Comparative analysis of air and CO_2 as working fluids for compressed and liquefied gas energy storage technologies

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Abstract:

With the large-scale use of intermittent renewable energy worldwide, such as wind energy and solar energy, energy storage systems are urgently needed and have been rapidly developed. Technologies of compressed gas energy storage (CGES) and liquefied gas energy storage (LGES) are playing an important role, and air has been commonly used as working fluid. CO_2 is another potential working fluid and attracting more and more attention due to the rise of CO_2 capture and utilization. However, it is still unclear which is the better working fluid. This paper comparatively analyzed the performance of CGES and LGES systems using air and CO_2 as working fluids. Both diabatic and adiabatic CGES are considered. Simulation results show that except diabatic CGES systems, using CO_2 could achieve a similar or even higher round-trip efficiency than using air. In addition, the use of CO_2 instead of air as a working fluid has additional advantages, such as a lower storage temperature can be achieved at the same storage pressure for the adiabatic CGES system; and a higher condensing temperature can be achieved at the same condensing pressure for the LGES system, which can benefit the system design and operation.

Keywords: compressed gas energy storage system; liquefied gas energy storage system; round-trip efficiency; simulation; CO_2 utilization;

Nomenclatures

Variable	Description	Unit
W	shaft work	kW
t	Working time	s
Abbreviations		
A-CAES	adiabatic compressed air energy storage	
A-CCES	adiabatic compressed CO_2 energy storage	
AA-CAES	advanced adiabatic CAES	
C	compressor	
CAES	compressed air energy storage	
CCES	compressed CO_2 energy storage	
CCU	CO_2 capture and utilization	
CGES	compressed gas energy storage	
D-CAES	Diabatic compressed air energy storage	
D-CCES	Diabatic compressed CO_2 energy storage	
ESS	energy storage system	
G	generator	
HT	heater	
IC	intercooler	
LAES	liquefied air energy storage	
LCES	liquefied CO_2 energy storage	
LGES	liquefied gas energy storage	
M	motor	
RTE	round-trip efficiency	
TES	thermal energy storage	
T	turbine	
Subscripts		
t	turbine	
c	compressor	
er	energy release	
es	energy storage	
in	input	

1. Introduction

Nowadays, renewable energy plays a key role in addressing the issue of climate change globally [1, 2] and many countries are actively developing renewable energy [3, 4]. It is expected that by 2022 the global power generation from renewable energy would reach 8000TWh, which is equivalent to the total consumption of China, India and Germany[5]. However, solar and wind energy show significant intermittency [6]. For a low penetration of variable renewable energy, the capacity credit may be guaranteed. However, as the penetration increases, challenges for operating the power system, such as power dispatching, power balancing and congestion, start to emerge. Today, the energy storage system has been considered as one of the most promising options to handle those challenges [7-9]. The existing energy storage systems for electricity mainly include batteries [10], supercapacitors [11], pumped hydro energy storage [12], and compressed air energy storage (CAES) [13, 14]. Among these technologies, supercapacitors have limited capacity and batteries have a high investment cost [15], so they are both not suitable yet for large-scale energy storage. Even though the pumped hydro energy storage has been widely applied to large-scale installed capacity above 200MW [12], it highly relies on geographic conditions [16]. CAES is attracting more and more attention, since it can not only be applied to large-scale energy storage but also enable seamlessly connection to existing gas power generation systems with relatively low capital costs [17-19]. Liquefied air energy storage (LAES) has also been developed. It only needs low-pressure storage tanks, resulting in fewer constraints about the local conditions.

For compressed gas energy storage (CGES) and liquefied gas energy storage (LGES) systems, there are other options in addition to air that can be used as working fluids, for example, CO_2. The need to mitigate anthropogenic emissions of CO_2 is globally recognized. Compared with air, CO_2 has some unique advantages. On the one hand, it has a higher dew point than air, which makes it easier to condense [20], therefore, pumps can be used instead of compressors to lift the pressure for storage; on the other hand, it offers a possibility for large-scale utilization of CO_2, which contributes to the CO2 emission reduction. Some works have already been done regarding the feasibility of compressed CO_2 energy storage (CCES) systems and liquefied CO_2 energy storage (LCES) systems. For example, Zhang et al. [21] developed a CCES based on transcritical CO_2 Brayton cycle, which uses two thermal energy storage (TES) systems to store thermal and cold energy and the estimated round-trip efficiency (RTE) is 60.69%. Zhang et al. [22] proposed to use hot water to store heat in the CCES system, which RTEs under transcritical and supercritical conditions are 61.4% and 71.41% respectively. Liu et al. [23] studied a dual-reservoir CCES system and analyzed the system under supercritical and transcritical conditions, which RTEs are 62.28% and 63.35% respectively. In addition, Wang et al. [24] proposed a LCES system that can be integrated with wind energy, which RTE can reach about 56.64%. Morandin et al. [25] optimized the parameters of transcritical CO_2 cycles in order to minimize the investment and maximize the RTE, and found that the operating pressure is the key parameter. Baik et al. [26] investigated the effect of storage temperature on the performance of a thermo-electric energy storage based on a transcritical CO_2 cycle and found that there exists an optimal temperature in the low temperature hot storage tank for maximizing RTE.

However, to the best of the author's knowledge, there have not been any comprehensive studies in the literature comparing the performance of CGES and LGES using air and CO_2 as working fluids. There is still a lack of knowledge about the proper configuration when using CO_2 as working fluid. To bridge the knowledge gaps, this work compares the performance of different configurations based on the existing compressed and liquefied air energy storage systems and investigates the possibility of using CO_2 to replace air. It will contribute to the development of energy storage systems based on gases by providing guidelines about system design and insights about parameter optimization. The content of this paper is organized as follows. Section 2 reviews the typical compressed and liquefied air. Simulation Models are introduced in Section 3 together with inputs and assumptions. Section 4 presents the results about performance comparison. Finally, conclusions are made in Section 5.

2. System description

Currently, compressed and liquefied air energy storage systems provide a wide array of technological approaches to managing the power supply, in order to create a more resilient energy infrastructure and bring cost savings to utilities and customers. For the CAES system, ambient air is compressed to a target pressure and stored in a cavern or a vessel during the charging process; while during the discharging process, heat is added to preheat the air before it is expanded in a turbine to produce power. The CAES system can be divided into two types: diabatic and adiabatic CAES. For the LAES system, air is liquefied in the air liquefier through refrigeration after being dehydrated. The liquefied air is stored in insulated tanks at low pressure and temperature. When power is required, liquefied air is drawn from the tanks and pumped to a high pressure, then it is heated and expands in a turbine. In this paper, the proposed CO_2 energy storage systems, including CCES and LCES, are designed according to their respective air energy storage systems and retain their original configuration to the greatest extent. In order to fairly compare the systems using air and CO_2 as working fluids, the operating pressures are kept same. For the components which temperature can be externally controlled, such as intercoolers and combustion chambers, the operating temperatures are also set same.

