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Integrating compressed CO_2 energy storage in an oxy-coal combustion power plant with CO_2 capture

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ABSTRACT

To compensate for the high cost of CO_2 capture, this study proposes a novel solution that integrates a compressed CO_2 energy storage (CCES) system into an oxy-coal combustion power plant with CO_2 capture (Oxy_CCES). The integration of energy storage has the potential to create arbitrage from variations in electricity prices. The proposed Oxy_CCES system can achieve a higher net efficiency of 34.1%, and a higher exergy efficiency of 57.5%, than that of a liquified oxygen storage-integrated oxy-coal combustion power plant (Oxy_O_2). Two scenarios, i.e., retrofitting an existing oxy-coal combustion power plant (S−I) and building a new plant (S-II), were established to compare the Oxy_CCES and Oxy_O_2. In S−I, the payback time of the Oxy_CCES is one year and in the S-II the levelized cost of electricity (LCOE) of the Oxy_CCES increases by 1.8%, which is lower than that of the Oxy_O_2. The sensitivity analysis shows that, when the difference between the peak and the valley electricity prices and the capacities of the energy storage systems increase by 50%, the net present value (NPV) and LCOE of the Oxy_CCES system increase by 113.4% and 1.7% respectively, which are lower than the NPV and LCOE increase of the Oxy_O_2.

1. Introduction

According to the International Energy Agency, fossil fuels account for more than 80% of the world's energy supply [1]. However, the heavy reliance on fossil fuels leads to global climate change and significant environmental problems due to CO_2 emissions [2]. To achieve the target of limiting global warming to below 2 °C, annual CO_2 emissions should decrease by 25% by 2030 and carbon capture and storage (CCS) plays an essential role in achieving the target [3].

CO_2 capture technologies can be generally divided into three categories: post-combustion capture, pre-combustion capture, and oxy-fuel combustion capture [4–6]. Compared to others, oxy-coal combustion CO_2 capture shows the advantages of robustness and no need for chemicals, which can create secondary pollution [7–10]. Even though the technical feasibility of CO_2 capture has been demonstrated, the high cost due to efficiency penalty is still the main barrier to its wide application.

Due to the intermittent nature of renewable energy, the rapidly growing deployment of renewable energy bring significant challenges to the grid on balancing the supply and demand. Consequently, it can lead to more significant fluctuations in electricity price [11,12]. To overcome such challenges, energy storage attracts increasing attention, which can not only increase the reliability of the power grid but also make arbitrage from the price variation. To this end, our previous work [13] proposed an innovative solution, which integrated liquified oxygen storage with oxy-coal combustion CO_2 capture. The liquified oxygen storage system works as an energy storage system, and therefore, can derive arbitrage from the variation of electricity price in the peak and off-peak hours. This solution can reduce the capture cost, and thus stimulate the application of CO_2 capture. However, the deployment of oxy-coal

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Abbreviations

CO_2	Carbon dioxide
CCES	Compressed carbon dioxide energy storage
CCS	Carbon capture and storage
CAES	Compressed air energy storage
Oxy_ref	Oxy-coal combustion power plant
ASU	Air separation unit
Oxy_O_2	Liquified oxygen storage-integrated oxy-coal combustion power plant
Oxy_CCES	Compressed CO_2 energy storage system-integrated oxy-coal combustion power plant
RTE	Round-trip efficiency
HP	High pressure
HPT	High pressure turbine
IPT	Inter pressure turbine
LPT	Low pressure turbine
HT	Heat exchanger
IC	Intercooler
TIC	Total investment cost
O&M	Operation and maintenance
LHV	Low heating value
S–I	Scenario I
S-II	Scenario II
NPV	Net present value
KPI	Key performance indication
CI	Cash inflow
CO	Cash outflow
LCOE	Levelized cost of electricity
TOU	Time of use
SOC	Stage of charge
UIC	Unit investment cost

combustion CO_2 capture is still struggling to tackle the challenges on the requirement of low temperature and system complexity of liquified oxygen storage [14]. Meanwhile, except for our previous work [13], no other studies on integrated carbon capture and energy storage have been found in the existing literature.

For large-scale energy storage, compressed air energy storage (CAES) represents a promising technology [15–18], which has the advantages of long lifetime, large capacity, and low levelized cost [19]. However, the energy efficiency of CAES is relatively low, i.e., about 50% [20]. Apart from compressed air, compressed CO_2 has been proposed to be the working fluid for energy storage, i.e., compressed CO_2 energy storage (CCES) [21–24]. By contrast, CCES can achieve a higher energy storage density since CO_2 has a larger molecular weight than air [25]. CO_2 also has a high dew point, and thus it is easy to condense. Therefore, a pump, instead of a compressor, can be used in a CCES system, and this can increase the energy efficiency of energy storage [26]. In addition, CCES can achieve low storage temperatures and low outlet temperatures for compressors, which is more conducive to the design and maintenance of the system [26]. However, compared to CAES, a low-pressure gas tank is needed to store low-pressure CO_2 in CCES, which will increase the investment cost.

Inspired by the idea of combining CO_2 capture with energy storage, this work proposes a novel design to integrate CCES technology with an oxy-coal combustion CO_2 capture system. Such a design can reduce the cost of CCES from two perspectives: (I) as the captured CO_2 can be directly used in the CCES system, the low-pressure gas tank for storing low pressure CO_2 can be omitted; and (II) the compressors for CO_2 transport can also be used in the CCES system. As a result, the proposed integrated system can potentially achieve a better economic outlook. The objective of this paper is to evaluate the techno-economic feasibility of integrating CCES in an oxy-coal combustion power plant with CO_2 capture. To illustrate its advantages, the integration of CCES will also be compared to the integration of a liquified oxygen storage. The results will provide guidance on how to select energy storage technology for the integration of CO_2 capture and insights on how the cost of CO_2 capture can be reduced.

