Applied Energy 251 (2019) 113355

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Flexible integration of liquid air energy storage with liquefied natural gas regasification for power generation enhancement☆

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HIGHLIGHTS

- Liquid Air Energy Storage (LAES) is coupled with LNG regasification for power generation.
- The LAES and LNG regasification work independently thanks to LNG cold storage.
- The proposed system has a high round trip efficiency of ~70% and system exergy efficiency of 57%.
- The round trip efficiency of the standalone LAES is improved by ~56.5%.
- The power generation per unit mass of LNG is above 300 kJ/kg.

ARTICLE INFO

Keywords:
Liquid air energy storage
LNG cold recovery
Flexible integration
Cold storage
Thermodynamic analyses

ABSTRACT

Liquid Air Energy Storage (LAES) is one of the most promising energy storage technologies for achieving low carbon emissions. Our research shows that the LAES produces a considerable amount of excess heat that cannot be cost-effectively utilised in a standalone LAES system. On the other hand, the regasification of liquefied natural gas (LNG) often leads to waste of a large amount of high-grade cold energy. Therefore, this paper proposes the integration of the LAES with the LNG regasification process via a Brayton cycle (denoted as LAES-Brayton-LNG), where pressurized propane is used as both the heat transfer fluid and storage material for the LNG cold energy. The excess heat from the LAES works as the heat source and the waste cold from the LNG regasification as the cold source for the Brayton cycle. Such an integrated LAES-Brayton-LNG system does not need to change the existing LAES system configuration, and the LNG regasification process is independent of the LAES system, thus allowing operation flexibilities. Our analyses show that the flexibly integrated LAES-Brayton-LNG system achieves a system exergy efficiency of 57% and could improve the system exergy efficiency of the standalone LAES system by 14.4%. What's more, it has an electrical round trip efficiency of ~70.6%, which is ~56.5% higher than that of the standalone LAES system. Hence, the proposed LAES-Brayton-LNG system is comparable with other large scale energy storage technologies in terms of the electrical round trip efficiency.

1. Introduction

Global warming due to greenhouse gas emission is beyond doubt given a numerous amount of published evidence including the increasingly more extreme weather, global temperature rise (~0.9 °C), warming oceans and shrinking ice sheets [1]. Clearly, renewable energy holds the key to address the potentially catastrophic disasters. As a result, there has been global effort toward the development and deployment of renewable energy technologies. The global renewable power capacity was doubled from 2007 to 2017, and reached

☆ The short version of the paper was presented at ICAE2018, Aug 22–25, Hong Kong. This paper is a substantial extension of the short version of the conference paper.

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https://doi.org/10.1016/j.apenergy.2019.113355
Received 3 January 2019; Received in revised form 13 May 2019; Accepted 16 May 2019
Available online 27 May 2019
0306-2619/ © 2019 Published by Elsevier Ltd.

~2195 GW by the end of 2017, accounting for ~26.5% of global electricity production [2]. However, the intermittent and fluctuating nature of the renewable energy sources poses a significant challenge to the power networks as a result of supply and demand mismatch. Energy storage provides a solution to meet such a challenge. Numerous energy storage technologies have been developed based on different principles and for different applications [3].

Liquid Air Energy Storage (LAES) is one of the technologies, aiming initially at grid scale storage. The LAES has attracted considerable attention in recent years due to several advantages including high energy storage density [4], no geographical constraints [5], and low capital cost [6]. A substantial amount of research has therefore been carried out on the LAES, including thermodynamic/economic analyses [7–15], system configurations and optimization [16–22], multi-functional LAES [23–24], and the integration with external cold/heat sources [25–30]. A brief summary of the research is given in the following.

For thermodynamic and economic analyses, Morgan et al. [7] presented experimental results of the world's first LAES pilot plant (350 kW/2.5 MWh, originally built in Slough and relocated to the University of Birmingham campus in 2013). Their data showed a low round trip efficiency of 8%, mainly due to the small plant size and without recovery and reuse of the compression heat. Guizzi et al. [8] performed a thermodynamic analysis on the LAES with both compression heat and cold storage. Their results showed a round trip efficiency of ~50%. Sciacovelli et al. [10] studied the dynamic performance of a LAES system with a packed bed cold store and a thermal oil based heat store. They showed that the capture and recycle of the cold from the discharge process could reduce the energy consumption of the air liquefaction by ~25%. Peng et al. [11] modeled a LAES system using propane/methanol for cold storage and packed beds for heat storage, and found a round trip efficiency of the LAES between 50 and 62%. She et al. [12] analysed the effects of liquid air storage tank and heat transfer on the performance of the LAES, and concluded liquid air storage tank played a very important role. Peng et al. [13] showed how the cold and heat storage in the LAES affected system performance. They found that the cold energy loss was more detrimental to the system performance than the heat energy loss. Yu et al. [14] examined the effect of heat exchange performance of the LAES evaporator and achieved an optimal operation of the evaporator. Xie et al. [15] assessed the economic feasibility of adopting the LAES technology in the UK. They found a payback period varying from 5.6 to 25.7 years for a 200 MW system.

In terms of system configurations and optimization, Morgan et al. [17] replaced the single cold turbine with three turbines in the cold recycle to optimize the air liquefaction process and increased the round trip efficiency from 47% to 57% under the studied conditions. She et al. [18] found that there was a large amount of excess heat of compression in a standalone LAES system and proposed a hybrid LAES configuration, which could improve the round trip efficiency by ~12%. Borri et al. [19] compared the use of Linde, Claude and Kapitza cycles for air liquefaction and concluded that the Kapitza cycle with two-stage compression at 40 bar was an optimal solution. Four-stage compression and four-stage expansion were suggested by He et al. [20] for the LAES system based on the exergy analysis. Hüttermann and Span [21] carried out an in-depth study on the effect of thermal storage materials on the performance of cryogenic packed beds in the LAES. Nine kinds of materials were selected and investigated, showing that the temperature-related heat capacity ratio had a significant influence on the heat storage performance.

To achieve multifunctional LAES, Ahmad et al. [23] studied the use of liquid nitrogen to provide both cooling and power for domestic residential houses, and showed it could be 36% more economical than traditional air conditioning systems. Al-Zareer et al. [24] proposed a hybrid LAES system with heating and cooling functions and indicated that an overall energy efficiency of 72.1% and an exergy efficiency of 53.7% could be achieved.

Both external cold and heat sources could significantly improve the LAES performance. This is because the external heat sources could increase the temperature of the working fluid before entering turbines to generate more power [25–26], whereas the external cold sources could reduce energy consumption of air liquefaction [27–30]. Antonelli et al. [25] investigated the use of combustion heat of methane as an external heat source for the LAES. They showed an equivalent round trip efficiency higher than 80%. Li et al. [26] proposed the integration of nuclear power plants with LAES and showed a round trip efficiency of ~70% achievable. Liquefied natural gas (LNG) releases a massive amount of cold energy (~830 kJ/kg) during the regasification process in the LNG terminals, which is usually wasted by sea water. Therefore, the LNG cold energy has been recommended for different applications [31]. One of the most popular methods is to use LNG cold energy to generate electricity through power cycles, such as the organic Rankine cycle [32], Brayton cycle [33], combined cycle [34], and the thermoacoustic Stirling cycle [35]. The application of LNG cold energy in the LAES system has also been studied. Lee et al. [27] studied the use of LNG cold energy for liquid air production. Their results showed that, even though the round trip efficiency was high, the power generation per unit mass of LNG was only 160.9 kJ/kg as a large amount of LNG cold energy was wasted. To address this issue, Lee and You et al. [28] suggested utilizing the remaining LNG cold energy to drive an organic Rankine cycle to produce electricity for covering the power consumption of air compressors. Kim et al. [29] studied the use of LNG cold energy to assist air liquefaction and combustion heat of methane for heating the air before entering turbines. It showed a round trip efficiency of ~73.4%. Zhang et al. [30] proposed and analysed an integrated LAES system with LNG cold energy for air liquefaction and an external heat source above 100 °C for enhancing power generation. Their results showed that the system could achieve a round trip efficiency of ~72%.