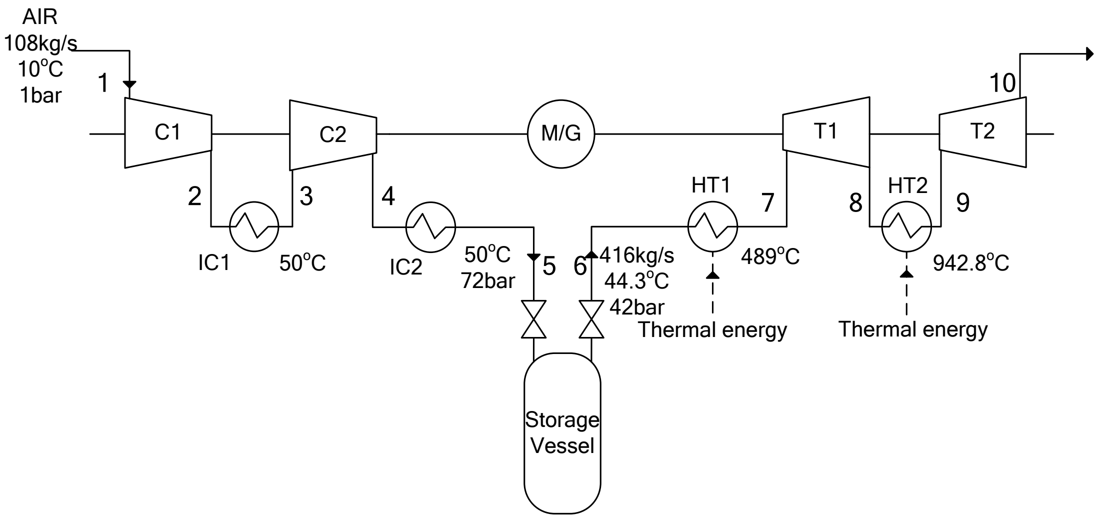
2.1 Diabatic CGES systems

The diabatic CAES (D-CAES) system is the only technology that has been commercialized, and many projects have been carried out [13]. The world's first D-CAES plant was built in

Huntorf, Germany in 1978, which can provide power at 321 MW for 2 hrs per day [13, 27]. Another D-CAES plant was built by the Alabama Electric Cooperative in 1991 [28], which can provide power at 110 MW for up to 24 hrs. Fossil fuel or other thermal energy sources are usually required to provide heat. D-CAES systems are normally characterized as low RTE. Depending on whether there is a recuperator, the diabatic systems are further divided into two types: without a recuperator (e.g. Huntorf plant) and with a recuperator (e.g. McIntosh plant).

2.1.1 Diabatic CGES systems without recuperator

A typical D-CAES system without recuperator [13] is shown in Figure 1(a). Ambient air is compressed to 72bar. during discharging, air is firstly heated in heaters (HT1 and HT2) to 489^{o}C and 942.8^{o}C [13] respectively and then expands in the high-pressure and low-pressure turbines (T1 and T2) to produce power. The high temperature exhaust gas is released directly into the atmosphere without heat recovery, resulting in a large amount of energy loss. When CO_2 is used instead, no big change is needed regarding the system configuration, except an additional low pressure storage tank is needed. Since CO_2 is not an inexhaustible resource like air, the system needs to store not only the compressed CO_2 but also the expanded CO_2, and the same applies to other CCES systems hereinafter. The proposed diabatic CCES (D-CCES) system in correspondence with the Huntorf plant is shown in Figure 1(b).



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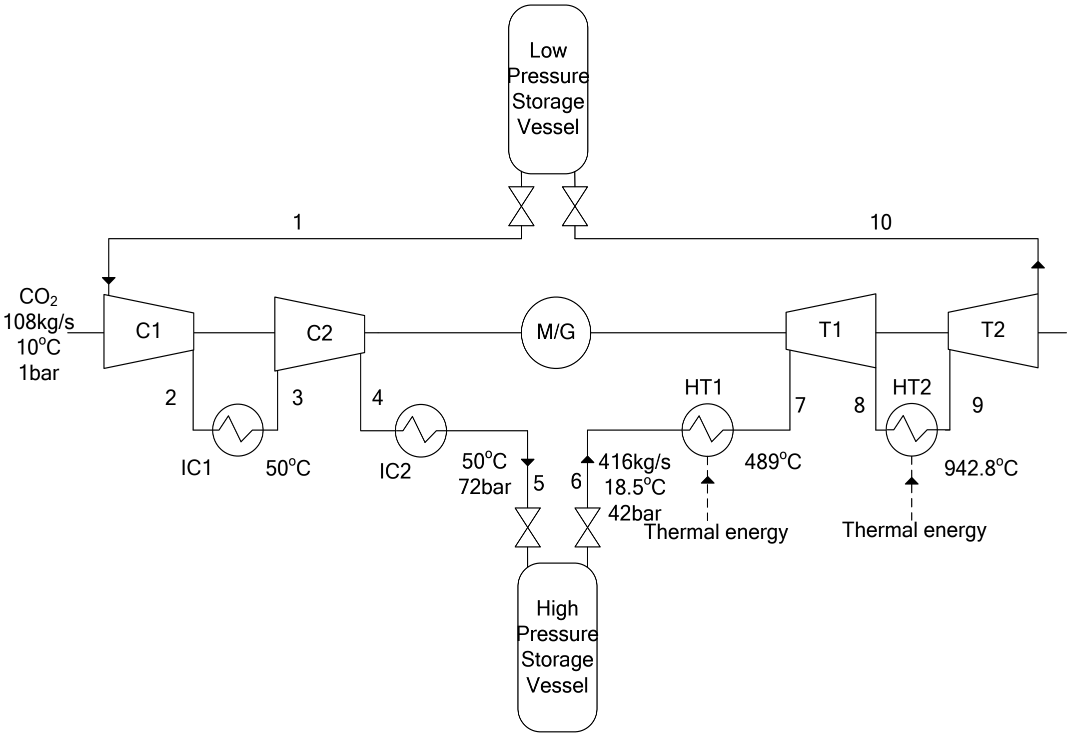


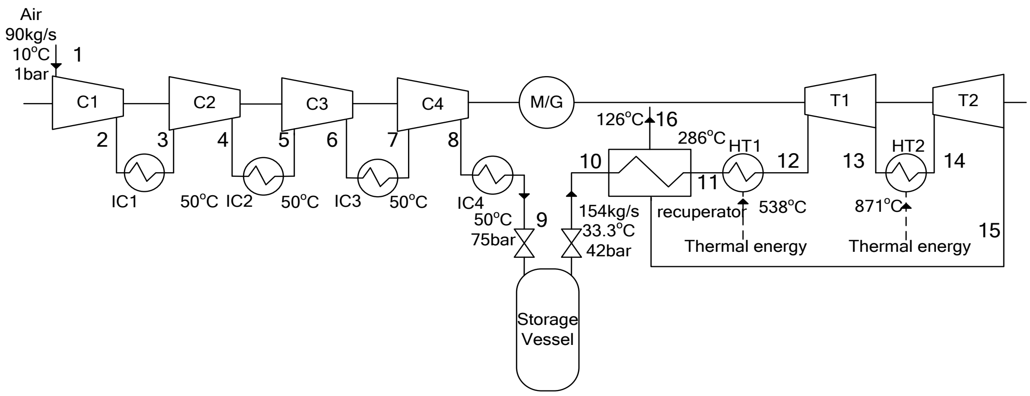
(b)

Figure 1. A typical D-CAES system without recuperator (a) and its corresponding D-CCES system (b)

2.1.2 Diabatic CGES systems with recuperator

A typical D-CAES system with recuperator [13] is shown in Figure 2(a). The recuperator is used to recover heat from exhaust gas to preheat the withdrawn air from the storage reservoir.