The main contributions of this paper include: 1) a novel system design that combines compressed CO_2 energy storage and carbon capture with an oxy-coal combustion power plant; and 2) the techno-economic assessment of the proposed system.

2. System description

Three systems, including an oxy-coal combustion power plant and two oxy-coal combustion power plants integrated with energy storage, i.e., a liquified oxygen storage and a CCES, are included in this study.

2.1. Oxy-coal combustion power plant without energy storage (Oxy_ref)

An oxy-coal combustion power plant with CO_2 capture (Oxy_ref) is illustrated in Fig. 1. Compared to conventional air-combustion power plants, an air separation unit (ASU) provides high purity oxygen for combustion. To control the flame temperature, a part of the flue gas after combustion is circulated back to the combustion chamber and mixed with oxygen [15]. The flue gas mainly consists of CO_2, moisture, and other pollutants, such as NO_x and SO_x. After flue gas cleaning and condensation, the CO_2 concentration in flue gas can reach more than 90% [27]. However, to meet the requirement of CO_2 purity for transportation, purification treatment should be further implemented to separate non-condensable gases, such as O_2, N_2, and Ar. The energy consumption of the ASU and the carbon dioxide purification and compression unit accounts for 9–13% of the gross power output [27].

2.2. Oxy-coal combustion power plant integrated with liquified oxygen storage (Oxy_O_2)

As the ASU consumes a large amount of electricity, shifting the ASU load to generate more electricity at high electricity prices can offset part of the cost of CCS. To achieve this purpose, the oxygen needed during peak hours should be produced during off-peak hours and stored, and the ASU can be shut down to increase power output. Oxy_O_2 is shown in Fig. 2. Compared to Oxy_ref, the ASU capacity in Oxy_O_2 should be enlarged since extra oxygen should be produced for storage. The capacity increase is mainly determined by the length of peak and off-peak periods. During off-peak hours, oxygen produced by AUS is divided into two streams: one is fed into the boiler, and the other is stored for peak hours.

2.3. Oxy-coal combustion power plant integrated with a compressed CO_2 energy storage system (Oxy_CCES)

The sketch of the Oxy_CCES is displayed in Fig. 3. Captured CO_2

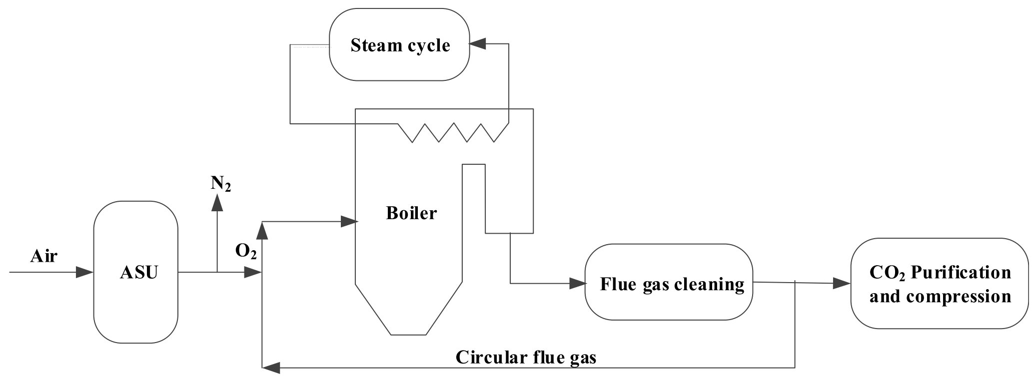

Fig. 1. An oxy-coal combustion power plant without energy storage (Oxy_ref) (ASU: air separation unit).

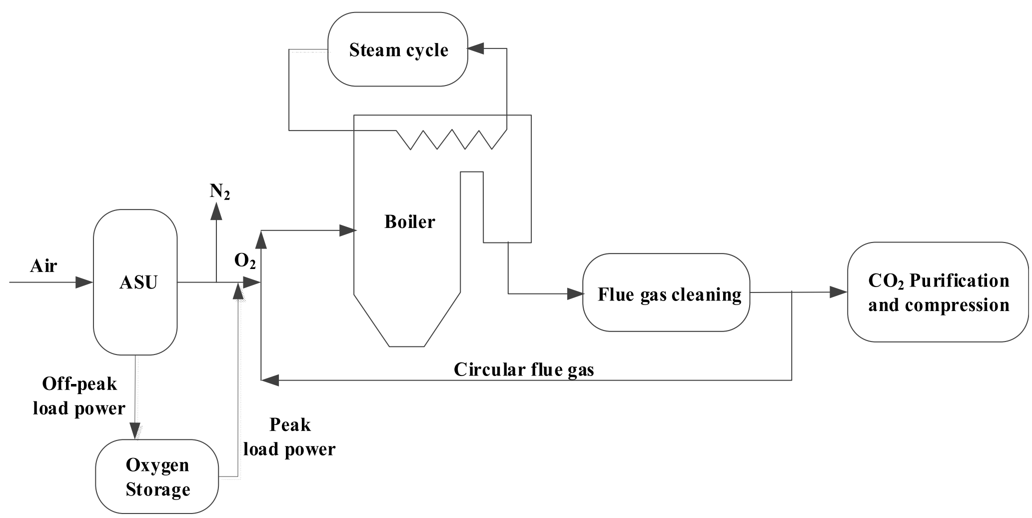

Fig. 2. An Oxy-coal combustion power plant integrated with liquified oxygen storage (Oxy_O_2) (ASU: air separation unit).