The above literature review suggested a clear benefit in the integration of the LAES system with the LNG regasification process. However, research on such an integration is very limited. Of the limited studies, all of the LAES-LNG integration requires the change of the current LAES configuration and also an external heat source, which is quite challenging and often impossible. In addition, since there is no cold storage for the LNG cold energy in these studies, the LNG regasification process has to work synchronously with the LAES system. This is again less practicable as the LNG regasification process may start at any time as long as there is a demand of natural gas. Here, this paper, for the first time, proposes the integration of the LAES system with the LNG regasification process through a Brayton cycle (denoted as LAES-Brayton-LNG), where the LNG cold energy is stored in pressurized propane. The excess heat of compression in the LAES system works as the heat source and LNG cold energy as the cold source for the Brayton cycle. The proposed LAES-Brayton-LNG system needs neither external heat sources nor changes to the current LAES configuration. More importantly, the LAES system and the LNG regasification process work independently thanks to the cold storage, which provides high operation flexibility. The LAES-Brayton-LNG system is analysed and optimized with different operation parameters, and it shows that a high round trip efficiency above 70% can be achieved, making the LAES comparable with other large-scale energy storage technologies in terms of the round trip efficiency.

2. The proposed novel LAES-Brayton-LNG system

In a standalone LAES system, ambient air, upon purification, is compressed with the compression heat captured and stored for later use in the power recovery process. In our recent study, it suggested that the stored compression heat cannot be fully used in a cost-effective manner in the power generation process. The main reason is that the liquid air yield never reaches 1.0, resulting in a large amount of excess heat. The amount of excess heat per MWh power consumption of air compression

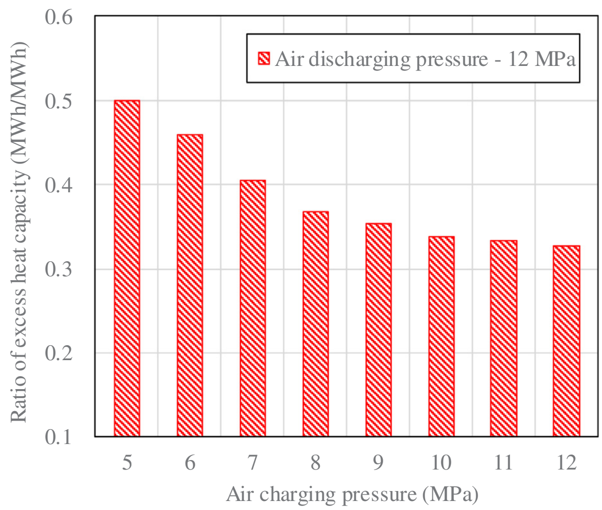

Fig. 1. The ratio of excess heat capacity to power consumption of air compressors in the LAES with different charging pressures.

is calculated with a reference temperature of 25 °C, as shown in Fig. 1. One can see a considerable decrease in the ratio of the excess heat to the power consumption of air compression from ∼0.5 to ∼0.37 as the charging pressure increases from 5 to 8 MPa. This is followed by a slow decrease with a further increase in the air charging pressure. At a charging pressure of 12 MPa, the ratio of the excess heat to the power consumption of air compressison is 0.33. Clearly, the higher the air charging pressure, the lower the relative excess heat of compression. On the other hand, in a typical LNG terminal, LNG is usually compressed to the transportation pressure or even higher before passing the cold energy to sea water, and then transported to users through pipelines. The cold energy has a temperature of ∼ −162 °C and is of a very high grade. The integrated use of the compression heat and the LNG cold energy has a clear synergy, which will be discussed in the following sub-sections.

2.1. The configuration of the LAES-Brayton-LNG system

Fig. 2 shows a schematic diagram of the LAES-Brayton-LNG system, which mainly consists of an air charging cycle (air liquefaction), air discharging cycle (power generation), Brayton cycle and a LNG cycle (LNG regasification).

The air charging cycle works at off-peak times to produce liquid air with off-peak electricity or renewables. Firstly, the purified air (State 2) is compressed to a high pressure (State 8) by a multi-stage air compressor with the heat of compression stored with thermal oil in the thermal oil storage tank. The high pressure air is cooled down in the HE #1 by cold methanol (State 20) and return air, and then is further cooled down to a low temperature (State 10) in the HE #2 by cold propane (State 22) and return air; the cold energy of propane and methanol is captured and stored from liquid air in the air discharging cycle. Finally, the high pressure air expands in a cryo-turbine with part of the air liquefied and stored in the liquid air tank. The unliquefied air (i.e. return air) goes through the HE #2 and HE #1 to cool down the compressed air.

The LNG cycle is independent of the LAES and works at any time (off-peak or peak times) to supply natural gas for users. Firstly, the LNG (State 43) is pumped to a high pressure (State 44) by a cryo-pump. The high pressure LNG then transfers cold energy to pressurized propane via the evaporator. The cold energy is stored in a pressurized propane storage tank for later use in the Brayton cycle. The high pressure natural gas (State 45) is further heated by the ambient heater, before expanding to a desired transportation pressure in a LNG turbine.

The air discharging cycle and Brayton cycle work together at peak times to generate peak electricity. In the air discharging cycle, the liquid air (State 24) is pumped to a high pressure (State 25), transfers the cold energy to propane and methanol in turn, before being heated up by part of the compression heat stored in the thermal oil storage tank and entering the multi-stage air turbine to generate electricity. In the Brayton cycle, the working fluid at the outlet of the Brayton turbine (State 42) is cooled down to a low temperature (State 38) by the LNG cold energy stored in the pressurized propane storage tank. It is then compressed by the Brayton compressor and heated by the ambient heater. Finally, it is further heated to a high temperature (State 41) by the remaining excess compression heat stored in the thermal oil storage tank before entering the Brayton turbine to generate electricity.

2.2. Selection of working fluids

In the air charging cycle, compression heat (∼200 °C) is recovered and stored with Dowtherm G, which is a widely-used thermal oil for heat recovery due to its good heat transfer performance and a wide temperature range. In the air discharging cycle, propane and methanol are selected as both heat transfer fluids and storage materials for cascade recovery and storage of liquid air cold energy. It is because liquid air has an extremely low temperature of 79 K and there is no single fluid that can work in such a wide temperature range of 79–293 K to recover the liquid air cold energy.

To recover the LNG cold energy, pressurized propane is selected both as a heat transfer fluid and a storage medium. The main reason for using this working fluid is that no liquid has been found to be able to work over a wide temperature range from −162 to 20 °C at the ambient pressure. Fig. 3 shows the temperature range of liquid propane at different working pressures. One can see that a higher working pressure of the propane gives a wider working temperature range; at a working pressure over 8 bar, the working temperature range is sufficient for recovering and storing the LNG cold energy. As a result, pressurized propane at a pressure of 10 bar is applied for the LNG cold energy recovery.

In the Brayton cycle, there are two popular working fluids for low temperature applications: nitrogen and argon, which have a lower triple point temperature than that of the natural gas, and are non-flammable, non-toxic and stable. Fig. 4 compares the power generation per unit mass of LNG in the Brayton cycle with nitrogen and argon as working media. In the figure, the heat source temperature is set as ∼200 °C based on the excess heat temperature in the LAES, liquid LNG is assumed to be compressed to 10 MPa, and the inlet and outlet pressures of the Brayton cycle turbine are taken in such a way that gives the maximum power generation. One can see that the Brayton cycle with nitrogen as the working medium has the maximum power generation of ∼ 225 kJ/kg, which is much higher than that with argon as the working medium (∼150 kJ/kg). Therefore, in the following analyses, nitrogen is used as the working medium in the Brayton cycle.

3. Thermodynamic model

In the air charging cycle, the off-peak electricity or renewables are used to drive the multi-stage air compressor. The power consumption for this process, $W_{air,com}$, is calculated by:

$$W_{air,com} = m_{air,ch}\cdot((h_3 - h_2) + (h_5 - h_4) + (h_7 - h_6)) \tag{1}$$

$$h_{i+1} = h_i + \frac{h_{i+1,s} - h_i}{\eta_{air,com}} \tag{2}$$

where $m_{air,ch}$ is the air mass flow rate in the air charging cycle; h is the specific enthalpy; $\eta_{air,com}$ is the isentropic efficiency of the multi-stage air compressor; subscript s represents an ideal isentropic process; and subscript i = 2, 4 and 6 represents the states.