After the recuperator, air is further heated before expansion. Due to the heat recovery, the RTE is improved. When CO_2 is used as a working fluid, it results in a lower outlet temperature after throttling (Stream10) than using air. For the comparison with the system using air the same heat transfer temperature difference on the cold fluid inlet side (Stream 10) of the heat exchanger was assumed, which implies that the temperature of the hot fluid outlet side (Stream 16) of the D-CCES system is reduced by 26ºCto 100ºC. The proposed D-CCES system in correspondence is shown in Figure 2(b).



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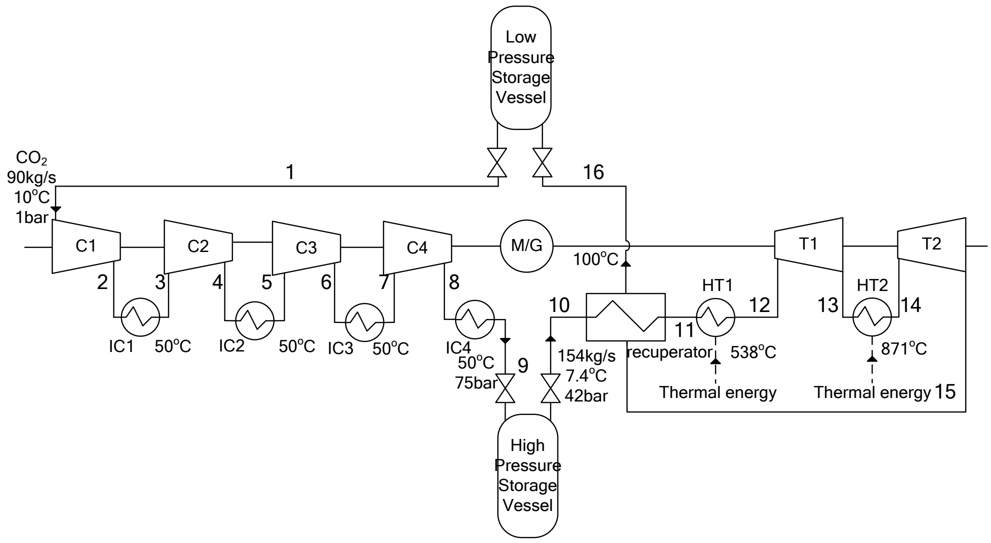


(b)

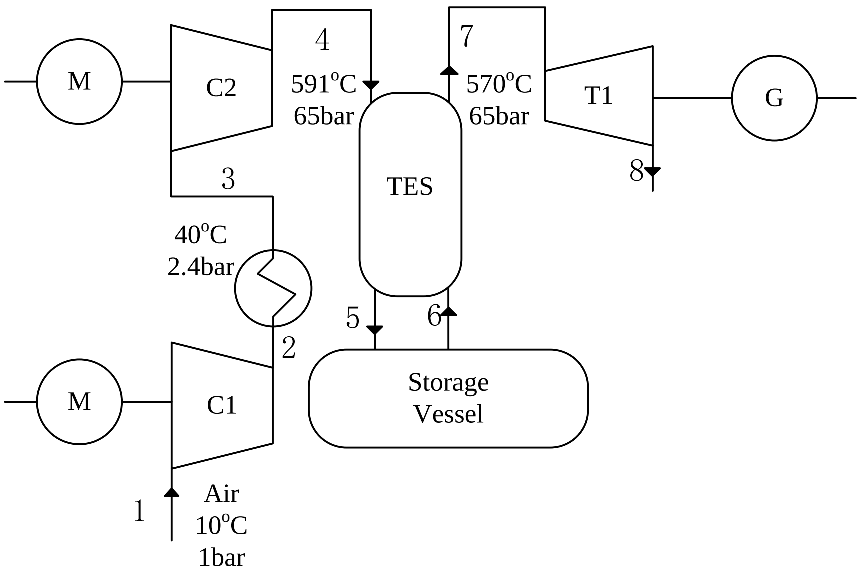
Figure 2. A typical D-CAES system with recuperator (a) and its corresponding D-CCES system (b)

2.2 Adiabatic CGES systems

The adiabatic CAES (A-CAES) system can have a higher efficiency than D-CAES. The worldwide first pilot A-CAES plant was built and successfully tested by ALACAES Company in 2016 [29, 30], which can achieve an overall RTE over 72%. Unlike the D-CAES system, the heat generated during the charging process in the A-CAES system is stored in TES rather than discarded [31]. As such a system does not need extra fuel input, it is considered to be more competitive. However, constrained by the development of TES, such systems are still in the developing stage. According to the storage temperature, the adiabatic system can be divided into high temperature systems (>400°C), medium temperature systems (200°C<=Temp<=400°C) and low temperature systems (<200°C) [32, 33].

2.2.1 High temperature A-CGES systems

A typical high temperature A-CAES system [13] is shown in Figure 3(a). A single-stage TES is included. In the charging process, the ambient air is first compressed to a moderate pressure of 2.4bar; and after cooling in the intercooler, it is further compressed to 65bar for storage. In the discharging process, the compressed air is heated by the TES to 570^{o}C and then expands in the turbine. The system's RTE can reach nearly 70%. However, the high storage temperature around 600^{o}C will pose a great challenge to the compressor and TES in terms of manufacturing and maintenance. When CO_2 is used, it results in a lower outlet temperature of the compressor, and therefore a lower storage temperature of the TES. Assuming the same temperature difference for heating the working fluid before expansion, the turbine inlet temperature is only 354°C for the corresponding high temperature adiabatic CCES (A-CCES), which is shown in Figure 3(b).



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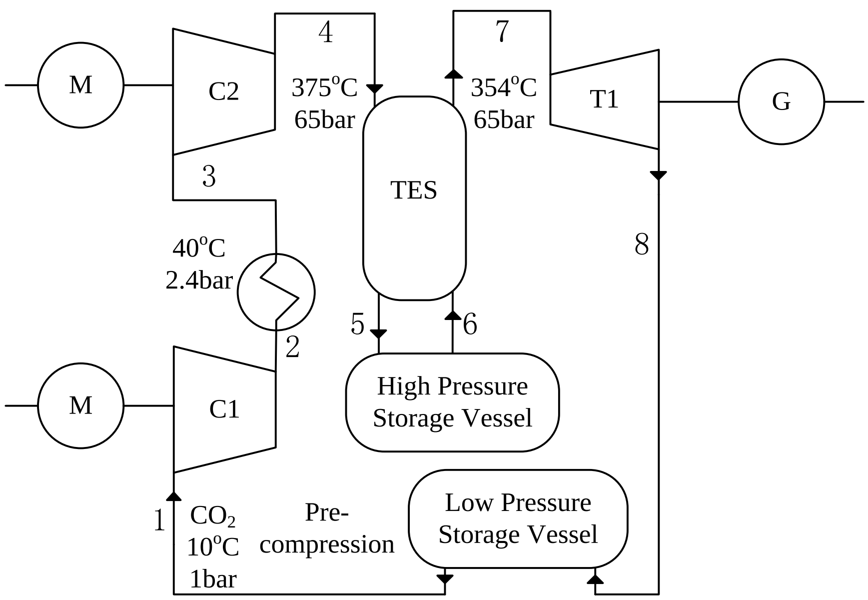