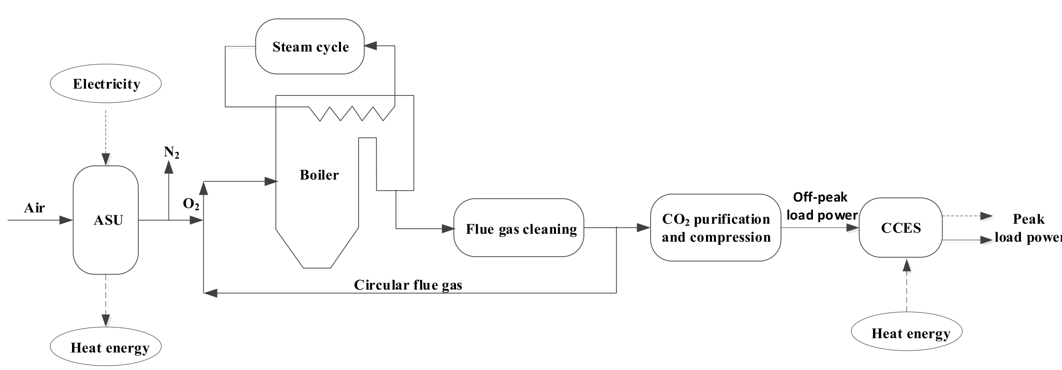

Fig. 3. Oxy-coal combustion power plant integrated with CCES (Oxy_CCES) (ASU: air separation unit, CCES: compressed carbon dioxide energy storage).

is compressed and stored during off-peak hours. During peak hours, compressed CO_2 is used to generate electricity, which can be sold to the grid. Although heat can be recovered from the compression process, extra fuel is still needed to heat CO_2 to reach the ideal inlet temperature of CCES.

The schematic diagram of the CCES system is shown in Fig. 4. A recuperator is involved in the CCES to improve the round-trip efficiency (RTE) [26]. In the charging process, CO_2 is firstly compressed to 73 bar and condensed to 30 °C, and then liquified CO_2 is further boosted to 110 bar using a pump. In the discharging process, the stored liquid CO_2 absorbs the recovered heat from the turbines and is sent into the expanders. To achieve a high efficiency, it is assumed that the inlet CO_2 is heated to 538 °C by feeding the recovered heat from the ASU and burning additional fuel. The fuel is the same as that used in the power plant. More information about the CCES can be found in our previous work [26].

2.4. *Case study*

To compare the performance of the three systems, an oxy-coal

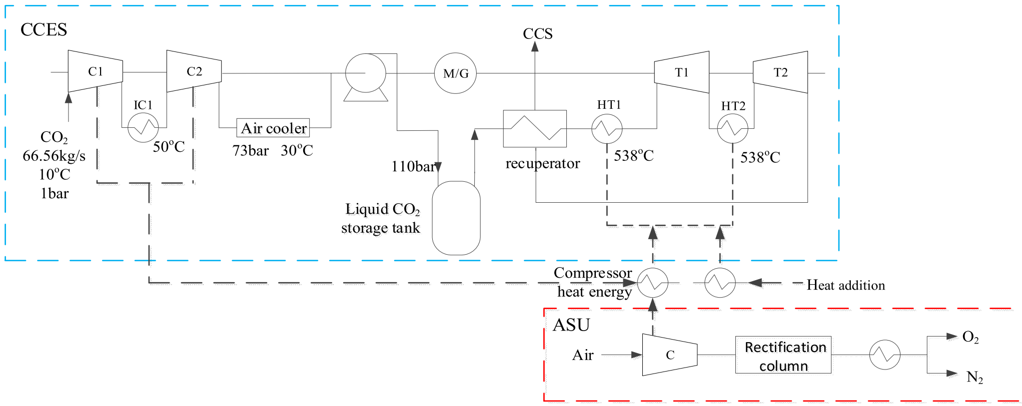

Fig. 4. A compressed CO_2 energy storage (CCES) system. (C: compressor; M: motor; G: generator; T: turbine; and CCS: CO_2 capture and storage).

combustion plant with CO_2 capture was employed as a case study [28]. The models of the Oxy_ref, the Oxy_O_2, and the Oxy_CCES were developed in ASPEN PLUS. The key inputs are summarized in Table 1. To compare the liquified oxygen storage and the CCES, it is assumed that the volume of the liquified oxygen storage tank is the same as the volume of the liquid CO_2 storage tank.

Table 1
Key inputs and assumptions used in the case study.

Parameter	Unit	Value
Oxy_ref		
Boiler capacity	MW	532
Excess oxygen	%	4
ASU capacity	MW	87
Oxygen temperature	°C	−33.1
Oxygen pressure	bar	1.4
HP stream pressure	bar	290
HP stream temperature	°C	600
Reheat stream pressure	bar	60
Reheat stream temperature	°C	620
HPT efficiency	%	90.3
IPT efficiency	%	93.5
LPT efficiency	%	88.2
Feed water pump efficiency	%	80
Annual operating hours	h/year	7446
Lifecycle	years	25
Total investment cost (TIC)	MUSD	1462.9
Fixed O&M cost (% of TIC)	%	4
Oxy_O_2		
Oxygen storage capacity	MW	54.7
Oxygen storage temperature	°C	−196
Oxygen storage pressure	bar	0.2
Total investment cost (TIC)	MUSD	77
Oxy_CCES		
Compressor inlet temperature	°C	21.5
Compressor inlet pressure	bar	1.01
Pump inlet temperature	°C	30
Pump inlet pressure	bar	72.1
Liquid CO_2 storage temperature	°C	21.5
Liquid CO_2 storage pressure	bar	110
Turbine inlet temperature	°C	538
Turbine inlet pressure	bar	110
Turbine outlet temperature	°C	144
Turbine outlet pressure	bar	1.01
Total investment cost (TIC)	MUSD	25.9
Fuel		
Proximate analysis		
Moisture		25
Fixed carbon		45.1
Ash		9.2
Volatile matter		45.7
Ultimate analysis		
C		67.2
H		4.8
N		1.1
S		1.3
O		16.4
LHV	MJ/kg	27.2

The unit investment cost (UIC) of energy storage systems is calculated as follows:

$$UIC = \frac{TIC}{Capacity} \tag{1}$$

2.5. Scenarios and key performance indicators

Two scenarios are considered for evaluating the economic performance of the three systems and performing the comparison.

