THERMODYNAMICS ANALYSIS AND OPTIMIZATION OF A NOVEL LIQUID CARBON DIOXIDE ENERGY STORAGE COUPLED WITH A COAL-FIRED POWER PLANT

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Abstract: In order to improve the performance of the liquid carbon dioxide energy storage (LCES) system, a coupled system including a coal-fired power plant and a LCES system is proposed in this paper. In the energy storage process, the condensate from the coal-fired power plant is used to absorb the heat of compression generated. In the energy release process, the condensate and feedwater are used to step-heat the high-pressure carbon dioxide entering the turbine inlet. The performance of the LCES subsystem is evaluated by the energy analysis, the conventional exergy analysis, and the advanced exergy analysis. Results show that the round-trip efficiency of the LCES subsystem can reach 60.52%, with an improvement of 2.35% compared with the single LCES system. The exergy efficiency of the LCES subsystem under the real cycle is 68.55% and under the unavoidable cycle is 84.16%, which indicates that the LCES subsystem has a great potential for improvement. The conventional exergy analysis indicates that the cold energy storage tank is the biggest exergy destruction component, accounting for 23.58% of the LCES subsystem exergy destruction. The split of the exergy destruction is carried out during the advanced exergy analysis, and the results show that the avoidable endogenous exergy destruction accounts for 47.44 % of all exergy destruction. The first turbine has the greatest avoidable endogenous exergy destruction, with 24.71%, indicating that it has the highest improvement potential. This paper may provide new ideas for the LCES system performance improvement.

Keywords: *Liquid carbon dioxide energy storage; Coal-fired power plant; Performance evaluation; Conventional exergy analysis; Advanced exergy analysis; Coupled system*

1. Introduction

With the emphasis and investment in renewable energy, the world's renewable energy generation capacity has reached 3,372GW by 2022, and is expected to grow to more than three times by 2030 [1]. However, renewable energy is fluctuating and intermittent, which results in the inability to be consumed on a large scale [2]. In recent years, the wide application of electric energy storage technology has proved that the energy storage system can increase the operational flexibility of the power system while simultaneously increasing the effective consumption of renewable energy, thus ensuring the steady and secure operation of the power grid [3]. Currently, the commonly used electrical energy storage technologies include flywheel storage, pumped storage, electrochemical storage, compressed air storage, and etc [4]. Among them, the compressed CO_2 energy storage (CCES) technology is considered to have a smaller footprint, lower energy storage costs, and a safer and more reliable energy storage process, making it more advantageous in the large-scale rollout process [5]. For the CCES system, low-pressure CO_2 is compressed into high-pressure CO_2 by a compressor that is powered by electrical energy, and a high-pressure storage tank holds the CO_2 at high pressure in the energy storage process. The released high-pressure CO_2 drives a turbine to do work in the energy release process, which in turn drives a generator to produce electricity [6]. In addition, since CO_2 is easy to liquefy and the density change is large after liquefaction in the low-pressure state, the liquid CO_2 has the potential to decrease the volume of the storage tank while simultaneously increasing the energy storage capacity. Therefore, some scholars proposed the liquid carbon dioxide energy storage (LCES) system, which greatly improves the safety and feasibility of the system [7]. However, the development of the LCES technology is currently limited by low operational efficiency, so effectively improving the capacity of the LCES system can successfully spur technological advancements [8].

In order to increase the efficiency of the LCES system, scholars have done a lot of research, including innovating the system design, optimizing the system equipment, and improving the operation strategy [9]. In addition, many scholars have tried to investigate the enhancement of system functionality by coupling the LCES system with other systems. Zhan et al. [10] presented a novel LCES system that integrated the Brayton cycle and the ejector condensing cycle, showing that when the ejector back pressure was 8.9MPa, the system efficiency reached its maximum. Xu et al. [11] combined a LCES system with a combined cooling, heating and power system, realizing the evaporation process without heat source charging, while meeting the diversified energy demands. Bahram et al. [12] developed a CO_2 liquefaction generator by using the solar collector, which was analyzed to achieve the storage efficiency of up to 67.87% and the round-trip efficiency of up to 41.22%. Xu et al. [13] proposed a novel LCES system, and examined how solar energy affected the LCES system. The results showed that solar energy variations have no significant effect on the turbine inlet temperature of the LCES system. The above studies show that there are many scholars who have coupled the LCES system with other energy systems in order to improve the capabilities of the LCES system. However, there are fewer researches on the integration of the coal-fired power plant with the LCES system.

