some of the optimization variables. The round-trip efficiency indicates that dual MCFC (61.75 %) is superior to the single MCFC (53.91 %) when it comes to energy efficiency.

*Table 1: Optimal values for decision variables and key performance indicators for Case study 1 and 2*

| Parameter | | Unit | Case study 1 | | Case study 2 | | | |
|---|---|---|---|---|---|---|---|---|
| Pressure after compressors | | bar | | 340.06 | | 165.77 | | |
| Pressure after pump | | bar | | 137.55 | | 96.60 | | |
| | | | MCFC | | MCFC 1 | | MCFC 2 | |
| Composition | | mole% | Nitrogen | 0.88 | Methane | 0.16 | Nitrogen | 3.86 |
| | | mole% | Methane | 1.19 | Ethane | 1.72 | Methane | 1.71 |
| | | mole% | Ethane | 0.67 | Propane | 53.02 | Ethane | 18.18 |
| | | mole% | Propane | 97.26 | n-Butane | 45.10 | Propane | 76.25 |
| Temperature (lowest) | | °C | MCFC | -185.15 | MCFC 1 | -47.72 | MCFC 2 | -187.05 |
| Pressure | | bar | MCFC | 51.38 | MCFC 1 | 9.59 | MCFC 2 | 23.89 |
| Heat duty of the cold box | | kW | | 207.33 | | 215.66 | | |
| LMTD | | °C | Cold box | 3.06 | Cold box 1 | 2.00 | Cox box 2 | 1.96 |
| Work | Charging | kW | | 488.89 | | 382.80 | | |
| | Discharging | kW | | 263.58 | | 236.38 | | |
| Exergy efficiency | Charging | % | | 82.38 | | 86.12 | | |
| | Discharging | % | | 78.50 | | 85.53 | | |
| Liquid yield | | % | | 87.11 | | 95.06 | | |
| Round trip efficiency | | % | | 53.91 | | 61.75 | | |

Further, by comparing the results from Case studies 1 and 2, it can be seen that considerably higher liquid yield (95.06 % vs. 87.11 %) and slightly larger heat duty in the cold box (215.66 kW vs. 207.33 kW) are obtained with dual MCFC in the LAES process. This leads to less work consumed in the charging process and a better use of cold regasification energy. The LAES process with a single MCFC needs more compression work to compensate for the reduced cold energy from the regasification of air. Apart from that, the exergy efficiencies are improved to 86.12 % in the charging process and 85.53 % in the discharging process. For the single MCFC, the corresponding numbers for exergy efficiency in charging and discharging parts are 82.38 % and 78.50 %. The LAES with dual MCFC is superior to the process with a single MCFC. This is primarily because the driving forces for heat transfer is reduced in the dual MCFC case. This is quantified in Table 1 by the values for the logarithmic mean temperature differences (LMTDs) between the hot and cold composite curves in the cold box that are smaller for the dual MCFC (2.00 °C and 1.96 °C for cold box 1 and 2) compared to the single MCFC (3.06 °C). This results in reduced exergy losses and a higher round-trip efficiency for the dual MCFC. In all cases, the optimization was carried out with a specification for heat exchangers in the cold box of $\Delta T_{min} = 1$ °C.

## 6. Conclusions

The liquid air energy storage (LAES) process with a single multi-component fluid cycle (MCFC) and dual MCFC are modelled in Aspen HYSYS and optimized by using a particle swarm optimization (PSO) algorithm. The objective is to maximize the round-trip efficiency of the process. By comparing the two cases, the case with dual MCFC in the process is able to liquefy 95 % of the total amount of air, which reduces the recirculation ratio of the process and the compression work in the charging process. The exergy efficiencies are improved to 86.12 % and 85.53 % for the charging and discharging processes, since the temperature differences between the hot and cold composite curves are reduced. A better heat transfer efficiency reduces the irreversibilities in the cold box. The performance of the LAES process with single MCFC is lower than with dual MCFC, but it is still comparable to the LAES with methanol and propane cycles. A single MCFC reduces complexity and capital cost for the LAES. In future work, the single MCFC with different compositions (other components) will be considered, and the LAES process will be attempted further improved and extended to the integration of refrigeration cycles that will influence the recirculation ratio and compression work.