2.5.1. Scenario I (S− I): retrofitting an existing oxy-coal power plant

In this scenario, an existing oxy-coal power plant is retrofitted by integrating a new energy storage system with the plant. The investment cost mainly covers the cost of the energy storage system.

Energy efficiency, net present value (NPV), and exergy efficiency are selected as key performance indicators (KPIs) for system comparison.

Energy efficiency is calculated as [29]:

$$\varphi_{ee} = \frac{P_{out} t_{dis}}{P_c t_{ch} + P_{in} t_{dis}} \tag{2}$$

where t denotes the working time; P_{out} is the total power output of the system; P_c is the total power consumption of the system; P_{in} is the total power input of the system; and the subscripts *ch* and *dis* refer to charging and discharging, respectively.

The exergy efficiency of the liquified oxygen storage system is shown as:

$$\eta_{ex} = \frac{E_{oxygen}}{E_{air} + E_{w,in}} \tag{3}$$

where E_{oxygen} is exergy of oxygen, E_{air} is exergy of air, and $E_{w,in}$ is input electricity energy.

The exergy efficiency of the CCES is shown as:

$$\eta_{ex} = \frac{E_{w,out}}{E_{fuel} + E_{w,in}} \tag{4}$$

where $E_{w,out}$ is output electricity energy, E_{fuel} is the exergy of fuels, and $E_{w,in}$ is input electricity energy.

NPV is calculated as:

$$NPV = \sum \frac{CI_t - CO_t}{(1+i)^t} \quad (5)$$

where *CI* denotes cash inflows which are from the income of selling electricity; *CO* is cash outflows which are mainly for investments and O&M cost, *t* is the life span of the power plant (hour), and *i* denotes discount rate.

It is assumed that the construction of the two systems has been finished before their operation. Since construction time may affect their NPVs and payback periods, the detailed effects can be investigated in future studies.

2.5.2. Scenario II (S− II): building a new oxy-coal power plant with energy storage

In this scenario, levelized cost of electricity (LCOE) is used as a KPI to examine the performance of the three plants, which can be calculated as [30]:

$$LCOE = \frac{I_0 + \sum \frac{TCM_t + TCF_t}{(1+i)^t}}{\sum \frac{E_e}{(1+i)^t}} \quad (6)$$

where I_0 is the total investment cost of a power plant; *t* is the life span of the power plant measured in hour; *TCF* is the cost of fuel consumption; *TCM* is the operation and maintenance (O&M) cost; E_e is the power generation (MWh); and the *i* denotes discount rate.

2.6. Electricity price

Electricity price is widely recognized as the most effective factor for stimulating load shifting [31]. With properly designed electricity prices, users can be encouraged to use less electricity at peak hours and more electricity at off-peak hours. Resultantly, load shifting relieves the pressure of power supply at peak hours and reduces the idle rate of power plants at off-peak hours. The design and operation of oxygen storage and CCES are dependent on the electricity price. As seen in Fig. 5, the time of use (TOU) price is used in this study, and the TOU price is one of the common pricing mechanisms for demand management. The daily peak period of the high electricity price is 8 h, and the off-peak period is 16 h, including the hours of the low and medium price. Both the liquified oxygen storage and the CCES system charge in the off-peak period, while they discharge in the peak period.

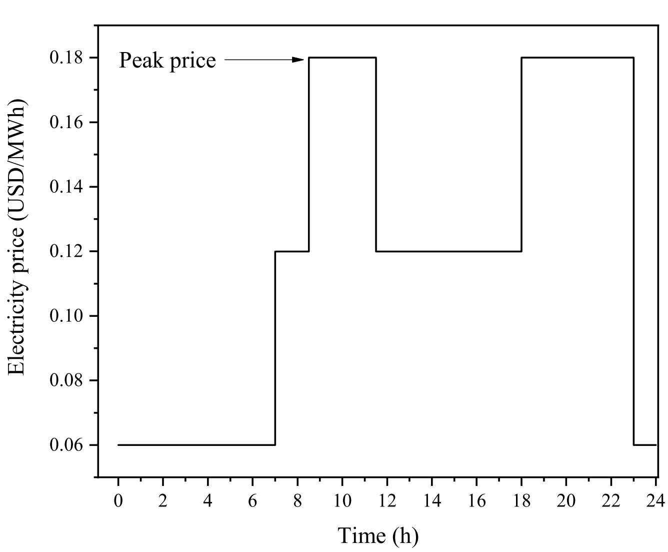

Fig. 5. Time-of-use electricity price used in this study [32].

3. Results and discussion

In this study, the proposed models are validated through comparisons with existing studies, and related results are summarized in Appendix II.

3.1. Technical performance of the three systems

Based on the oxygen demand of the oxy-coal combustion power plant, the volume of the liquefied oxygen storage tank is determined as 2020 m^3. The liquefied oxygen storage system could supply oxygen at a flowrate of 184.2 kg/s, which corresponds to a power capacity of 54.7 MW.

Since the liquified CO_2 storage tank has the same volume as the oxygen tank, the CO_2 storage pressure is 110 bar, and the stored liquefied CO_2 is 1.7×10^3 ton (ambient temperature 21.5 °C). Based on the storage capacity, the discharge power of the CCES is 55.3 MW and the charge power is 19.6 MW. The additional heat that should be fed into the CCES is 34.5 MW.