In many countries, coal-fired power plants with mature technology are responsible for the primary power generation duty of the power grid [14]. With the expanding share of renewable energy generation, coal-fired power plants are increasingly applicable to grid peaking. Currently, coupling energy storage systems with coal-fired power plants is considered as a technical solution in order to make coal-fired power plants more flexible [15]. In addition, as a complex thermal system, the coal-fired power plant has many fluids with different temperature intervals inside the plant. Therefore, based on the principle of energy gradient utilization, integrating the LCES system can significantly increase the capacity of the coal-fired power plant. Besides, investigating the integration of the LCES system can be a way to improve the peaking capacity of coal-fired power plants, and thus contributing to the decarbonization transition of the power industry.

In addition, in the evaluation of the capacity of the LCES system, the energy analysis, the conventional exergy analysis, and the economic analysis have been used in many studies [16]. In the pursuit of maximizing thermodynamic efficiency, the exergy analysis evaluates the magnitude of energy conversion. Nevertheless, the conventional exergy analysis estimates the irreversibility of components, but cannot determine the interaction between components. In order to better break through the limitations, the advanced exergy analysis method has been developed [17]. The exergy destruction is made up of four parts: the endogenous part, the exogenous part, the avoidable part, and the unavoidable part. At present, the advanced exergy analysis is now widely analyzed in a variety of energy-saving systems, including the ejector refrigeration system [18], the underwater CAES system [19], the coal-fired ultra-supercritical power plant [20], and etc. Less research has been done on the use of the advanced exergy analysis method to improve the capability of the LCES system integrated with the coal-fired power plant.

2. System description

A novel system coupling a coal-fired power plant and a LCES system is developed, as shown in Figure 1. In the energy storage process, CO_2 is compressed in the C1, and the compressed CO_2 is cooled by the HE1. The feedwater is used as the cooling medium during the heat transfer process, and is discharged in front of the deaerator when the heat transfer process is complete. The CO_2 from the HE1 enters the C2 to be pressurized and the exchanges heat by the HE2 again. During the energy storage process, partial feedwater is heated by compressed CO_2, thus saving the extracted steam and helping to generate more electricity while supplying the same coal consumption. In the energy release process, liquid CO_2 stored in the HST is released and is heated by the feedwater in the HR2 and the HE4. Then, the CO_2 drives the T2 to work. The low-temperature CO_2 enters the HR1 and the HE3 to be heated again, and then enters the T1 to work. Ultimately, the electricity generated is transmitted to the power grid. Through coupling with the coal-fired power plant, the feedwater and condensate are utilized to heat and cool the circulating fluid of the LCES subsystem, thus realizing the gradient utilization of energy. At the same time, the system integration can save the investment in heat and cold storage tanks of the traditional LCES system, thus increasing the flexibility and safety of the system operation. In addition, thermodynamic data for different operating points are displayed in Table 1.