The compressed air leaving the multi-stage air compressor (State 8) is cooled down via the HE #1 and HE #2, which follows the energy conservation with a pinch point limitation. Then, it enters the cryo-

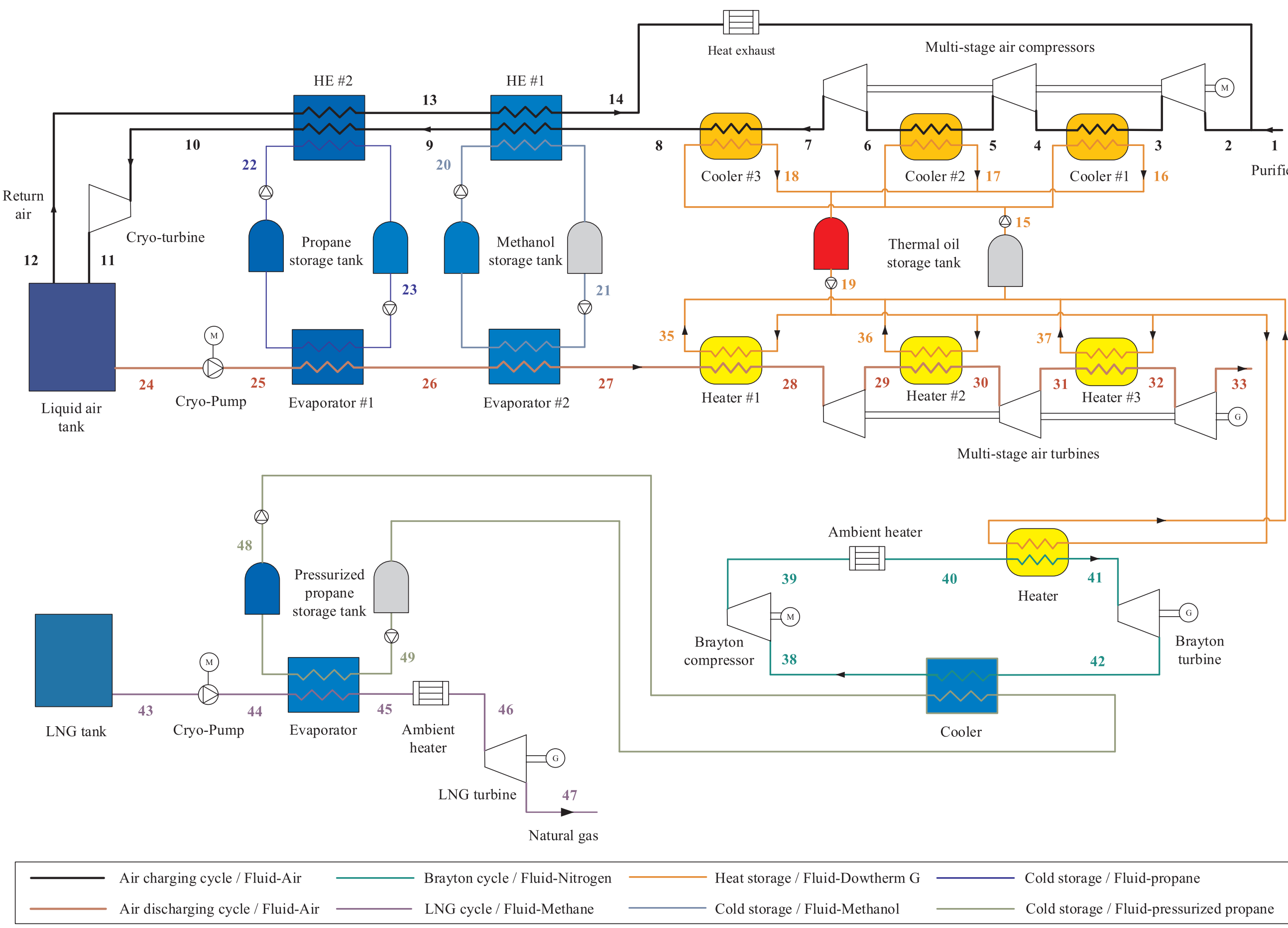

Fig. 2. A schematic diagram of the LAES-Brayton-LNG system.

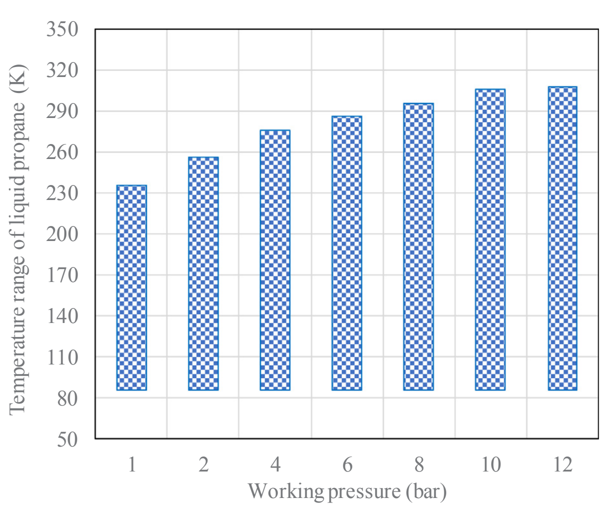

Fig. 3. Temperature range of liquid propane with different working pressures.

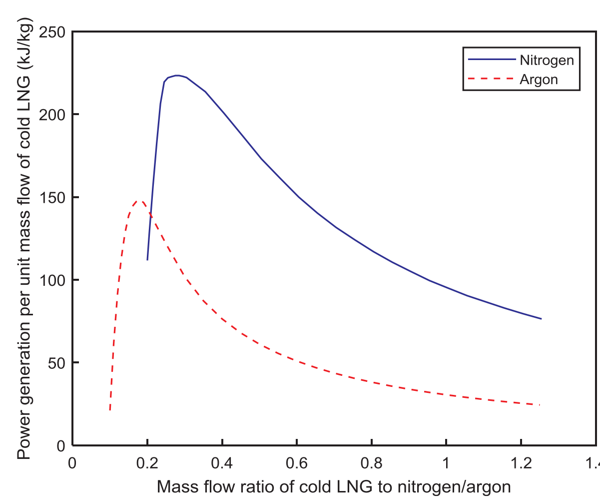

Fig. 4. Comparison of nitrogen with argon as a working medium for the Brayton cycle.

turbine to generate electricity. The amount of power generation, $W_{air,cry\text{-}tur}$, is given by:

$$W_{air,cry-tur} = m_{air,ch}\cdot(h_{10} - h_{11}) \tag{3}$$

$$h_{11} = h_{10} - \eta_{cry-tur}\cdot(h_{10} - h_{11,s}) \tag{4}$$

where $\eta_{cry\text{-}tur}$ is the isentropic efficiency of the cryo-turbine. The net power consumption ($W_{air,in}$) and liquid air yield (Y) in the air charging cycle are therefore calculated as follows:

$$W_{air,in} = W_{air,com} - W_{air,cry-tur} \tag{5}$$

$$Y = \frac{m_{air,ch} - m_{12}}{m_{air,ch}} \tag{6}$$

where m_{12} is the mass flow rate of non-liquified air (i.e. return air).