Based on simulations, the net power output and net efficiency of the three systems are reported in Table 2. The net power output of the Oxy_ref is 516.6 MW. Compared to the Oxy_ref, the net power output of the Oxy_O_2 and the Oxy_CCES increases by 87.0 MW and 35.7 MW at peak hours, respectively. However, the net efficiency of the Oxy_O_2 and the Oxy_CCES decreases by 1.5% and 1.2%, respectively, which is mainly due to the low charging efficiency.

The net power outputs of the three systems are shown in Fig. 6(a). The power output of the Oxy_Ref remains constant during the 24 h because the load is assumed to be constant. The other two systems produce more electricity than the Oxy_ref does when the electricity price is at its peak level. At the same time, less electricity is generated when the price is at the valley level. As regards the Oxy_O_2, the magnitude of the changes in the power outputs equals the capacity of the ASU, i.e., 87 MW. The Oxy_O_2 adjusts its operation by turning on or switching off the ASU according to the electricity price. In contrast, the variation magnitude in the power outputs of the Oxy_CCES at the peak hours is higher than the variation magnitude at the off-peak hours. Note that the variation magnitude is dependent on the capacity of oxygen storage and CO_2 storage, while the influence of energy demand is ignored in the study. In addition, the state of changes (SOCs) of the two energy storage systems are identical, as shown in Fig. 6(b). It is because the operations of the two energy storage systems correspond to the same variation pattern of electricity price. It is assumed that the liquified oxygen storage and the compressed carbon dioxide storage systems are always operating, and thus their starting up and shutting down stages are neglected. The above results imply that the integration of an energy storage system into an oxy-coal combustion power plant would negatively affect the net efficiency and power output of the plant.

3.2. Economic performance

3.2.1. Scenario I: retrofitting an existing oxy-coal power plant

Table 3 compares the capacity, unit investment cost, exergy efficiency, and energy efficiency of the liquified oxygen storage and the CCES. With the same tank volume, the unit investment costs of the Oxy_O_2 and the Oxy_CCES are 77.0 MUSD and 25.9 MUSD, respectively, both higher than that of the Oxy_Ref. However, the

Table 2
Key technical parameters of different systems.

	Oxy_ref	Oxy_O_2		Oxy_CCES	
		Off-peak	Peak	Off-peak	Peak
Net power output (MW)	516.6	461.9	603.6	497.0	552.3
Daily net power output (MWh)	12398.4	7390.4	4828.8	7952.0	4418.4
Net efficiency (%LHV)	34.4%	30.8%	40.2%	33.1%	36.0%

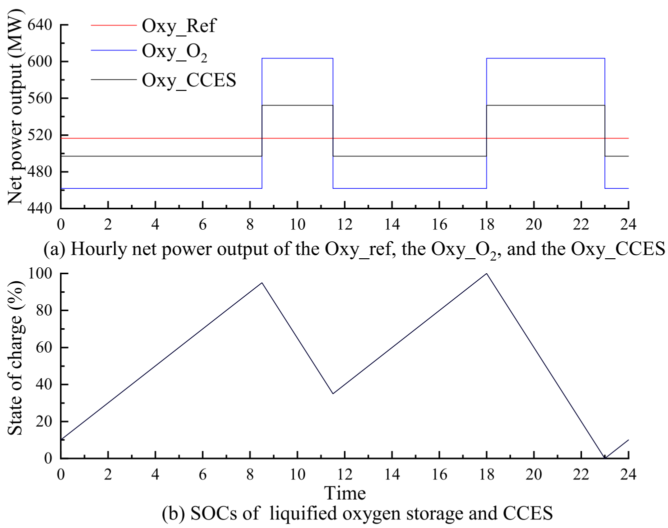

Fig. 6. Dynamic performance of the three systems (SOC: state of charge).

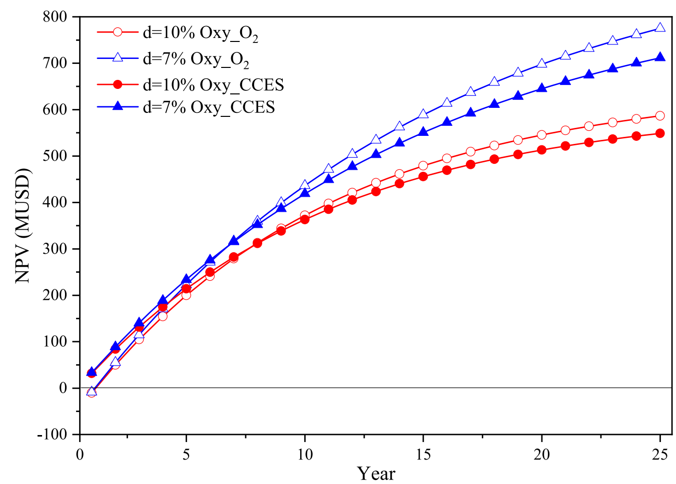

Fig. 7. NPV analysis for the investment to the Oxy_CCES and Oxy_O_2 (NPV: net present value).

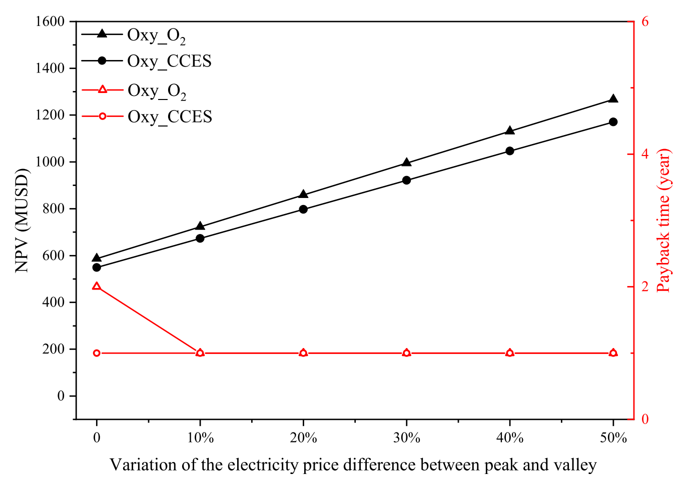

Fig. 8. Effects of the difference between the peak and the valley electricity prices on NPVs (NPV: net present value).