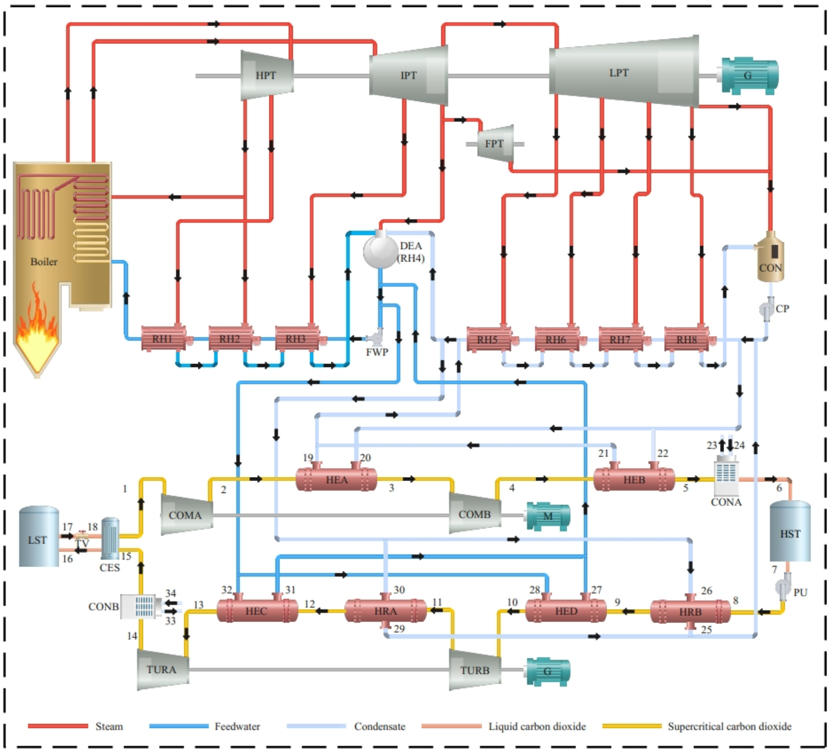


Figure 1. Diagram of the proposed system

Table 1.
Thermodynamic parameters of the LCES subsystem

Stream	Working fluid	P (MPa)	T (K)	M (kg/s)
1	CO_2	1.00	287.52	251.43
2	CO_2	4.47	417.87	251.43
3	CO_2	4.47	307.76	251.43
4	CO_2	20.00	447.59	251.43
5	CO_2	20.00	307.76	251.43
6	CO_2	20.00	302.76	251.43
7	CO_2	20.00	302.15	251.43
8	CO_2	22.00	304.00	251.43
9	CO_2	22.00	398.80	251.43
10	CO_2	22.00	420.34	251.43
11	CO_2	5.74	313.07	251.43
12	CO_2	5.74	398.80	251.43
13	CO_2	5.74	402.86	251.43
14	CO_2	1.50	309.03	251.43
15	CO_2	1.50	300.03	251.43
16	CO_2	1.50	238.03	251.43
17	CO_2	1.50	238.03	251.43
18	CO_2	1.00	233.03	251.43
19	Water	0.77	378.74	100.00
20	Water	0.77	302.76	100.00
21	Water	0.77	400.05	182.20

22	Water	0.77	302.76	182.20
23	Water	1.00	302.76	75.00
24	Water	1.00	293.15	75.00
25	Water	0.73	304.85	130.00
26	Water	0.73	403.80	130.00
27	Water	1.37	403.80	74.10
28	Water	1.37	434.89	74.10
29	Water	0.73	321.68	80.00
30	Water	0.73	403.80	80.00
31	Water	1.37	403.80	8.58
32	Water	1.37	434.89	8.58
33	Water	1.00	293.15	48.00
34	Water	1.00	304.03	48.00

3. Methodology

3.1 Thermodynamic model

In this paper, the round-trip efficiency (RTE) is used to evaluate the capability of the LCES subsystem:

$$RTE = \frac{W_{\text{out}}}{W_{\text{in}}} \times 100\% = \frac{(w_{\text{ch-out}} - w_{\text{ref-out}}) \times t_{\text{ch}} + (w_{\text{disch-out}} - w_{\text{ref-out}}) \times t_{\text{disch}}}{w_{\text{LCES-in}} \times t_{\text{ch}}} \times 100\%$$

where RTE is the round-trip efficiency of the LCES subsystem, %; W_{out} is the outlet energy of the LCES subsystem, MWh; W_{in} is the inlet energy of the LCES subsystem, MWh; $w_{\text{ch-out}}$ is the outlet power of the LCES subsystem in the energy storage process, MW; $w_{\text{disch-out}}$ is the outlet power of the LCES subsystem in the energy release process, MW; $w_{\text{ref-out}}$ is the outlet power of the reference coal-fired power plant, MW; $w_{\text{LCES-in}}$ is the inlet power of the LCES subsystem in the energy storage process, MW; t_{disch} is the energy release time, h; t_{ch} is the energy storage time, h.

3.2 Conventional exergy analysis model

Conventional exergy analysis is a widely used approach for evaluating the capability of a component to convert various forms of energy into "higher energy". The exergy fuel and exergy production for the components are given in Table 2.

Table 2.

Exergy fuel and exergy production of the LCES subsystem components

Components	$\dot{E}_{F,k}$	$\dot{E}_{P,k}$
C	W_C	$\dot{E}_{C,out} - \dot{E}_{C,in}$
T	$\dot{E}_{T,in} - \dot{E}_{T,out}$	W_T
HX(HE、HR)	$\dot{E}_{HX,H,in} - \dot{E}_{HX,H,out}$	$\dot{E}_{HX,c,out} - \dot{E}_{HX,c,in}$
CES	$\dot{E}_{CES,H,in} - \dot{E}_{CES,H,out}$	$\dot{E}_{CES,c,out} - \dot{E}_{CES,c,in}$
CON	$\dot{E}_{CON,H,in} - \dot{E}_{CON,H,out}$	$\dot{E}_{CON,c,out} - \dot{E}_{CON,c,in}$
TV	$\dot{E}^{M}_{TV,out} - \dot{E}^{M}_{TV,in} - \dot{E}^{T}_{TV,out}$	$\dot{E}^{T}_{TV,out}$

PU	W_{pu}	$\dot{E}_{PU,out} - \dot{E}_{PU,in}$

3.3 Advanced exergy analysis model

The concept of exergy destruction is further refined in the advanced exergy model to include four distinct categories: endogenous, exogenous, avoidable, and unavoidable exergy destruction. It gains a more in-depth analysis of the LCES subsystem exergy performance and provides more supportive solutions for improving the LCES subsystem. In Figure 2, the precise calculating procedure is displayed.