In the air discharging cycle, the cryo-pump is used to pressurize liquid air to a high pressure. The power consumption of the cryo-pump, $W_{air,cry\text{-}pump}$, is given by:

$$W_{air,cry-pump} = m_{air,dis}\cdot(h_{25} - h_{24}) \quad (7)$$

$$h_{25} = h_{24} + \frac{h_{25,s} - h_{24}}{\eta_{cry-pump}} \quad (8)$$

where $m_{air,dis}$ is the air mass flow rate in the air discharging cycle; $\eta_{cry\text{-}pump}$ is the isentropic efficiency of the cryo-pump. The compressed air (State 27) is heated by the hot thermal oil before expansion in the multi-stage air turbine to generate electricity. The amount of power generation, $W_{air,tur}$, is calculated by:

$$W_{air,tur} = m_{air,dis}\cdot((h_{28} - h_{29}) + (h_{30} - h_{31}) + (h_{32} - h_{33})) \quad (9)$$

$$h_{i+1} = h_i - \eta_{air,tur}\cdot(h_i - h_{i+1,s}) \quad (10)$$

where $\eta_{air,tur}$ is the isentropic efficiency of the multi-stage air turbine; the subscript i = 28, 30 and 32 stands for the state. The net power generation, $W_{air,out}$, in the air discharging cycle is therefore given by:

$$W_{air,out} = W_{air,tur} - W_{air,cry-pump} \quad (11)$$

In the Brayton cycle, the working fluid (State 41) is heated first by the excess compression heat carried by the hot thermal oil before expansion in the Brayton turbine to generate electricity. The amount of power generation, $W_{bray,tur}$, is calculated by:

$$W_{bray,tur} = m_{bray}\cdot(h_{41} - h_{42}) \quad (12)$$

$$h_{42} = h_{41} - \eta_{bray,tur}\cdot(h_{41} - h_{42,s}) \quad (13)$$

where m_{bray} is the mass flow rate of the working fluid in the Brayton cycle; $\eta_{bray,tur}$ is the isentropic efficiency of the Brayton turbine. The working fluid (State 38) is then cooled by the cold pressurized propane before compressed to a high pressure by the Brayton compressor. The power consumption, $W_{bray,com}$, is given by:

$$W_{bray,com} = m_{bray}\cdot(h_{39} - h_{38}) \quad (14)$$

$$h_{39} = h_{38} + \frac{h_{39,s} - h_{38}}{\eta_{bray,com}} \quad (15)$$

where $\eta_{bray,com}$ is the isentropic efficiency of the Brayton compressor. The net power generation of the Brayton cycle, $W_{bray,out}$, is therefore calculated by:

$$W_{bray,out} = W_{bray,tur} - W_{bray,com} \quad (16)$$

In the LNG cycle, the LNG (State 43) is pumped to a high pressure, and the amount of power consumption, $W_{LNG,cry\text{-}pump}$, is given by:

$$W_{LNG,cry-pump} = m_{LNG}\cdot(h_{44} - h_{43}) \quad (17)$$

$$h_{44} = h_{43} + \frac{h_{44,s} - h_{43}}{\eta_{cry-pump}} \quad (18)$$

where m_{LNG} is the LNG mass flow rate in the LNG cycle. The LNG (State 46) transfers cold energy to the pressurized propane before expanding in the LNG turbine. The amount of power generation in this step, $W_{LNG,tur}$, is:

$$W_{LNG,tur} = m_{LNG}\cdot(h_{46} - h_{47}) \quad (19)$$

$$h_{47} = h_{46} - \eta_{LNG,tur}\cdot(h_{46} - h_{47,s}) \quad (20)$$

where $\eta_{LNG,tur}$ is the isentropic efficiency of the LNG turbine.

3.1. Round trip efficiency

The standalone LAES system only includes the air charging and discharging cycles. Therefore, the round trip efficiency, $\eta_{RTE,LAES\text{-}alone}$, is defined as:

$$\eta_{RTE,LAES-alone} = \frac{W_{air,out}\cdot t_{dis}}{W_{air,in}\cdot t_{ch}} \quad (21)$$

where t_{ch} and t_{dis} are the air charging and discharging time, respectively.

For the LAES-Brayton-LNG system, the Brayton cycle and the air discharging cycle work synchronously at peak times to generate electricity. As a consequence, the round trip efficiency of the LAES-Brayton-LNG, $\eta_{RTE,LAES\text{-}hybrid}$, is defined as:

$$\eta_{RTE,LAES-hybrid} = \frac{(W_{air,out} + W_{bray,out})\cdot t_{dis}}{W_{air,in}\cdot t_{ch}} \quad (22)$$

The improvement of round trip efficiency is calculated by:

$$\eta_{RTE,LAES-imp} = \frac{\eta_{RTE,LAES-hybrid} - \eta_{RTE,LAES-alone}}{\eta_{RTE,LAES-alone}} \quad (23)$$

3.2. System exergy efficiency

For the standalone LAES system, the input exergy is off-peak electricity consumed by the air charging cycle and output exergy is peak electricity generated by the air discharging cycle. Therefore, the system exergy efficiency is same as the round trip efficiency:

$$\eta_{exergy,LAES-alone} = \frac{W_{air,out}\cdot t_{dis}}{W_{air,in}\cdot t_{ch}} \quad (24)$$

For the LAES-Brayton-LNG system, the input exergy includes off-peak electricity consumed by the air charging cycle and LNG cold energy; output exergy is peak electricity produced by the air discharging cycle and Brayton cycle. Hence, the system exergy efficiency is defined as:

$$\eta_{exergy,LAES-hybrid} = \frac{(W_{air,out} + W_{bray,out})\cdot t_{dis}}{W_{air,in}\cdot t_{ch} + Ex_{LNG}\cdot t_{dis}} \quad (25)$$

$$Ex_{LNG} = m_{LNG}\cdot(e_{44} - e_{45}) \quad (26)$$

where e is specific exergy and Ex_{LNG} is the exergy of LNG cold energy contributing to the power generation.

The improvement of system exergy efficiency is obtained by:

$$\eta_{exergy,LAES-imp} = \frac{\eta_{exergy,LAES-hybrid} - \eta_{exergy,LAES-alone}}{\eta_{exergy,LAES-alone}} \quad (27)$$

3.3. Power generation per unit mass of LNG

To evaluate the performance of the LNG cycle, the net power generation per unit mass of LNG is considered. If direct expansion is used without LNG cold energy recovery (denoted as LNG-expansion), the net power generation of the LNG cycle, $w_{LNG,\exp}$, is given by:

$$w_{LNG,exp} = \frac{W_{LNG,tur} - W_{LNG,cry-pump}}{m_{LNG}} \quad (28)$$

When the LNG cold energy is recovered for the Brayton cycle combined with the excess heat of compression from the LAES (denoted as LNG-Brayton), the net power generation of the LNG cycle, $w_{LNG,bray}$, is:

$$w_{LNG,bray} = \frac{W_{LNG,tur} - W_{LNG,cry-pump} + W_{bray,out}}{m_{LNG}} \quad (29)$$

3.4. Thermal and exergy efficiencies of the Brayton cycle

In the Brayton cycle, the pressurized propane which recovers LNG cold energy works as a cold source and the excess hot thermal oil as a heat source. Therefore, the thermal efficiency ($\eta_{bray,thermal}$) and exergy efficiency ($\eta_{bray,exergy}$) of the Brayton cycle are defined as:

$$\eta_{bray,thermal} = \frac{W_{bray,out}}{m_{oil,excess}\cdot(h_{19} - h_{34}) + m_{p-propane}\cdot(h_{49} - h_{48})} \quad (30)$$

Table 1
Default working parameters of the LAES-Brayton-LNG system.

Ambient temperature T_{amb} (K)	293
Ambient pressure P_{amb} (kPa)	100
Air charging time (h)	8
Air discharging time (h)	8
Air discharging pressure P_{25} (kPa)	12,000
Isentropic efficiency of air, Brayton and LNG turbines	0.9
Isentropic efficiency of air and Brayton compressors	0.89
Isentropic efficiency of the cryo-pump	0.7
Isentropic efficiency of the cryo-turbine	0.8
Pinch point of Heaters, Coolers and HEs (K)	5
Pinch point of Evaporators (K)	2
Relative pressure drop in heat exchangers	1%
Storage temperature of the propane T_{23} (K)	214
Storage temperature of the methanol T_{21} (K)	293
Storage temperature of the thermal oil T_{15} (K)	293
LNG storage pressure T_{43} (kPa)	100
Transportation pressure of natural gas T_{47} (kPa)	7000

$$\eta_{bray,exergy} = \frac{W_{bray,out}}{m_{oil,excess}\cdot(e_{19} - e_{34}) + m_{p-propane}\cdot(e_{48} - e_{49})} \tag{31}$$

where $m_{oil,excess}$ and $m_{p\text{-}propane}$ are the mass flow rates of excess hot thermal oil and pressurized propane, respectively.