Table 3
The capacity, unit investment cost, exergy efficiency and energy efficiency of liquified oxygen storage and the CCES.

	Liquified oxygen storage	CCES
Capacity (MWh)	437.6	442.4
Unit investment cost (MUSD/MWh)	0.18	0.06
Exergy efficiency (%)	41.0	57.5
Energy efficiency (%)	79.5	75.0

heat consumption in the CCES leads to an extra fuel cost of 2.6 MUSD/year. In the meantime, the exergy efficiency of the CCES is much higher than that of the liquified oxygen storage, while the energy efficiency of the CCES is slightly lower than that of the liquified oxygen storage.

Discount rate, the difference between the peak and the valley electricity prices, and the capacity of the energy storage systems are major parameters affecting the techno-economic performance of the Oxy_O_2 and the Oxy_CCES systems. Therefore, sensitivity analysis are implemented to examine the effects of these parameters.

The discount rate has a significant effect on the NPV and the payback time, and thus two different discount rates, i.e., 7% and 10%, were considered. Fig. 7 shows the influence of the discount rate on the NPVs of the Oxy_CCES and the Oxy_O_2. In general, the CCES has a shorter payback time than the liquified oxygen storage, due to a smaller investment. However, due to a smaller annual income, i.e., 468.8 MUSD for the CCES in contrast to 476.0 MUSD for the Oxy_O_2, the Oxy_CCES has a smaller NPV than the liquified oxygen storage.

The difference between the peak and off-peak electricity prices is another key factor affecting the economic performance of the energy storage systems. Fig. 8 shows the NPV and payback time of the Oxy_O_2 and the Oxy_CCES against the difference between the peak and off-peak electricity prices. Given the baseline difference between the peak and off-peak electricity prices is 0.12 USD/kWh, the variations from 0% to +50% are considered.

Results imply that both retrofitting projects can benefit from a larger difference between the peak and the valley electricity prices. In general, the NPVs of the Oxy_O_2 and Oxy_CCES increase with the difference between the peak and the valley electricity prices. When the difference between the peak and the valley prices increases by 50%, the NPVs of the Oxy_O_2 and Oxy_CCES increase by 115.9% and 113.4%, respectively. Because the income of the Oxy_O_2 is slightly higher than that of the Oxy_CCES, the NPV of the Oxy_O_2 grows marginally faster than that of the Oxy_CCES. When the electricity price difference is larger than the baseline level, the payback time of both projects is only one year.

The capacity of the energy storage systems can also significantly affect the revenues of the energy storage systems. Fig. 9 shows the NPVs of the Oxy_O_2 and the Oxy_CCES when the energy storage capacity is varied by −30%−50%.

In general, variations in energy storage capacity do not affect the payback time of the Oxy_O_2 and the Oxy_CCES. At the same time, the NPVs of the two systems decline with the increase in energy storage capacity. The findings indicate that the enormous investment costs for energy storage negatively affect the economic performance of the entire integrated systems, and that the high investment costs are a significant barrier for the deployment of large-scale energy storage technologies. By comparison, the NPV of the Oxy_O_2 declines faster than that of the Oxy_CCES, and the NPV of the Oxy_CCES becomes higher than that of the Oxy_O_2 when the energy storage capacity increases by 10%. The findings imply that the Oxy_CCES represents a more economically attractive option than the Oxy_O_2 for large-scale applications.

3.2.2. Scenario II: building a new oxy-coal power plant with energy storage

The LCOE and related economic parameters for building a new oxy-coal plant with energy storage are reported in Table 4. Compared with the Oxy_ref, although the Oxy_O_2 and the Oxy_CCES can respectively gain an extra income of 14.4 MUSD/year and 7.2 MUSD/year through load shifting, their LCOE increases by 5.6 USD/MWh and 2.6 USD/MWh, mainly due to the high investment cost of the two energy storage systems. Meanwhile, extra O&M cost enhances cost of Oxy_O_2 and Oxy_CCES, which leads to bad economic performance when a new power plant is built.

A sensitivity analysis was implemented to evaluate the effects of the energy storage capacity on the LCOEs and the net power outputs of the Oxy_O_2 and the Oxy_CCES system. Results are illustrated in Fig. 10, where the energy storage capacity varies from −30% to +50%.

In general, the LCOEs increase with the energy storage capacity, and the net power outputs decline with the energy storage capacity. The results show that the integration of energy storage systems negatively affects the techno-economic performance of power plants and that the larger the energy storage capacity is, the more significant the effects are. By comparison, the effects of energy storage capacity in the Oxy_CCES system are less significant than the effects in the Oxy_O_2 system.

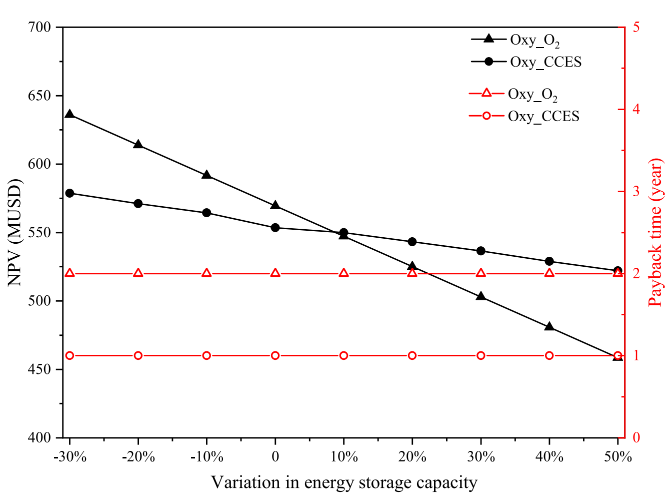

Fig. 9. Effects of energy storage capacity on net present values and payback time (NPV: net present value).