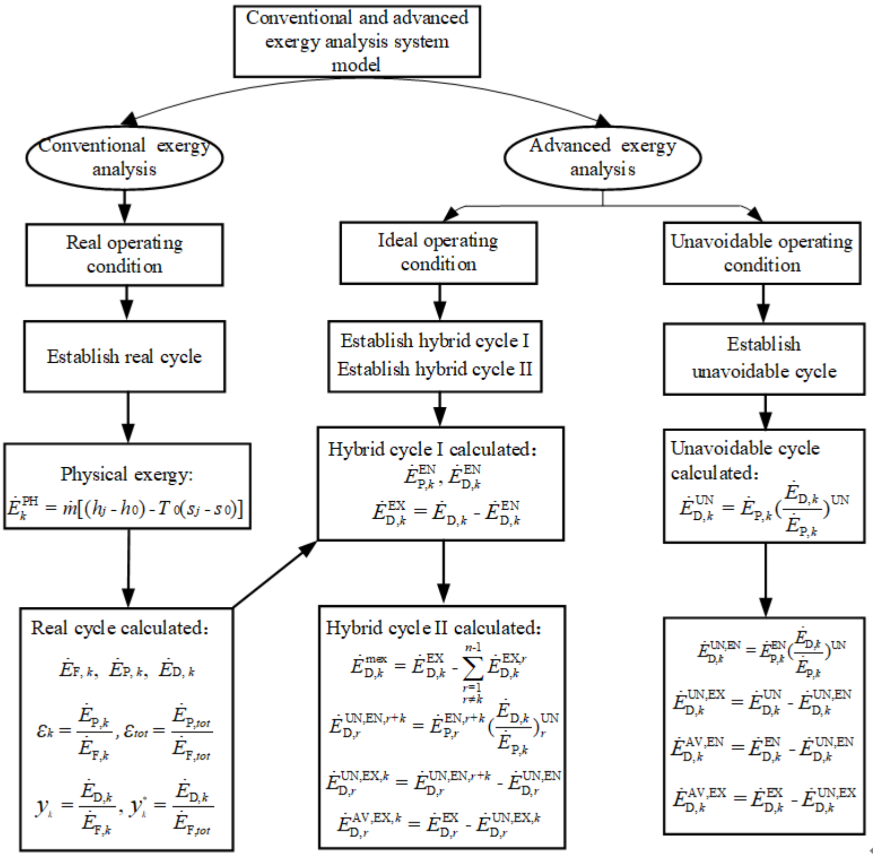


Figure 2. A flow chart of the calculation procedure

4. Results and discussion

4.1 Parameters of the proposed system

To increase the efficiency of the LCES system and maximize the utilization of heat from the coal-fired power plant, the CO_2 flow rate is increased to three times that of the reference LCES system during the 8-hour cycle. The data of the LCES subsystem under optimal conditions are shown in Table 3.

Table 3.

LCES subsystem parameters for optimal performance in the proposed system

Parameter	Unit	Value
Flow rate of CO_2	kg/s	251.43

LST pressure	MPa	1.50
LST temperature	K	238.03
HST pressure	MPa	20.00
HST temperature	K	302.15
Isentropic efficiency of compressor	%	85.00
Isentropic efficiency of turbine	%	85.00
Energy storage time	h	4.00
Energy release time	h	4.00

Based on the system simulation and thermal calculations, the results of the energy analysis for the proposed system are shown in Table 4. During the 4-hour energy storage process, compared to the base system, due to that the heat of compression in the LCES subsystem is recycled by the feedwater, the net power output of the coal-fired power plant increases by 71.00 MWh. During the 4-hour energy release process, the high-pressure CO_2 does the work in the turbine, generating 118.00 MWh of electricity. In conclusion, the LCES subsystem consumes 205.92 MWh of electricity over the whole cycle, while the LCES subsystem generates 124.63 MWh of electricity, resulting in the RTE of 60.52% for the LCES subsystem.