4. Results and discussion

To obtain the performance of the LAES-Brayton-LNG system, the following assumptions are made:

- Air consists of nitrogen (78.12%), oxygen (20.96%) and argon (0.92%);
- Nitrogen is chosen as the working fluid in the Brayton cycle;
- LNG contains pure methane;
- Dowtherm G is used as the thermal oil for recovering and storing the heat of compression;
- Propane and methanol are used to store the cold energy of liquid air;
- Pressurized propane is used to store the LNG cold energy.

Table 1 shows the parameters of the LAES-Brayton-LNG system. The default values are given as follows unless otherwise specified:

- The air charging pressure is 12 MPa;
- The inlet and outlet pressures of the Brayton turbine are 12 MPa and 2 MPa, respectively;
- The storage temperature of the pressurized propane (T_{49}) is 253 K;
- The inlet pressure of the LNG turbine is 12 MPa;
- The air discharging pressure is set at 12 MPa, considering a trade-off between power generation per unit mass of liquid air and mechanical requirements on the air turbines;
- The transportation pressure of natural gas is set as 7 MPa, which is commonly used for long-distance transport.

Matlab is used to calculate the system performance. Table 2 shows the stream parameters of the LAES-Brayton-LNG system with the above default working parameters, and Table 3 shows the performance of the LAES-Brayton-LNG system. The liquid air yield is 0.707, system exergy efficiency is 57%, and the electrical round trip efficiency is 70% which is ~30% higher than that of a large scale standalone LAES system.

4.1. Effects of air charging pressure on the performance of the LAES-Brayton-LNG system

As shown in Fig. 1. the amount of excess heat of compression decreases with increasing air charging pressure in the LAES system. This in turn will affect the performance of the LAES-Brayton-LNG system. Fig. 5(a) shows that the round trip efficiency of the LAES system

Table 2
Stream parameters of the LAES-Brayton-LNG system.

State	Mass flow rate (kg/s)	Pressure (kPa)	Temperature (K)	Fluid
1	1.414	100	293	Air
2	2	100	293	Air
3	2	498	483	Air
4	2	493	305.6	Air
5	2	2454	504	Air
6	2	2430	305.6	Air
7	2	12,097	506.3	Air
8	2	11,976	305.6	Air
9	2	11,856	226.2	Air
10	2	11,738	116.8	Air
11	2	103	79.5	Air
12	0.586	103	81.9	Air
13	0.586	102	221	Air
14	0.586	101	297.5	Air
15	4.17	101	293	Dowtherm G
16	1.39	100	450	Dowtherm G
17	1.39	100	468.3	Dowtherm G
18	1.39	100	482.5	Dowtherm G
19	4.17	101	468.3	Dowtherm G
20	0.82	101	211.8	Methanol
21	0.82	100	293	Methanol
22	1.47	101	88.9	Propane
23	1.47	100	214	Propane
24	1.414	103	79	Air
25	1.414	12,000	84.9	Air
26	1.414	11,880	209.3	Air
27	1.414	11,761	290.7	Air
28	1.414	11,644	462.2	Air
29	1.414	2401	309.1	Air
30	1.414	2377	462.2	Air
31	1.414	490	311.3	Air
32	1.414	485	462.2	Air
33	1.414	100	311.9	Air
34	1.326	100	298.3	Dowtherm G
35	0.948	100	297.2	Dowtherm G
36	0.948	100	331.6	Dowtherm G
37	0.948	100	338.2	Dowtherm G
38	1.936	1980	123.1	Nitrogen
39	1.936	12,000	215.5	Nitrogen
40	1.936	11,880	293	Nitrogen
41	1.936	11,761	463.3	Nitrogen
42	1.936	2000	295.3	Nitrogen
43	0.788	100	111.5	Methane
44	0.788	12,000	118	Methane
45	0.788	11,880	235.1	Methane
46	0.788	11,761	293	Methane
47	0.788	7000	257.6	Methane
48	1.41	1000	120	Pressurized propane
49	1.41	1010	253	Pressurized propane

Table 3
Performance of the LAES-Brayton-LNG system with typical working conditions.

	Air charging cycle	Air discharging cycle	Brayton cycle	LNG cycle
Net Power kW	1155 (−)	620.4 (+)	188 (+)	10.6 (+)
Exergy efficiency	0.852	0.838	0.51	
Thermal efficiency			0.241	
Liquid air yield	0.707			
Electrical round trip efficiency	70% (LAES-Brayton-LNG), 53.7% (standalone LAES)			
System exergy efficiency	57% (LAES-Brayton-LNG), 53.7% (standalone LAES)			

Note: symbols '+' and '−' mean power generation and consumption, respectively.

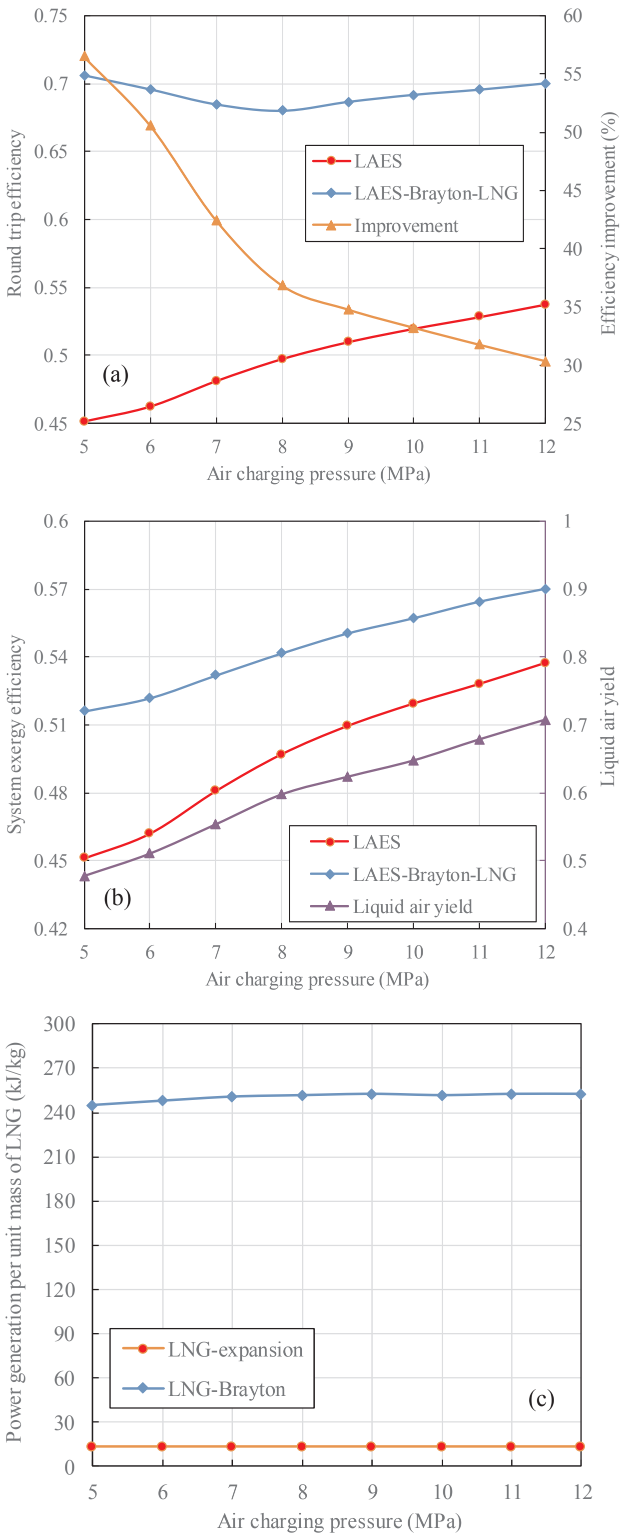

Fig. 5. Effects of air charging pressure on the LAES-Brayton-LNG system performance.

increases considerably from 45.1% to 53.7% when the air charging pressure increases from 5 to 12 MPa. The LAES-Brayton-LNG system has a high round trip efficiency, which can be up to ~56.5% higher than that of the LAES system. With an increase in the air charging pressure from 5 to 12 MPa, the round trip efficiency of the LAES-Brayton-LNG system shows a minimum at ~8 MPa, namely, decreasing first from 70.6% to 68% and then increasing from 68% to 70%. This is because, in the LAES-Brayton-LNG system, power generation comes from both of the air discharging cycle and the Brayton cycle. At a lower charging pressure, the air discharging cycle has lower output power, but there is more excess heat of compression which can be used in the Brayton cycle to generate more power; at a higher charging pressure, the air discharging cycle produces more output power, but there is less excess heat of compression which leads to lower power generation in the Brayton cycle. It should be noted that the LAES-Brayton-LNG system has a high round trip efficiency of ~70.6% at an air charging pressure of ~5 MPa, which is almost the same as that when the air charging pressure is above 10 MPa. Therefore, a low air charging pressure of ~5 MPa is recommended for the LAES-Brayton-LNG system, which has a lower mechanical requirement on the components in the air charging cycle and hence a lower capital cost.