Table 4
The LCOE and related economic parameters of the three systems.

	Oxy_ref	Oxy_O_2	Oxy_CCES
Total investment cost (MUSD)	1462.9	1539.9	1488.8
Extra O&M cost (MUSD)	0.0	2.4	2.4
Net power output (GWh)	96165.1	94775.0	95947.5
Levelized cost of electricity (USD/MWh)	146.0	151.6	148.6

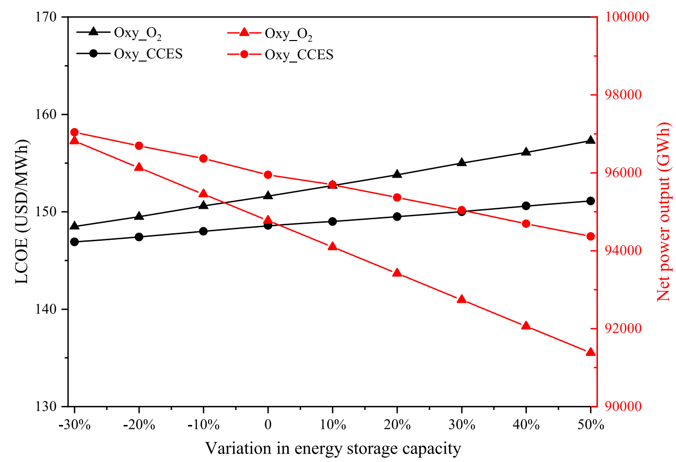

Fig. 10. Effects of energy storage capacity on LCOEs (LCOE: levelized cost of electricity).

4. Conclusions

This paper proposes to integrate compressed CO_2 energy storage (CCES) into an oxy-coal combustion power plant (Oxy_CCES) with carbon capture, which can reduce the cost of CO_2 capture. The proposed system is further compared with an oxy-coal combustion power plant integrated with a liquefied oxygen energy storage system (Oxy_O_2). The following conclusions have been obtained:

1) The integration of a CCES with an oxy-coal combustion power plant (Oxy_CCES) can achieve a higher net efficiency (34.1%) than the integration of a liquified oxygen storage with the plant (Oxy_O_2) (34.0%).
2) The liquified oxygen energy storage system can achieve an energy efficiency of 79.5%, which is higher than that of the CCES, i.e., 75.0%, while the CCES can achieve an exergy efficiency of 57.5%, which is higher than that of the liquified oxygen storage, i.e., 41.0%.
3) In the scenario of retrofitting an existing oxy-fuel combustion power plant (S–I), the payback time of the proposed Oxy_CCES is one year, which is shorter than that of the Oxy_O_2.
4) In the scenario of building a new plant (S-II), the levelized cost of electricity (LCOE) of the Oxy_CCES increases from 146.0 USD/MWh to 148.6 USD/MWh due to the integration of a CCES. In contrast, it is lower than the LCOE of the Oxy_O_2, which is 151.6 USD/MWh.
5) The sensitivity analysis shows that, when the difference between the peak and the valley electricity prices increases by 50%, the net present value (NPV) of the Oxy_CCES system increases by 113.4%, which is lower than the NPV increase of the Oxy_O_2; When the capacities of the energy storage systems increase by 50%, the LCOE of the Oxy_CCES increases by 1.7%, which is lower than the LCOE increase of the Oxy_O_2.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix I

Simulations of the combustion process are based on the following assumptions: (1) The combustion process is divided into four continuous steps: pulverized coal drying, pyrolysis, combustion, and flue gas dedusting; (2) All modules are in a stable running state, and the parameters do not change with time; (3) O2, CO2, and pulverized coal are uniformly mixed in the combustion reactor; (4) Ash does not participate in chemical reactions during combustion; and (5) There is no pressure loss in heat exchange processes. The processes of the power plant, the air separation unit (ASU), and the compressed carbon dioxide energy storage (CCES) are simulated in Aspen Plus, as shown in Fig. A1. The property methods for coal, air, carbon dioxide and flue gas streams are Peng-Robnson, and the method for water streams is STEAMNBS. In the power plant model, the RGibbs and RYield reactor units are used. The oxy-coal combustion power plant, the air separation unit (ASU), and the compressed carbon dioxide energy storage (CCES) are simulated in Aspen Plus, as shown in Fig. A1. In the Oxy_CCES model, carbon dioxide passes through heat exchanger 28, then goes into the splitter (stream 38), and finally is fed into compressor 1 (stream 9). The state parameters of streams 39 and 9 are identical. In the Oxy_O2 model, oxygen from the heat exchanger (stream 7) is fed into the boiler (steam 25).