Table 4.

Energy analysis of the base system and the proposed system

Parameter	Unit	Base system	Proposed system
In the energy storage process			
Net power output of coal-fired power plant	MW	594.88	612.63
Electricity consumption of the LCES subsystem	MW	-	51.48
Electricity consumption of the LCES subsystem in the energy storage process	MWh	-	205.92
Power output of the LCES subsystem	MW	-	17.75
Power output of the LCES subsystem in the energy storage process	MWh	-	71.00
Power output of the proposed system in the energy storage process	MWh	2379.52	2521.52
In the energy release process			
Net power output of coal-fired power plant	MW	594.88	578.79
Power output of the turbine	MW	-	29.50
Power output of the turbine in the energy release process	MWh	-	118.00
Power output of the LCES subsystem	MW	-	13.41
Power output of the LCES subsystem in the energy release process	MWh	-	53.64
Power output of the proposed system in the energy release process	MWh	2379.52	2486.80
Evaluation criteria			
Electricity consumption of the LCES	MWh	-	205.92

subsystem			
Electricity generation of the LCES subsystem	MWh	-	124.63
Round-trip efficiency	%	-	60.52

4.2 Conventional exergy analysis

By establishing thermodynamic models of real, unavoidable and ideal conditions, the exergy analysis of the LCES subsystem is performed. MATLAB simulation software describes the thermodynamic properties of the mass by introducing the REFPROP reference data. Table 5 and Figure 3 give the outcomes of conventional exergy analysis and the exergy flow graph, separately. It is evident that the CES (5093.21 kW) is the component with greatest exergy destruction in the LCES subsystem, accounting for 23.58%. The relatively low exergy efficiency of the CES is caused by the high irreversible destruction resulting from the phase change process of CO_2 in the CES. The second largest exergy destruction is the HE2 (3075.12 kW), accounting for 14.24%, and it is caused by the large temperature variations of heat transfer in the HEB. In addition, the exergy destruction of C1, C2, T1 and T2 is also significant, which is due to the low isentropic efficiency (0.85) of the component. Besides, the exergy destruction of CON1, CON2, PU and HE3 is small, which implies that these components have less potential for improvement.

Table 5.

Conventional exergy analysis of the LCES subsystem

Component	$\dot{E}_{F,k}$ /kW	$\dot{E}_{P,k}$ /kW	$\dot{E}_{D,k}$ /kW	ε_k /%	y_k /%
C1	26685.44	23826.21	2859.23	89.29	4.16
C2	23729.43	21373.33	2356.10	90.07	3.43
HE1	5752.94	4338.72	1414.22	75.42	2.06
HE2	15044.85	11969.73	3075.12	79.56	4.48
HE3	344.74	307.99	36.75	89.34	0.05
HE4	2977.18	2808.81	168.37	94.34	0.25
HR1	5217.05	4589.62	627.43	87.97	0.91
HR2	9062.45	8659.73	402.72	95.56	0.59
T1	20013.98	17093.34	2920.64	85.41	4.25
T2	15849.75	13585.56	2264.19	85.72	3.30
CES	22004.89	16911.68	5093.21	76.85	7.42
CON1	116.99	48.27	68.72	41.26	0.10
CON2	81.37	39.52	41.85	48.57	0.06
TV	22192.92	22017.53	175.39	99.21	0.26
PU	658.76	563.29	95.47	85.51	0.14