The liquid air yield increases gradually from 0.477 to 0.707 as the air charging pressure increases from 5 to 12 MPa, as shown in Fig. 5(b). This is because a high air charging pressure gives a low air specific heat capacity at low temperatures, allowing the air to be easily cooled down and hence leading to an increased liquid air yield. A higher air charging pressure is also beneficial to the system exergy efficiency of the LAES-Brayton-LNG system, and the maximum of 57% is achieved as the air charging pressure is at 12 MPa. What's more, the LAES-Brayton-LNG system has a higher system exergy efficiency than the LAES system, with the maximum improvement of 14.4% at a low air charging pressure of 5 MPa. This is mainly because there is more excess heat of compression in the LAES system at lower air charging pressures (see Fig. 1), which leads to more power generation by the Brayton cycle and hence contributes to a higher increase of the system exergy efficiency.

Fig. 5(c) shows the amount of power generation per unit mass of LNG in the LNG cycle. For the case of direct expansion without LNG cold recovery (LNG-expansion), the LNG cycle has a low power generation of ~13.4 kJ/kg. When the LNG cold energy is recovered for the Brayton cycle combined with the excess heat of compression (LNG-Brayton), the LNG cycle produces a high power of ~253 kJ/kg, indicating it is a very efficient way for the LNG-Brayton to use the LNG cold energy.

4.2. *Effects of working pressure of the Brayton cycle on the LAES-Brayton-LNG system*

The Brayton cycle contributes a considerable amount of power generation to the LAES-Brayton-LNG system. It is therefore necessary to evaluate the optimum working conditions for the Brayton cycle. Fig. 6 shows how the outlet pressure of the Brayton turbine affects the LAES-Brayton-LNG system performance. As shown in Fig. 6(a), the round trip efficiency of the LAES-Brayton-LNG system shows a maximum value at an outlet pressure of ~2.0–2.5 MPa depending on the storage temperature of pressurized propane. It is because a lower outlet pressure gives more power by the Brayton turbine, but the Brayton compressor also consumes more power. Fig. 6(a) also indicates that the storage temperature of the pressurized propane (T_{49}) has a considerable effect on the round trip efficiency of the LAES-Brayton-LNG system - the lower the storage temperature, the higher the round trip efficiency. This is mainly due to the temperature decrease of the nitrogen after cooled by the pressurized propane in the cooler, leading to less power consumption by the Brayton compressor.

Fig. 6(b) shows the effect of outlet pressure of the Brayton turbine on the power generation per unit mass of LNG. For the LNG-Brayton case, the power generation per unit mass of LNG decreases with the increase of outlet pressure of the Brayton turbine, with a maximum value of 300 kJ/kg and a minimum value of 81 kJ/kg under the present conditions. It can be explained by the fact that, with an increase in the outlet pressure, more cold energy would be needed for the LNG to cool the nitrogen down in the cooler and consequently more consumption of the LNG. For the LNG-expansion case, the amount of power generation is ~13.4 kJ/kg, which is much lower than that of the LNG-Brayton

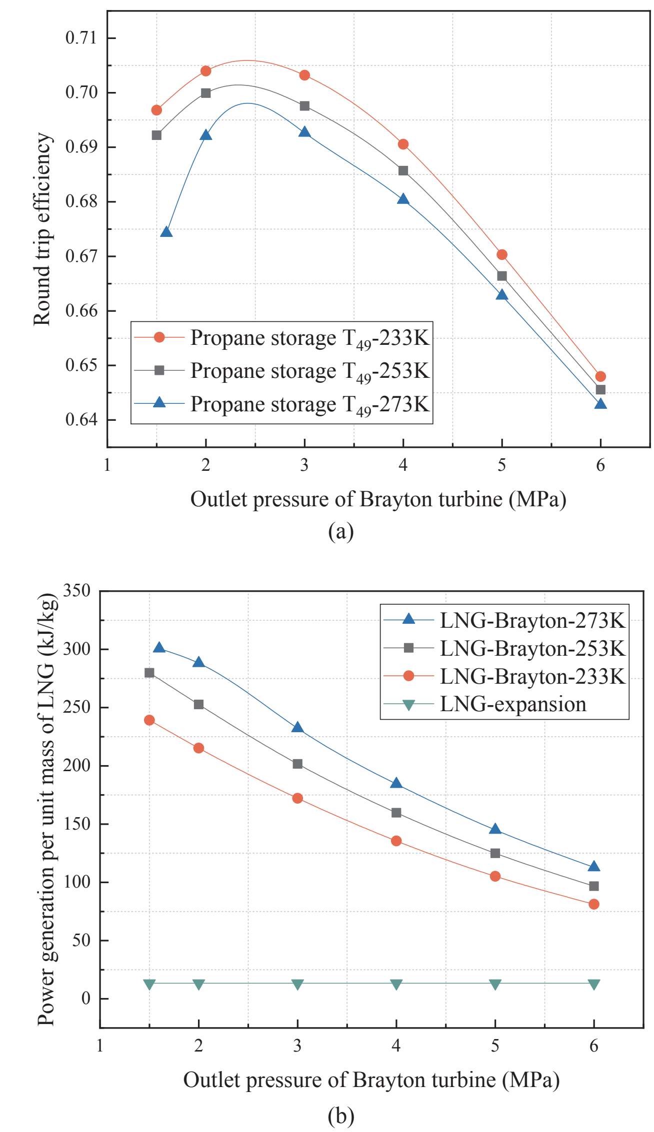

Fig. 6. Effects of outlet pressure of the Brayton turbine on the LAES-Brayton-LNG system performance with different storage temperatures of the pressurized propane.

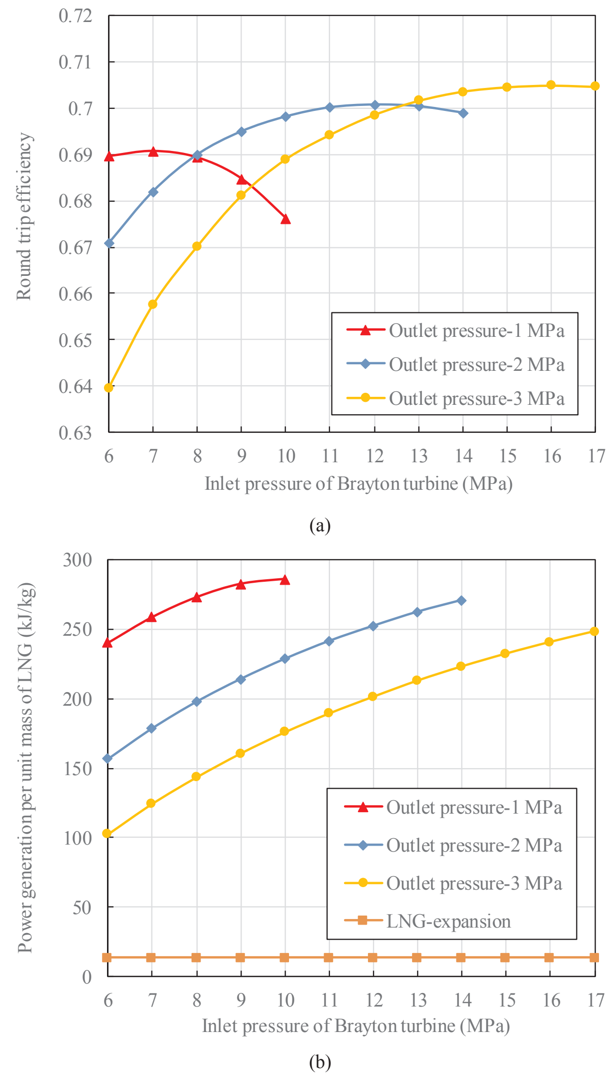

Fig. 7. Effects of inlet pressure of the Brayton turbine on the LAES-Brayton-LNG system performance.

system. In addition, a lower storage temperature of the pressurized propane (T_{49}) gives a lower power generation per unit mass of LNG, but it results in a higher round trip efficiency of the LAES-Brayton-LNG system, as shown in Fig. 6(a). Therefore, an optimal storage temperature of the pressurized propane should be considered in a comprehensive way.