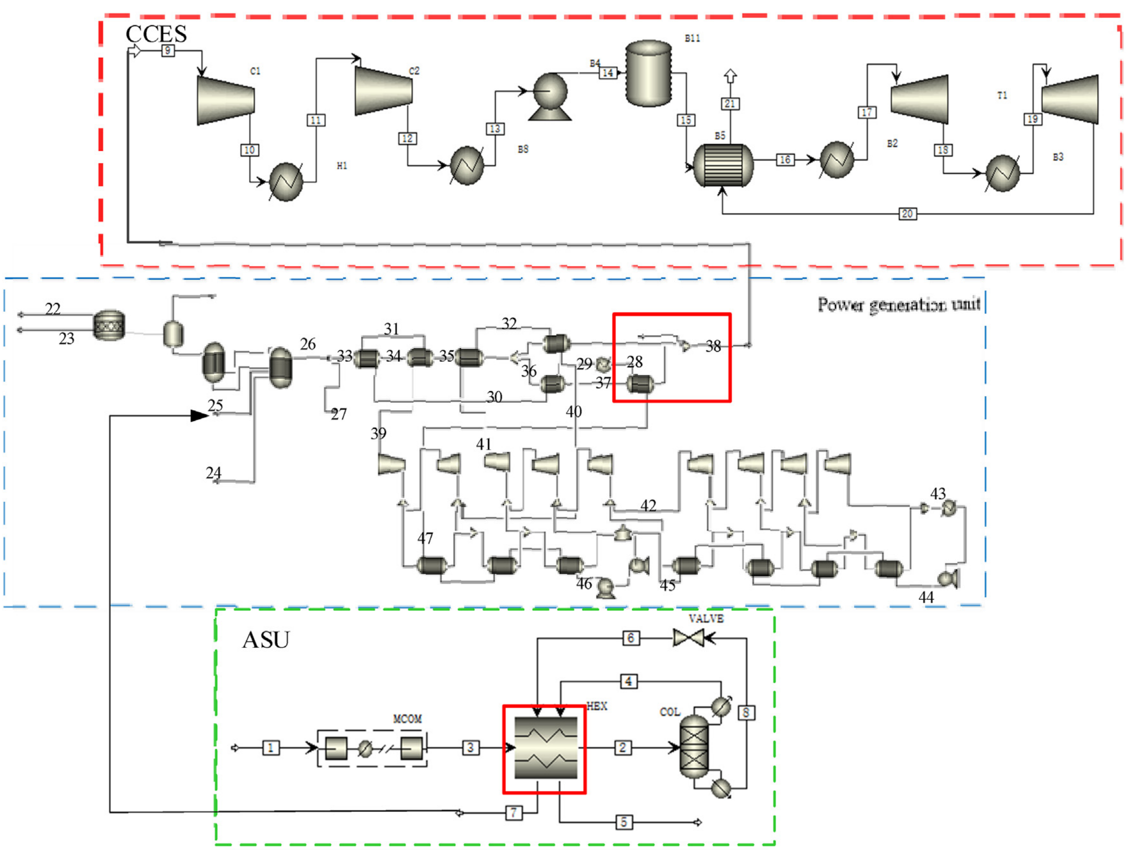

Fig. A1. Model of an oxy-coal combustion power plant with CO_2 capture and CCES (CCES: compressed carbon dioxide energy storage, MCOM: multi-compression, ASU: air separation unit, HEX: heat exchanger).

Table A1
Integrated power plant input parameters

ASU						
Stream	1	2	3	4	5	6
T (°C)	25	−171.8	20	−191.9	−33.1	−180
P (bar)	1	6.2	6.3	1.5	1.4	1.5
Flowrate (kg/s)	533.3	533.3	533.3	406.2	406.2	127.1
Stream	7	8				
T (°C)	−33.1	−163.3				
P (bar)	1.4	5.8				
Flowrate (kg/s)	127.1	127.1				
CCES						
Stream	9	10	11	12	13	14
T (°C)	21.5	224	50	273	30	44
P (bar)	1	8.6	8.6	73	73	110
Flowrate (kg/s)	66.6	66.6	66.6	66.6	66.6	66.6
Stream	15	16	17	18	19	20
T (°C)	21.5	59	538	386	538	241
P (bar)	110	110	110	26	26	1
Flowrate (kg/s)	66.6	66.6	66.6	66.6	66.6	66.6
Stream	21					
T (°C)	51					
P (bar)	1					
Flowrate (kg/s)	66.6					
Power cycle						
Stream	22	23	24	25	26	27
T (°C)	25	132	300	300	1744	1744
P (bar)	1	1	1	1	1	1
Flowrate (kg/s)	270.0	55.2	127.1	408.2	578.0	3.2
Stream	28	29	30	31	32	33
T (°C)	300	420	469	529	515	1165
P (bar)	320.0	315	300	300	64.5	1.01
Flowrate (kg/s)	516	516	516	516	411	585.5
Stream	34	35	36	37	38	39
T (°C)	981.82	803.61	654.14	487.63	325.1	600
P (bar)	1	1	1	1	1	290
Flowrate (kg/s)	585.5	585.5	585.5	234.2	585.5	516.0
Stream	40	41	42	43	44	45
T (°C)	72	620	409	29	12	47
P (bar)	64.5	60	13	0.04	17	17
Flowrate (kg/s)	411	411	401	379	401	401
Stream	46	47				
T (°C)	155	270				
P (bar)	325	325				
Flowrate (kg/s)	516	516				

Appendix II

The models are validated through comparisons with existing studies and related results are summarized in Table A2.Table A2
Validation of proposed models

Models	Parameters	Results in references	Results of the proposed Models	Deviation
Oxy_ref	Gross power output (MW)	621.0 [33]	663.0	6.8%
	Efficiency (%LHV)	34.2 [33]	36.6	6.8%
ASU	Power of compressor (kW)	24719.0 [33]	23964.0	3.1%
	Quantity of O_2 (kmol/h)	2677.0 [33]	2672.0	0.2%
	Quantity of N_2 (kmol/h)	9550.6 [33]	9756.9	2.2%
CCES	Power of compressor (kW)	193.1 [34]	193.4	0.1%
	Power of turbine (kW)	157.1 [34]	153.4	2.3%
	Energy efficiency (%)	66.0 [34]	65.0	2.0%

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