The impact of this research on global pollution reduction can be expressed by the following two key observations: First, the use of energy storage in general, including the use of LAES, is crucial for the transition from fossil fuels to renewable energies. Second, the increase in round-trip efficiency for the LAES will improve the utilization of renewable energy forms. The quantification of these impacts is a very challenging task and beyond the scope of this publication.

### Acknowledgements

This publication has been funded by HighEFF - Centre for an Energy-Efficient and Competitive Industry for the Future. The authors gratefully acknowledge the financial support from the Research Council of Norway and user partners of HighEFF, an 8-years Research Centre under the FME-scheme (Centre for Environment-friendly Energy Research, 257632).

## References

Abdollahi-Demneh F., Moosavian M. A., Omidkhah M. R., Bahnmanyar H., 2011, Calculating exergy in flowsheet simulators: A HYSYS implementation, Energy, 36, 5320-5327.

Alanne K., Saari A., 2006, Distributed energy generation and sustainable development, Renewable Sustainable Energy Reviews, 10(6), 539-558.

Ameel B., T'Joen C., De Kerpel K., De Jaeger P., Huisseune H., Van Belleghem M., De Pape M., 2013, Thermodynamic analysis of energy storage with a liquid air Rankine cycle, Applied Thermal Engineering, 52(1), 130-140.

Antonelli M., Barsali S., Desideri U., Giglioli R., Paganucci F., Pasini G., 2017, Liquid air energy storage: Potential and challenges of hybrid power plants, Applied Energy, 194, 522-529.

Aspen Technology, Inc., 2017, Aspen Plus, V10. 0, Burlington, MA.

British Petroleum, 2019, BP statistical review of world energy report, BP: London, UK.

Guizzi G. L., Manno M., Tolomei L. M., Vitali R. M., 2015, Thermodynamic analysis of a liquid air energy storage system, Energy, 93, 1639-1647.

Higginbotham P., White V., Fogash K., Guvelioglu G., 2011, Oxygen supply for oxyfuel $CO_2$ capture, International Journal of Greenhouse Gas Control, 5 (Suppl.1), S194−S203.

Highview Power, 2019, Benefits, < www.highviewpower.com/technology/ > accessed 29.03.2020.

Kim D., Gundersen T., 2018, Development and use of exergy efficiency for complex cryogenic processes, Energy Conversion and Management, 171, 890-902.

Kotas T. J., 2012, The exergy method of thermal plant analysis, Exergon Publishing Company with Paragon Publishing, London, UK.

Lee I., Park J., Moon I., 2017, Conceptual design and exergy analysis of combined cryogenic energy storage and LNG regasification processes: Cold and power integration, Energy, 140, 106-115.

Lee I., You F., 2019, Systems design and analysis of liquid air energy storage from liquefied natural gas cold energy, Applied Energy, 242, 168-180.

Li Y., Cao H., Wang S., Jin Y., Li D., Wang X., Ding Y., 2014, Load shifting of nuclear power plants using cryogenic energy storage technology, Applied Energy, 113, 1710-1716.

Marmolejo-Correa D., Gundersen T., 2015, A new efficiency parameter for exergy analysis in low temperature processes, International Journal of Exergy, 17(2), 135-170.

Morgan R., Nelmes S., Gibson E., Brett G., 2015, An analysis of a large-scale liquid air energy storage system, Proceedings of the Institution of Civil Engineers - Energy, 168(2), 135-144.

Peng X., She X., Cong L., Zhang T., Li C., Li Y., Wang L., Tong L., Ding Y., 2018, Thermodynamic study on the effect of cold and heat recovery on performance of liquid air energy storage, Applied Energy, 221, 86-99.

Rozali N. E. M., Alwi S. R. W., Manan Z. A., Klemeš J. J., Hassan M. Y., 2013, Optimisation of pumped-hydro storage system for hybrid power system using power pinch analysis, Chemical Engineering Transactions, 35, 85-90.