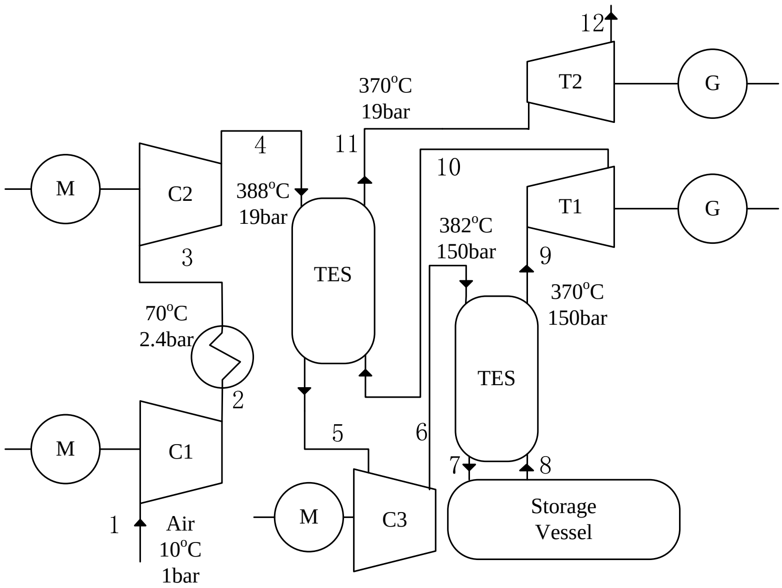
(b)

Figure 3. A typical A-CAES system with high storage temperature (a) and its corresponding A-CCES system (b)

2.2.2 Medium temperature A-CGES systems

A typical medium temperature A-CAES system [13] is shown in Figure 4(a). A two-stage TES is adopted, so the storage temperature can be reduced to below 400°C. During discharging, the high-pressure air is expanded in a two-stage turbine, and heat is provided by the two-stage TES.

When CO_2 is used, similar to the case of high temperature A-CCES, the same temperature difference is assumed during the heating process, as shown in Figure 4(b).



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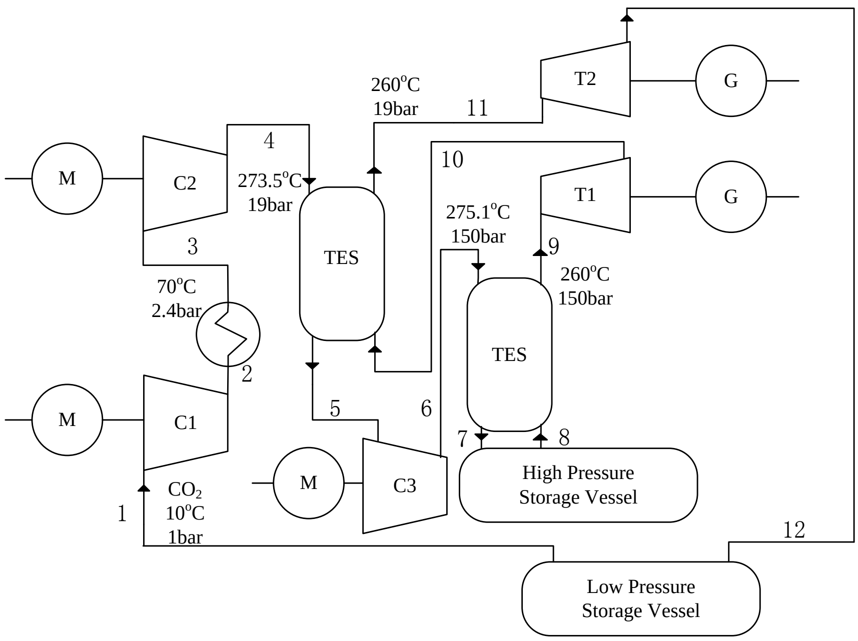
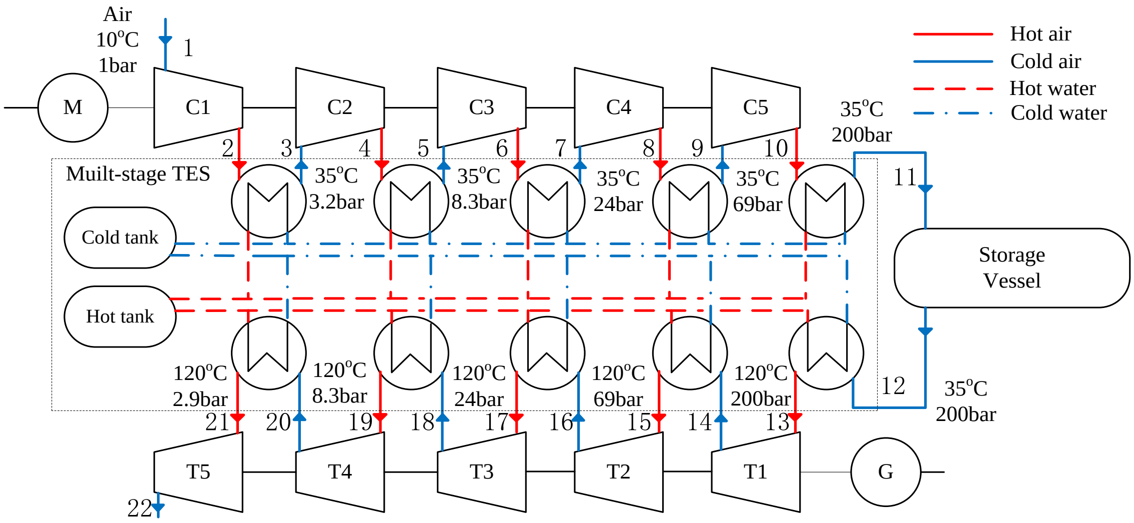


(b)

Figure 4. A typical A-CAES system with medium storage temperature (a) and its corresponding A-CCES system (b)

2.2.3 Low temperature A-CGES systems

A typical low temperature A-CAES system [13] is shown in Figure 5(a). This system has a multi-stage heat exchanger for collecting heat from compression and providing heat during expansion. Due to the multi-stage heat exchanger, the storage temperature is much lower, approximately 130°C. During discharging, air is heated to 120°C before expanding in the next stage turbine. When CO_2 is used, similar to the other cases of CCES, the same assumed temperature difference is used in the heating process, as shown in Figure 5(b).