The effect of inlet pressure of the Brayton turbine on the LAES-Brayton-LNG system performance is shown in Fig. 7. For a given outlet pressure, the round trip efficiency of the LAES-Brayton-LNG system increases first, reaches a maximum and then decreases with increasing inlet pressure from 6 to 17 MPa, as shown in Fig. 7(a). This is because, given the outlet pressure, a higher inlet pressure of the Brayton turbine leads to more power generation, but higher inlet pressures lead to more power consumption by the Brayton compressor. The maximum round trip efficiencies at the outlet pressures of the Brayton turbine of 1, 2 and 3 MPa are 69.1%, 70% and 70.5% for the inlet pressures of 7, 12 and 16 MPa, respectively. An inlet pressure of the Brayton turbine of ~12 MPa is suggested based on the combination of less mechanical requirements and high round trip efficiencies.

Fig. 7(b) shows the effect of inlet pressure of the Brayton turbine on the power generation per unit mass of LNG. For the LNG-Brayton case, the amount of power generation per unit mass of LNG increases with increasing inlet pressure for a given outlet pressure. The reason is that a higher inlet pressure of the Brayton turbine gives a lower cold consumption for nitrogen cooling, and hence a lower consumption of LNG and a higher power generation per unit mass of LNG.

4.3. Effects of working pressure of the LNG cycle on the LAES-Brayton-LNG system

The inlet pressure of the LNG turbine affects not only the amount of power generation, but also the cold energy recovered for the Brayton cycle. Fig. 8 shows how the inlet pressure of the LNG turbine affects the LAES-Brayton-LNG system performance with the outlet pressure of the LNG turbine set at 7 MPa. The round trip efficiency of the LAES-Brayton-LNG system is seen to decrease only slightly, by ~1.4%, with increasing inlet pressure of the LNG turbine from 7 to 16 MPa, as shown in Fig. 8(a). A higher inlet pressure of the LNG turbine leads to a lower amount of cold energy recovered from the LNG in the evaporator, leading to a decrease in the power generation by the Brayton cycle and a lower round trip efficiency of the LAES-Brayton-LNG system. Therefore, a lower inlet pressure of the LNG turbine is suggested for the LAES-Brayton-LNG system. In addition, the storage temperature of the pressurized propane (T_{49}) also affects the round trip efficiency of the LAES-

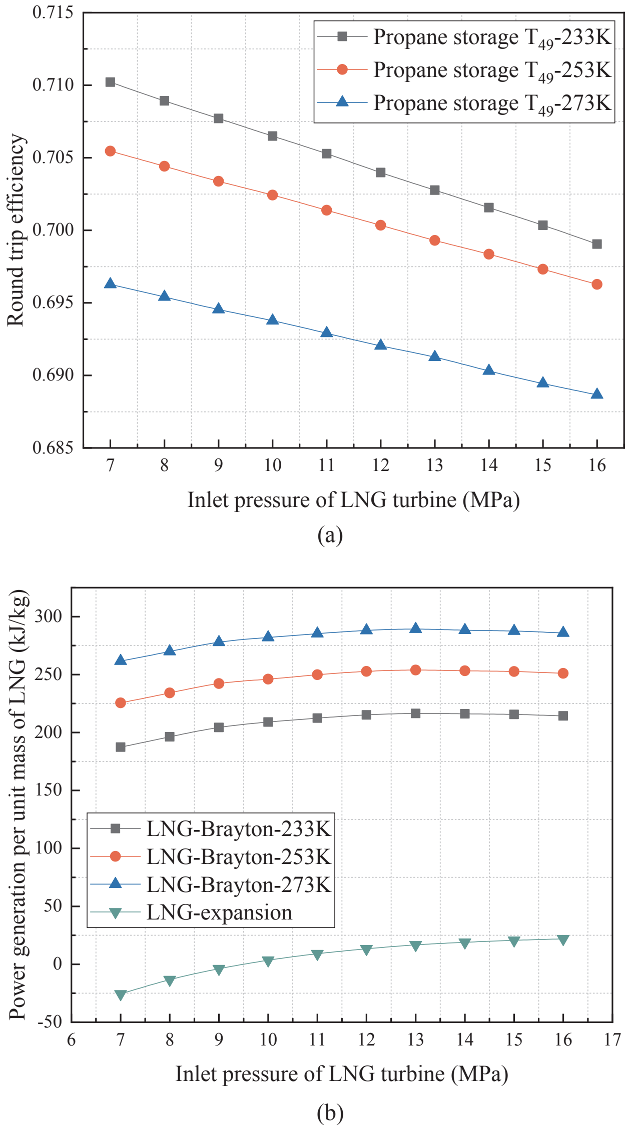

Fig. 8. Effects of inlet pressure of the LNG turbine on the LAES-Brayton-LNG system performance.

Brayton-LNG system. With an increase in the storage temperature from 233 to 253 K, the round trip efficiency decreases slightly by ~0.6%, whereas a further increase in the temperature from 253 to 273 K leads to a more significant decrease in the round trip efficiency by ~1.3%. Therefore, a storage temperature of 253 K is suggested for the pressurized propane.

Fig. 8(b) shows the effect of the inlet pressure of the LNG turbine on the amount of power generation per unit mass of LNG. For the LNG-Brayton case, the amount of power generation per unit mass of LNG increases first, reaches a maximum of 289 kJ/kg at ~13 MPa, and then decreases, with increasing inlet pressure. It could be attributed to that a higher inlet pressure is beneficial to the power generation of the LNG turbine, but it decreases the amount of cold energy recovered from the LNG, which in turn decreases the power generation of the Brayton cycle. In addition, a higher storage temperature of the pressurized propane (T_{49}) also contributes to the higher power generation per unit mass of LNG. For the LNG-expansion case, the amount of power generation per unit mass of LNG increases slowly to 21.9 kJ/kg with increasing inlet pressure of the LNG turbine from 7 to 16 MPa. It is noted that the amount of power generation per unit mass of LNG is negative when the inlet pressure of the LNG turbine is below ~9 MPa, indicating that the power generation of the LNG turbine is less than the power consumption of the cryo-pump. Therefore, to achieve a high round trip efficiency and avoid negative power generation in the LNG cycle, the inlet pressure of the LNG turbine is proposed to be at 10 MPa.

4.4. Further improvement of the LAES-Brayton-LNG system performance

In the current configuration of the LAES-Brayton-LNG system, the LNG cold energy is recovered to cool the gas nitrogen to a low temperature in the cooler, and the low temperature nitrogen is then compressed to a high pressure by the Brayton compressor. However, the nitrogen at the outlet of the Brayton compressor still contains some high grade cold energy which can be further used to improve the system performance. To make use of the remaining cold energy, double-stage and triple-stage Brayton cycles are considered as shown in Fig. 9. In the second-stage of the Brayton cycle, the working medium is cooled down by the cold nitrogen at the outlet of the Brayton compressor #1 and is heated by the ambient heat at 293 K. In the third-stage of the Brayton cycle, the working medium is cooled down by the cold fluid at the outlet of the Brayton compressor #2 and is heated with the ambient heat at 293 K. Methane is chosen as the working medium for both the second-stage and third-stage Brayton cycles. The inlet pressures of the Brayton turbine #2 and #3 are fixed at 12 MPa and their outlet pressures are changeable to achieve the largest amount of power generation.