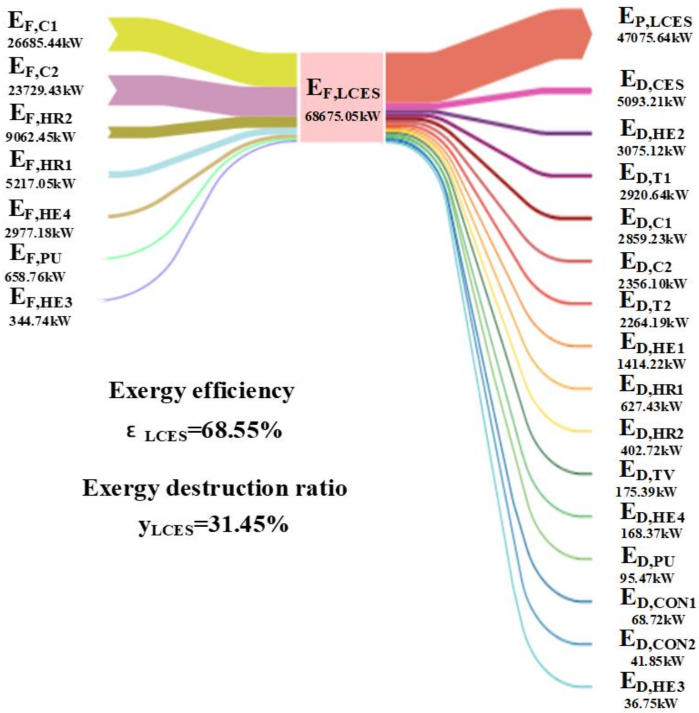


Figure 3. Detailed exergy flow of the LCES subsystem

4.3 Advanced exergy analysis

4.3.1 Exogenous and endogenous exergy destruction

From Figure 4, as can be observed: 1) Overall, compared to exogenous exergy destruction, endogenous exergy destruction is much larger. It can be inferred that the interdependence between the components is weak, suggesting that the interaction between different components is less effective in reducing exergy destruction. Therefore, more consideration should be given to modifying the components themselves when considering improvements in system performance. 2) The exogenous exergy destruction of the PU is 0, indicating that the structural is the only factor affecting its exergy destruction. 3) C2, HR2, CON1, CON2 and TV have negative exogenous exergy destruction, indicating that increasing the efficiency of the remaining components will cause the increases in their exergy destruction. When considering improvements these components, consideration should be given to increasing the exergy destruction of other components.

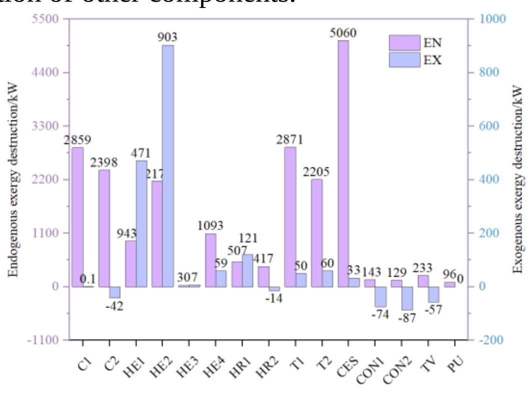


Figure 4. Exogenous and endogenous exergy destruction

4.3.2 Avoidable and unavoidable exergy destruction

As can be seen from Figure 5: 1) As a whole, the avoidable exergy destruction is far higher, so LCES subsystem performance can be greatly improved by increasing component efficiency. 2) T1 and C1 have the largest avoidable exergy destruction, followed by C2 and T2, so it is crucial to prioritize the improvement of these components. 3) For C1, C2, T1 and T2, the avoidable exergy destruction is much greater compared to the unavoidable exergy destruction, suggesting that the upgrading of these components will be more affected on the decrease of exergy destruction.

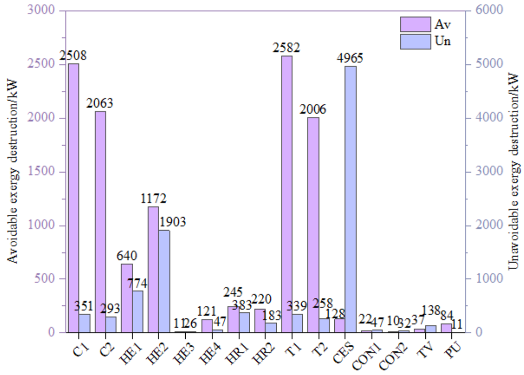


Figure 5. Avoidable and unavoidable exergy destruction

4.3.3 Avoidable exogenous and avoidable endogenous exergy destruction

Figure 6 gives avoidable endogenous and avoidable exogenous exergy destruction of each component. As can be seen from Figure 8: 1) In general, the avoidable endogenous exergy destruction is significantly greater. It shows that components themselves are mostly to blame for the avoidable exergy destruction. Therefore, when considering improvements to the LCES subsystem, the focus should be on component improvements. 2) The avoidable exogenous exergy destruction of C2, HR2, CON1, CON2 and TV is all negative, indicating that decreasing their exergy destruction leads to increasing the exergy destruction of other components. 3) The avoidable endogenous exergy destruction of C1, C2, T1 and T2 is much larger compared to the avoidable exogenous exergy destruction, suggesting that these components have less interaction with other components and should be prioritized for optimization during the improvement process.