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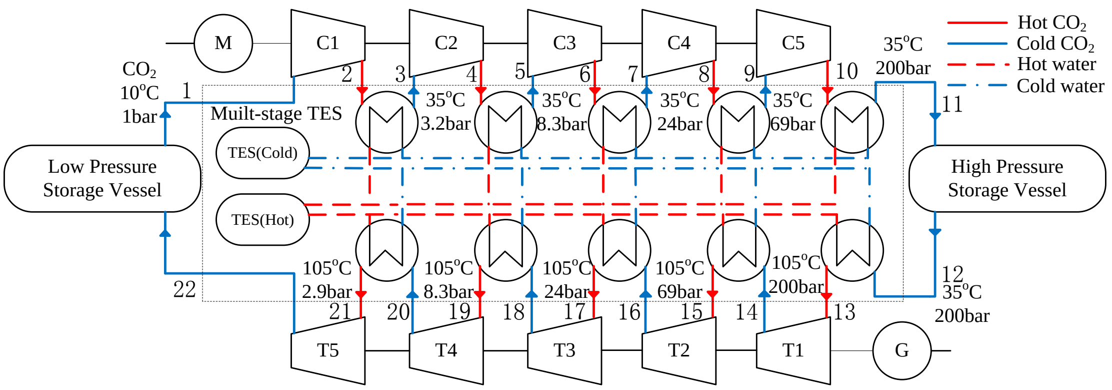
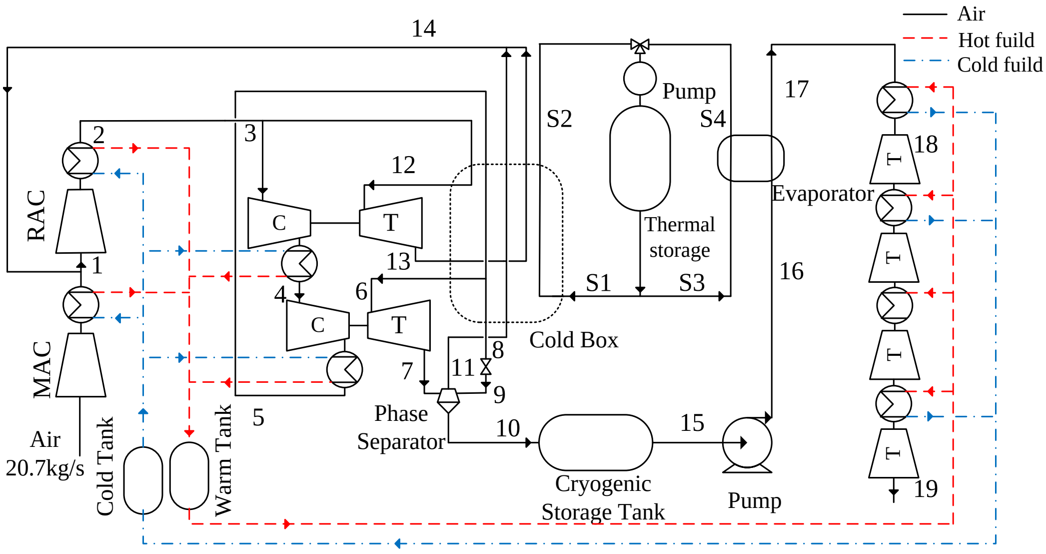


(b)

Figure 5. A typical A-CAES system with low storage temperature (a) and its corresponding A-CCES system (b)

2.3 LGES systems

The first pilot LAES plant was developed by Highview Power Storage and University of Birmingham [34, 35], as shown in Figure 6(a). During the charging process, air is first compressed to 9bar and mixed with the recycled air. The mixed air is then further compressed to a higher pressure and split into two parts (Streams 3 and 10). Stream10 enters the heat exchanger (Cold Box) for primary cooling and then expands in the turbine to provide cooling energy; and Stream 3 is compressed to a higher pressure by the two-stage compressor and then flows into the multi-stream heat exchanger (Cold Box). Where Stream 3 is first pre-cooled and then split into Streams 8 and 6. Stream 8 is further cooled to a temperature below -168.4^{o}C in the Cold Box before entering a throttle valve, and Stream 6 expands to a pressure of 9bar for condensing. The liquefied air (Stream 10) is then separated from the cold air (Streams 7 and 9) and stored in the tank and the remaining air (Stream 11) is recycled to provide cooling energy. During the discharge process, the pressure of the liquefied air is first increased by a pump to 190bar. After the high pressure air is evaporated by using the heat stored in TES, it passes through the multi-stage reheater and expands in turbines. The thermal energy produced by compressor is stored in TES and used for preheating and evaporating air. there is also a cold energy storage system to capture and store waste cold energy. When CO_2 is used, due to its different thermodynamic properties, it requires a relatively higher condensing temperature, which is -42.4^{o}C, resulting in a different inlet temperature of the cold box. Using CO_2 also results in lower temperature of TES, and therefore a lower inlet temperature of the turbine. The proposed LCES system in correspondence with the LAES system is shown in Figure 6(b).



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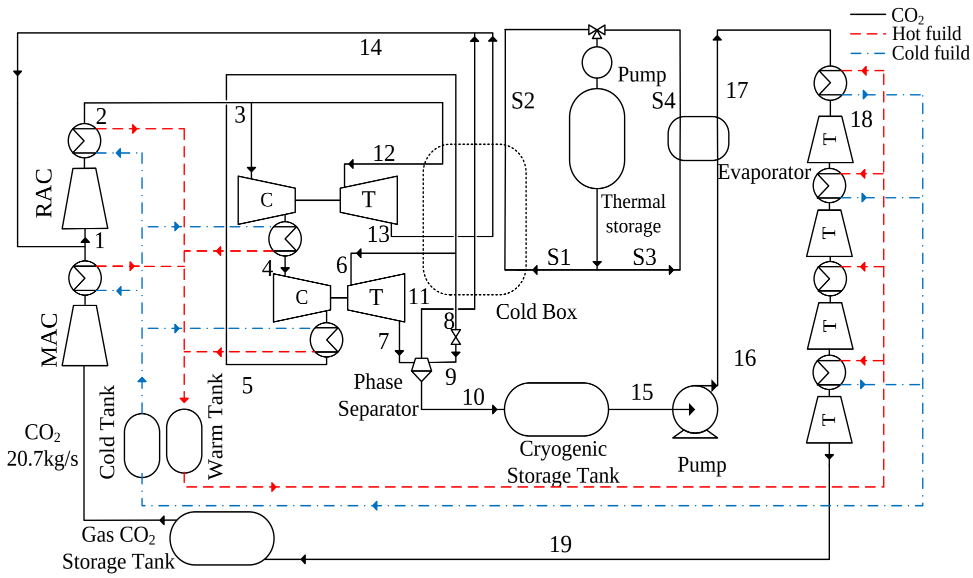

(b)

Figure 6. A typical LAES system (a) and its corresponding LCES system (b)

3. Methodology

To compare the performance, the commercial software Aspen Plus® is used to model and simulate various systems. Aspen Plus® is a recognized large-scale process simulation software with a comprehensive database of thermodynamic properties. The world's major chemical, petrochemical, refining and other process industrial manufacturing enterprises and well-known engineering companies are its users.

3.1 Assumptions of the thermodynamic model

The key input parameters of simulations are summarized in Table 1. As explained in system introduction (Section 2), there are some different specifications between the systems using air and CO_2 as working fluid. For example, for the diabatic systems, to ensure a same heat-exchange temperature difference, the outlet temperature of the throttle valve (Stream 10) in the D-CCES system with recuperator (Figure 2(b)) is 26^{o}C lower than that in the C-CAES system with recuperator, the temperature of Stream 16 in the D-CCES system is consequently lower and set as 100^{o}C. For adiabatic systems, the storage temperature is dependent on the outlet temperature of the compressor; therefore, when using CO_2 instead of air, lower turbine inlet temperatures are used when assuming the same temperature difference for heating. Similarly, since LCES has a lower storage temperature than LAES, a lower turbine inlet temperature is also used when using CO_2 instead of air. Detailed simulation results for each stream are given in the appendix.