The round trip efficiency of the LAES-Brayton-LNG system is shown in Fig. 10 for different stages of Brayton cycles. With the single-stage Brayton cycle, the LAES-Brayton-LNG system has the maximum round trip efficiency of 70%, whereas the maximum round trip efficiency is 72% and 72.6% respectively for the double-stage and triple-stage Brayton cycles. Considering that the LAES-Brayton-LNG system with either the double-stage or triple-stage Brayton cycle does not show any significant difference on the round trip efficiency, the double-stage Brayton cycle is suggested for the LAES-Brayton-LNG system, where the optimum outlet pressure of the Brayton turbine #1 is ~4 MPa.

5. Conclusions

This paper proposes the integration of the LAES system with the LNG regasification process via a Brayton cycle and a cold store using pressurized propane as the storage material. The excess heat from the LAES system works as the heat source and the waste cold from the LNG regasification as the cold source for power generation in the Brayton cycle. The integrated LAES-Brayton-LNG system does not involve the change to the existing LAES system configuration, and the LNG regasification process is independent of the LAES system, thus allowing operation flexibilities. Thermodynamic analyses are carried out and the following conclusions are obtained:

- The proposed LAES-Brayton-LNG system achieves a system exergy efficiency of 57% and improves the system exergy efficiency of the standalone LAES by up to 14.4%. What's more, it has a high round trip efficiency of ~70.6%, which is up to ~56.5% higher than that of the standalone LAES system and is comparable with other large-scale energy storage technologies. This high round trip efficiency could be achieved at an air charging pressure of ~5 MPa, suggesting the LAES-Brayton-LNG system should be operated at a lower charging pressure of ~5 MPa.
- The proposed LAES-Brayton-LNG system significantly improves the amount of power generation per unit mass of LNG. With the use of LNG cold energy and excess heat of compression, the power generation per unit mass of LNG could reach 300 kJ/kg. Without the use of the LNG cold, the amount of power generation is only ~21.9 kJ/kg under the studied conditions. In addition, with the LNG cold storage, the LAES and LNG regasification could work independently, providing a great operational flexibility.

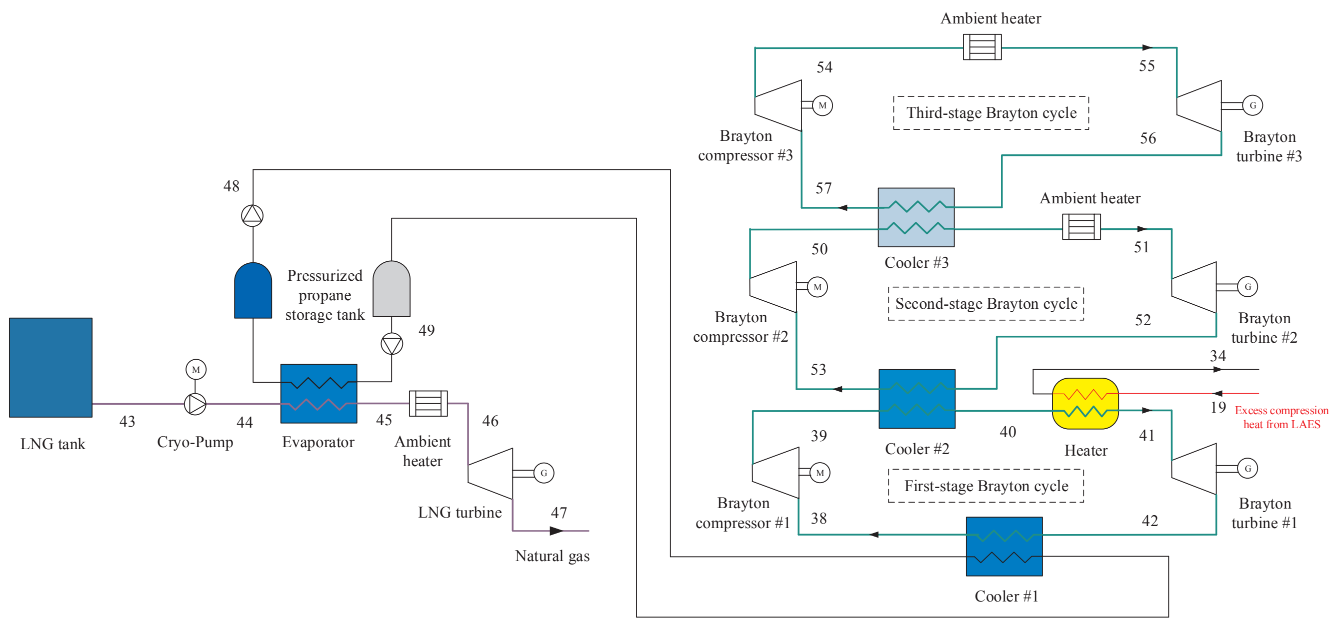

Fig. 9. Schematic diagrams of the LAES-Brayton-LNG system with a multi-stage Brayton cycle.

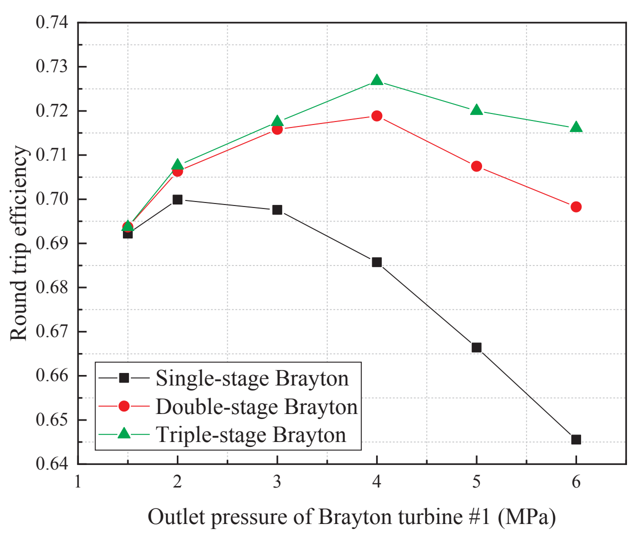

Fig. 10. Performance comparisons of the LAES-Brayton-LNG system with different stages of Brayton cycles.

- The Brayton cycle makes a large contribution to the amount of power generation of the LAES-Brayton-LNG system. The analyses lead to the following recommendations: nitrogen as the working medium, the optimum outlet pressure of the Brayton turbine at ~2.5 MPa, and the inlet pressure of the Brayton turbine at ~12 MPa.
- A lower inlet pressure of the LNG turbine is beneficial to the LAES-Brayton-LNG system. However, an inlet pressure lower than ~9 MPa produces negative net power of the LNG cycle. As a result, the inlet pressure of the LNG turbine is proposed to be at 10 MPa. A higher storage temperature of the pressurized propane gives a larger amount of power generation per unit mass of LNG, but reduces the round trip efficiency of the LAES-Brayton-LNG system. A trade-off for the confliction is to take a storage temperature of the pressurized propane at 253 K.
- As a single-stage Brayton cycle cannot make full use of the LNG cold energy, a double-stage Brayton cycle is therefore suggested for the LAES-Brayton-LNG system, which could give a round trip efficiency of 72%.

The main advantage of the LAES plant is that it could be installed anywhere since liquid air is stored with ambient pressure (1 bar). In addition, power plants for recovering the LNG cold energy have been well developed now. Therefore, the integration of the LAES plant with the LNG terminals is practical for real application.

Acknowledgements

The authors are grateful for the partial support from UK EPSRC under EP/N032888/1, EP/P003605/1, a UK FCO Science & Innovation Network grant (Global Partnerships Fund) and a GCRF grant of Institute for Global Innovation and Birmingham Energy Institute at the University of Birmingham.

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