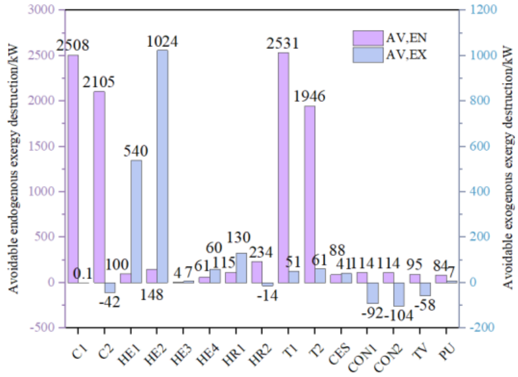


Figure 6. Avoidable endogenous and avoidable exogenous exergy destruction

The conventional exergy analysis can only calculate specific values of exergy destruction, whereas the advanced exergy analysis can pinpoint the real improvement priority of components and provide specific information about the interconnections between components. According to Figure 7, by comparing the outcomes of the conventional exergy analysis, the improvement priority of each component can be determined. It is demonstrated that the conclusions drawn from the conventional and advanced exergy analysis are very different. For example, in the conventional exergy analysis, CES has the greatest exergy destruction and is prioritized as the first level of improvement. In contrast, CES is ranked ninth in the advanced exergy analysis, since most of its exergy destruction is unavoidable.

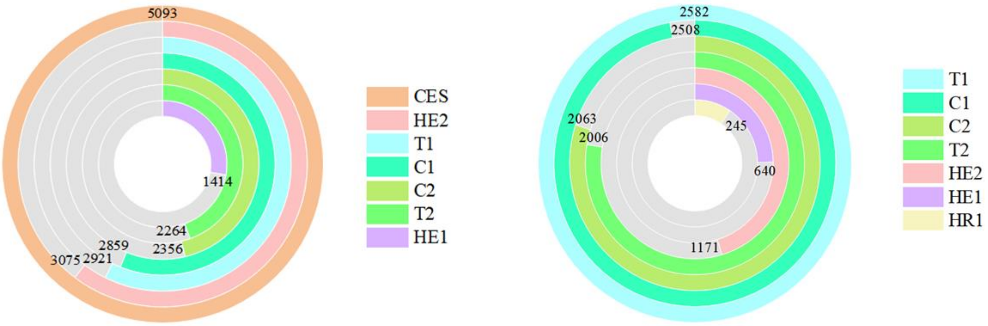
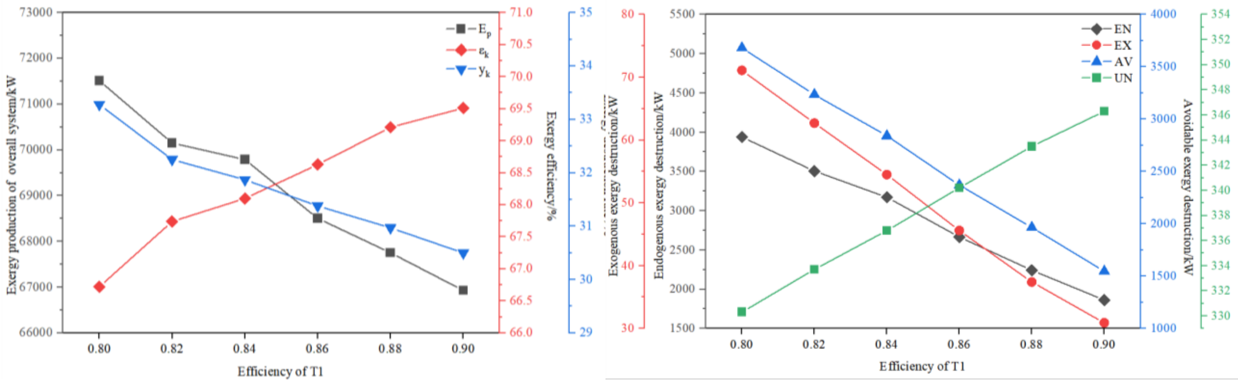


Figure 7. Comparison with improvement priority of components in conventional and advanced exergy analysis

5. Sensitivity analysis

5.1 Effect of the efficiency of T1

As illustrated in Figure 8, when the efficiency of T1 increases from 0.80 to 0.90, the exergy fuel of the LCES subsystem decreases from 71.51 MW to 66.95 MW, while the exergy efficiency increases from 66.72% to 69.51%. As the T1 efficiency increases, it leads to a decrease in turbine outlet pressure and a decrease in the work done by the turbine, which in turn affect the exergy performance of the LCES subsystem. When the efficiency of T1 increases from 0.80 to 0.90, exogenous, endogenous and avoidable exergy destruction of T1 decrease, but unavoidable exergy destruction increases, showing that the improvement capacity of the turbine is greatly reduced by boosting the isentropic efficiency.