Table 1. The key input parameters of simulations

	D-CGES without recuperator	D-CGES with recuperator	High Temp A-CGES	Medium Temp A-CGES	Low Temp A-CGES	LGES
1st stage compressor outlet pressure, bar	8.5	2.9	2.4	2.4	3.2	
2nd stage compressor outlet pressure, bar	72	8.6	65	19	8.3	
3rd stage compressor outlet pressure, bar		24.7		150	24	
4th stage compressor outlet pressure, bar		75			69	
5th stage compressor outlet pressure, bar					200	
Turbine inlet temperature, °C			570(air)/ 354(CO_2)	370(air)/ 260(CO_2)	120(air)/ 109(CO_2)	231.8 (air)/ 160(CO_2)
1st stage turbine outlet pressure, bar	13	15	1.01	12	69	188.65
2nd stage turbine outlet pressure, bar	1.01	1.01		1.01	24	89
3rd stage turbine outlet pressure, bar					8.3	13.9
4th stage turbine outlet pressure, bar					3.2	1
5th stage turbine outlet pressure, bar					1.01	
Intercooler outlet temperature, °C	50	50	40	70		
Throttling valve outlet pressure, bar	42	42				
HT1 outlet temperature, °C	489	538				
HT2 outlet temperature, °C	942.8	841				
Highest pressure in charge process, bar						56.4
Condensing pressure, bar						9
Evaporating pressure, bar						190

3.2 System performance evaluation

to compare the performance of the systems using air and CO_2 as working fluids, round-trip efficiency (RTE) is employed as the key performance indicator, and is defined as the ratio of energy retrieved from storage to energy put:

$$RTE = \frac{W_{out} \cdot t_{er}}{W_c \cdot t_{es} + W_{in} \cdot t_{es}} \quad (1)$$

where t denotes the working time, W_{out} is the total energy output of the system, W_c is the total power consumption of the system, and W_{in} is the total external energy input.

The RTE of the system without external energy input is denoted as follow:

$$RTE = \frac{W_{out} \cdot t_{er}}{W_c \cdot t_{es}} \quad (2)$$

In addition, if two systems have comparable RTEs, working temperature is also considered as a key indicator because it has a significant impact on the system design and maintenance.

4. Results and discussion

4.1 model validation

To validate the model developed in Aspen Plus, a comparison on key output parameters between the simulated results and the actual data of the plants is done, as shown in Table 2.

Table 2. The main parameters of simulation results and actual operating data of the plants

	D-CAES without recuperator (actual data) [13]	D-CAES without recuperator (simulation results)	D-CAES with recuperator (actual data) [13, 28]	D-CAES with recuperator (simulation results)
RTE	42%	41.5%	54%	51.7%
Power consumption of compressor	60MW	69.2MW	50MW	53.8MW
Power generation of turbine	321MW	328MW	110MW	110.4MW
Exhaust gas temperature	480°C	449.2°C	370°C (before recuperator)	382.8°C (before recuperator)

As can be seen from the above table, the simulated results generally agree with the actual operating data, for example, for D-CAES without and with recuperator, the relative deviation on RTEs are only 1.2% and 4.2% respectively. In additional, our simulated results are also compared with the results from the literature. For the high temperature CAES and the medium temperature CAES systems, the simulated RTE in this work are 68.6% and 67.7% respectively which are very close to the results (68.7% and 68.0%) in the literature [13] .

4.2 Diabatic CGES systems

4.2.1 Diabatic CGES system without recuperator

The simulation results of D-CGES system without recuperator are shown in Table 3 and Figure 7. Comparing the D-CAES without recuperator system with its corresponding D-CCES system shows that the RTE of the latter is about 7.3% lower than that of the former. Although the energy consumption of the D-CCES is less than the D-CAES in the compression process, the turbine outlet temperature of D-CCES is much higher than D-CAES based on the same inlet temperature and pressure. Although reducing the turbine inlet temperature in the D-CCES system will reduce the turbine outlet temperature accordingly, thereby having closer turbine outlet temperature between the D-CCES system and the D-CAES system, this reduction in turbine inlet temperature will also reduce the expansion output of the D-CCES system. Thus, the RTE of the D-CCES system is difficult to improve in this way. In addition, in the D-CGES systems, air can be mixed with natural gas and burned in combustor to obtain heat, whereas in the D-CCES systems, CO_2 cannot directly obtain heat in this same way. Alternatively, heat can only be added through heat exchangers in D-CCES systems, which results in inevitable heat loss. Therefore, CO_2 is not suitable a working fluid for this type of compressed gas energy storage system.

4.2.2 Diabatic CGES system with recuperators

The simulation results of D-CGES systems with recuperators are also shown in Table 3 and Figure 7. Different from the systems without recuperators, the D-CAES system with recuperator and its corresponding D-CCES system have relatively closer RTEs, only with a difference of 1.3%. Compared with the D-CCES system with recuperator, the exhaust gas temperature in the D-CCES system is significantly reduced during the discharge process, which results in a 42% reduction in heat consumption; however, this reduction in the D-CAES system is much lower, only 29.1%, which means that the recuperator is more helpful to improve the RTE in the D-CCES system. In general, the power consumption of compressors in the D-CGES system with recuperator is lower than that in the D-CGES system without recuperator. It can also be found that the outlet temperature of each compressor in the D-CAES system is always higher than that in the D-CCES system. Considering the close RTE, it may be more suitable to use CO_2 as working fluid.

Table 3. Power and RTE of D-CAES/CCES systems without and with recuperator

	D-CAES without recuperator	D-CCES without recuperator	D-CAES with recuperator	D-CCES with recuperator
Power consumption of compressor, kW/kg	641.0	377.0	597.5	360.6
Power generation of turbine, kW/kg	741.3	539.9	717.2	524.5
Power consumption of heat, kW/kg	1176.8	1221.5	834.6	708.0
Round-trip efficiency	41.5%	34.2%	51.7%	50.4%

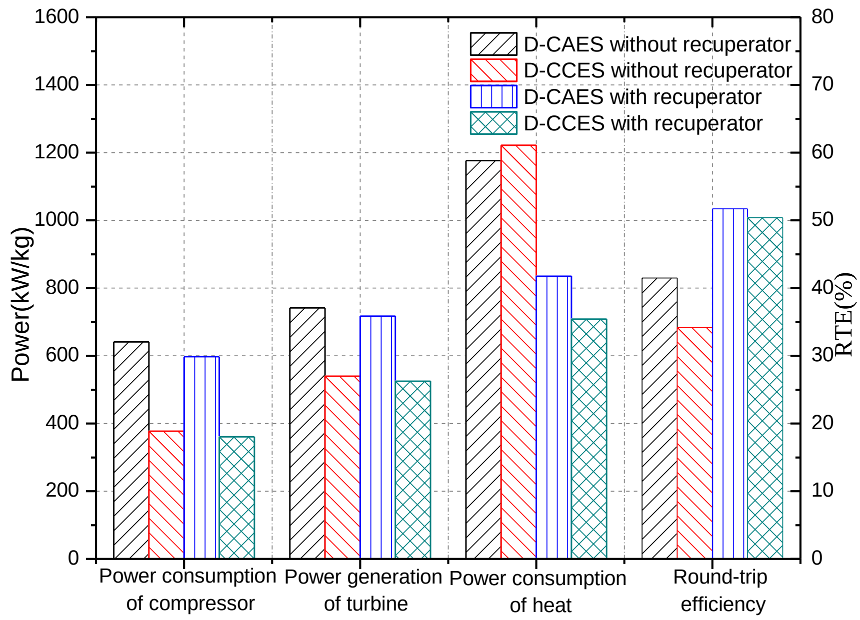

Figure 7. Comparison on power consumption of compressor, power generation of turbine, power consumption of heat and RTE between the D-CAES and D-CCES systems without and with recuperator

4.3 Adiabatic CGES systems

4.3.1 High temperature A-CGES systems

The simulation results of the high temperature A-CGES systems are shown in Table 4 and Figure 8. For the high temperature systems, the RTE of A-CCES is about 1.9% lower than that of A-CAES. However, the operating temperature of TES storage in the A-CCES system is 216.3°C lower than that in the A-CAES system. This is because that compared to air, CO_2 has a lower heat capacity ratio, resulting in the lower outlet temperature of CO_2 compressor for the same compression ratio. And the relatively lower temperature in A-CCES system can make the design and operation of TES much easier, which is a great advantage. It can also benefit compressors and TES in terms of manufacturing and maintenance and also have the potential to reduce their O&M costs. If the storage temperature of TES is fixed, the A-CCES system can have a higher storage pressure, which implies a larger energy storage density and a smaller storage capacity. Therefore, CO_2 is suitable as a working fluid for this type of compressed gas energy storage system.

4.3.2 Medium temperature A-CGES systems

The simulation results of the high temp A-CGES systems are also shown in Table 4 and Figure 8. The simulation results of the medium temperature systems are similar to those of the high temperature systems. The difference on RTE between A-CAES system and its corresponding A-CCES system is only about 1.5%, and the storage temperature of TES in A-CCES system is nearly 110°C lower than that in A-CAES system. This comparison shows that the medium temperature A-CCES system has a great advantage in terms of the storage temperature of TES. Therefore, CO_2 is suitable as a working fluid for this type of compressed gas energy storage system.

4.3.3 Low temperature A-CGES systems

The simulation results of the high temp A-CGES systems are also shown in Table 4 and Figure 8. The A-CAES system with low thermal storage temperature and its corresponding A-CCES system have almost the same RTE. Unlike the previous two A-CGES systems, the operating temperature of TES in the A-CAES is only about 10°C higher than that in A-CCES. Although the advantage in thermal storage temperature is not appreciable compared to the previous two A-CGES systems, an increase of RTE of 1.6% in the low temperature A-CAES system is still attractive. Therefore, CO_2 is suitable as a working fluid for this type of compressed gas energy storage system.

Table 4. RTE of A-CAES/CCES systems at different thermal storage temperatures

	High temper system (Air)	High temp system (CO_2)	Medium temp system (Air)	Medium temp system (CO_2)	Low temp system (Air)	Low temp system (CO_2)
Storage temperature	591.2°C	374.9°C	387.9°C/ 382.1°C	273.5°C/ 275.1°C	129.8°C	118.9°C
Turbine inlet temperature	570°C	354°C	370°C/ 370°C	260°C/ 260°C	120°C	109°C
RTE	68.6%	66.7%	67.7%	66.2%	60.1%	61.7%

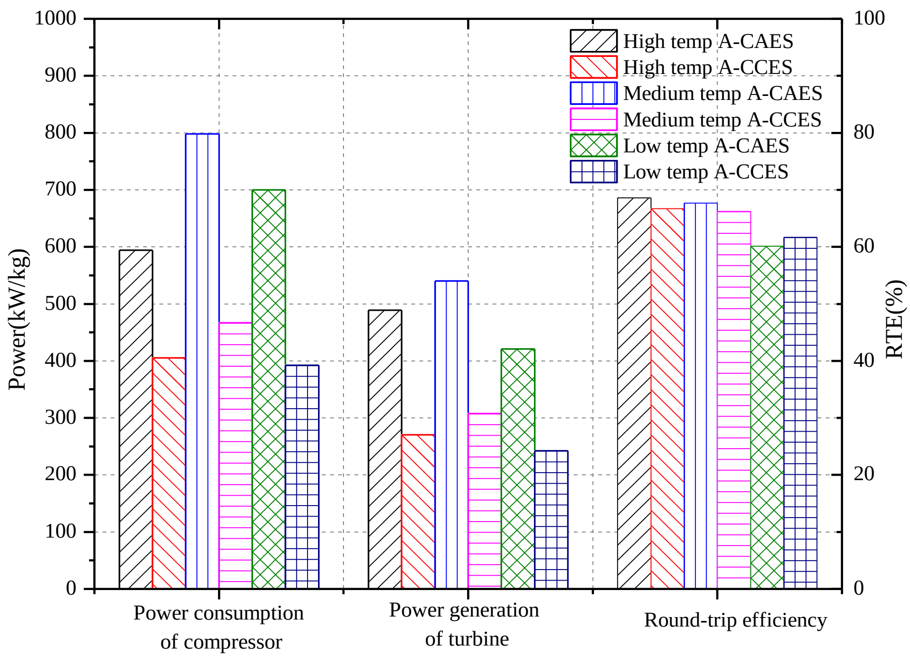

Figure 8. Comparison on power consumption of compressor, power generation of turbine and RTE between the A-CAES and A-CCES systems at different thermal storage temperatures

4.4 LGES system

The simulation results of the LAES system and the LCES system are shown in Table 5 and Figure 9. Compared with its corresponding LCES system, the LAES system has a lower RTE. This is because although the power generation of LAES is 257.1kW/kg higher than that of LCES, LAES consumes much more compression work, which is 430.7kW/kg more. In addition, the condensing temperature of the LCES system is -42.4°C, which is 120°C higher than that of LAES system. Such a large temperature difference has clear advantages. On the one hand, it is beneficial to the storage system that a storage temperature close to ambient temperature can reduce heat loss; on the other hand, compared to the much lower turbine inlet temperature (i.e. -50°C) in the LAES system, the higher turbine inlet temperature in LCES is also beneficial for turbine designing and maintenance. Therefore, CO_2 is a much better working fluid than air for LGES system.