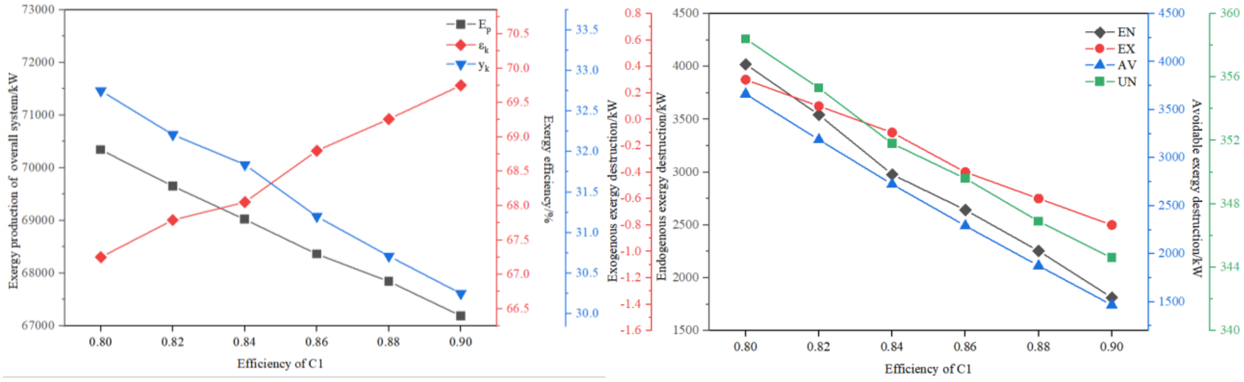


a). Conventional exergy analysis results **b).** Advanced exergy analysis results

Figure 8. Effect of the efficiency of T1 on conventional and advanced exergy analysis results of the LCES subsystem

5.2 Effect of the efficiency of C1

As illustrated in Figure 9, when the efficiency of C1 increases from 0.80 to 0.90, the exergy fuel of the LCES subsystem decreases from 70.32 MW to 67.24 MW, while the exergy efficiency increases from 67.25% to 69.75%. As the C1 efficiency increases, it causes an increase in compressor outlet pressure and a decrease in compressor power consumption, which in turn affect the exergy performance of the LCES subsystem. When the efficiency of C1 increases from 0.80 to 0.90, endogenous, exogenous, avoidable and unavoidable exergy destruction of C1 decrease. However, the reduction pace of avoidable exergy destruction is faster than the reduction pace of unavoidable exergy destruction, suggesting that the potential for improvement will be increased by upgrading the isentropic efficiency.



a). Conventional exergy analysis results **b).** Advanced exergy analysis results

Figure 9. Effect of the efficiency of C1 on conventional and advanced exergy analysis results of the LCES subsystem

6. Conclusion

This paper proposes a novel integrated system that couples a liquid carbon dioxide energy storage (LCES) system and a coal-fired power plant. The proposed system is investigated by energy analysis and exergy analysis. The conclusions reached are as follows:

1) The energy analysis results indicate that in the whole cycle, the electricity consumption and electricity generation of the LCES subsystem is 205.92 MWh and 124.63 MWh. The RTE is 60.52%, which is 2.35% greater than the reference LCES system (58.17%).

2) In the conventional exergy analysis, the CES (5093.21 kW) is the component with the greatest exergy destruction in the LCES subsystem, accounting for 23.58%, and the exergy destruction is brought on by the phase change of CO_2 in CES.

3) The advanced exergy analysis shows that 47.44% of exergy destruction is attributable to avoidable endogenous exergy destruction. The first turbine has the greatest avoidable endogenous exergy destruction, with 24.71%, indicating that it has the maximum improvement possibility.

4) Sensitivity analysis reveals that improving the isentropic efficiency of the first turbine (T1) and the first compressor (C1) has a positive impact on optimizing the exergy performance of the LCES subsystem

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Nomenclature

E	exergy (kW)	t	time (h)
h	specific enthalpies (kJ/kg)	T	temperature (K)
m	mass flow rate (kg/s)	w	power (MW)
P	pressure(MPa)	W	power (MWh)
Q	caloric value (kJ/kg)	y	exergy destruction ratio (%)
s	specific entropies (kJ/(kg·K))	y^*	relative exergy destruction ratio (%)

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