Table 5. Power and RTE of LAES and LCES systems

	LAES	LCES
Power consumption of compressor	863.7kW/kg	433.0kW/kg
Power generation of turbine	557.1kW/kg	300.0kW/kg
Round-trip efficiency	62.5%	64.9%

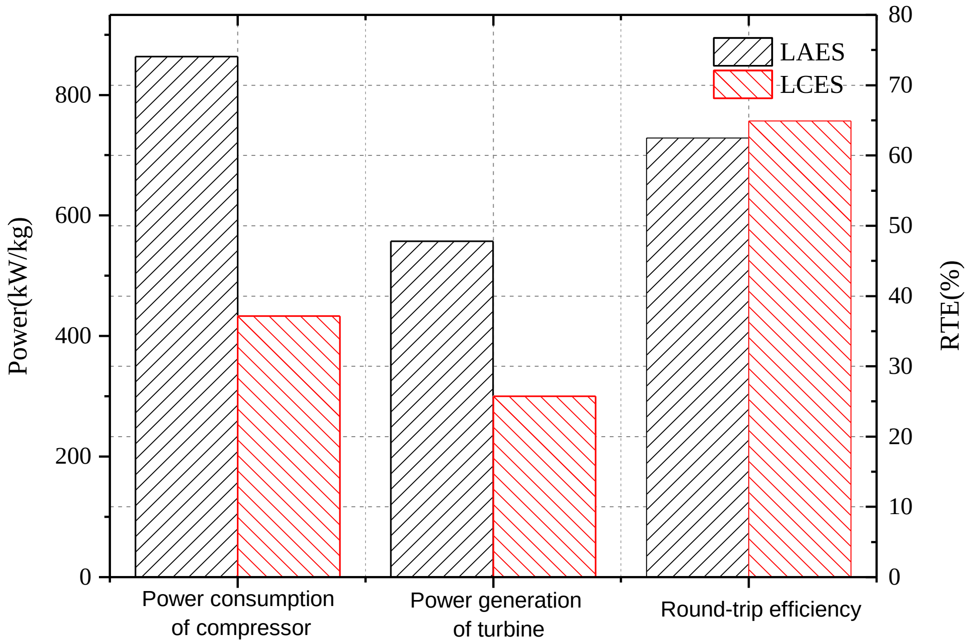

Figure 9. Comparison on power consumption of compressor, power generation of turbine and RTE between the LAES and LCES systems

4.5 Discussions

In view of the above simulation results and analyses, CO_2 is an important alternative to air in CGES and LGES systems. However, there are still some challenges and limitations in using CO_2 as a working fluid. First of all, CO_2 is not as inexhaustible as air. Although the application of CO_2 capture technology might provide large amounts of CO_2, the leakage and replenishment problems in transportation still need to be overcome. Second, the use of CO_2 requires additional storage tanks, which increases the front-end investment in the system. Moreover, as an acidic gas, CO_2 dissolved in water may cause corrosion problems, thereby increasing the requirements for equipment materials.

5. Conclusion

This paper compared the performances of compressed gas energy storage (CGES) systems and liquefied gas energy storage (LGES) systems using air and CO_2 as working fluid. Based on the results, the following conclusions can be drawn:

1. For the diabatic CGES system, using CO_2 results in a lower round-trip efficiency (RTE) than using air, which are 7.3% and 1.3% lower for systems without and with recuperators respectively.

2. For the adiabatic CGES system, using CO_2 achieves similar RTE to using air, which are 1.9% and 1.5% lower for the high and medium temperature systems and 1.6% higher for low temperature systems. However, using CO_2 can achieve a lower storage temperature than using air, which is beneficial to the high temp- and medium temp A-CCES systems design and maintenance.

3. For the LGES system, using CO_2 results in a higher RTE than using air, which is 2.4% higher. Moreover, compared to system using air, the system using CO_2 has a higher storage temperature, which is closer to the ambient temperature and thus has a lower thermal stress and lower cooling loss.

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Appendix A

The detail simulation results of these systems are shown in Table.A.1, Table, A.2, Table, A.3, Table, A.4, Table, A.5, Table, A.6 and Table, A.7.2

Table. A1 The detail data in each stream of D-CAES\CCES systems without recuperator

streams	D-CAES\CCES systems without recuperator Pressure, bar	D-CAES system without recuperator Temperature, ^{o}C	D-CCES system without recuperator Temperature, ^{o}C
1	1.01	10	10
2	8.5	296.7	201.9
3	8.5	50	50
4	72	454.3	308.2
5	72	50	50
6	42	44.3	18.5
7	42	490	490
8	13	313.7	371.6
9	13	945	945
10	1.01	449.2	611.4

Table. A2 The detail data in each stream of D-CAES\CCES systems with recuperator

Stream	D- CAES\CCES systems with recuperator Pressure, bar	D-CAES system with recuperator Temperature, ^{o}C	D-CCES system with recuperator Temperature, ^{o}C
1	1.01	10	10
2	2.9	136.6	102
3	2.9	50	50
4	8.6	194.5	150.5
5	8.6	50	50
6	24.7	196.3	153
7	24.7	50	50
8	75	196.7	156.4
9	75	50	50
10	42	33.3	7.4
11	42	330.9	388.8
12	42	538	538
13	15	350.6	428.6
14	15	871	871
15	1.01	413	538.7
16	1.01	126	100

Table. A3 The detail data in each stream of High temperature process

Stream	High temperature system Pressure, bar	High temperature system (Air) Temperature, °C	High temperature system (CO_2) Temperature, °C
1	1.01	10	10
2	2.4	107.1	81.9
3	2.4	40	40
4	65	591.2	374.9
5	65	60	60
6	65	60	60
7	65	570	360
8	1.01	81.2	59.3

Table. A4The detail data in each stream of Medium temperature process

Stream	Medium temperature system Pressure, bar	Medium temperature system (Air) Temperature, °C	Medium temperature system (CO_2) Temperature, °C
1	1.01	10	10
2	2.4	107.1	82.1
3	2.4	70	70
4	19	387.9	273.5
5	19	60	60
6	150	382.1	275.1
7	150	60	60
8	150	60	60
9	150	370	260
10	12	90.6	65.3
11	12	370	260
12	1.01	96.6	85.2

Table. A5 The detail data in each stream of Low temperature process

Stream	Medium temperature system Pressure, bar	Medium temperature system (Air) Temperature, ^{o}C	Medium temperature system (CO_2) Temperature, ^{o}C
1	1.01	10	10
2	3.2	144.9	107.6
3	3.2	35	35
4	8.3	152.6	119.4
5	8.3	35	35
6	24	168.1	131.4
7	24	35	35
8	69	167.2	134.9
9	69	35	35
10	200	167.3	124.2
11	200	35	35
12	200	35	35
e	200	120	109
14	69	28.3	32
15	69	120	109
16	24	30.5	29.9
17	24	120	109
18	8.3	31.5	38.7
19	8.3	120	109
20	2.9	32.8	42.8
21	2.9	120	109
22	1.01	32.9	43.9

Table. A6 The detail data in each stream of the LAES system and the LCES system

Stream	LAES Pressure, bar	LAES Temperature, ^{o}C	LCES Pressure, bar	LCES Temperature, ^{o}C
1	1	31.8	1	31.8
2	9	31.8	9	31.8
3	40.8	31.8	24.4	75
4	43	31.8	25.8	31.8
5	56.8	31.8	56.8	75
6	56.4	-97.8	56.6	73.3
7	9	-168.4	9	-42.4
8	56.2	-168.4	56.2	-42.4
9	9	-168.4	9	-42.4
10	9	168.4	9	-42.4
11	9	168.4	9	-42.4
12	40.4	-50	24	60
13	9	-124.7	9	-4.6
14	9	31.3	9	31.3
15	9	-168.5	9	-42.5
16	190	-155.4	190	-34
17	188.65	-12.2	188.65	70.8
18	188.65	231.8	188.65	160
19	1	91	1	67
S1	9	-153.1	9	-32
S2	8.5	30.1	8.5	71.4
S3	8.5	30.1	8.5	71.4
S4	8.5	-153.1	8.5	-32