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A calcium looping process for simultaneous CO_2 capture and peak shaving in a 1000 MW_e coal-fired power plant

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Abstract

CO_2 capture and peak shaving are two of the main challenges for coal-fired power plants in China. This paper proposed a calcium looping (CaL) combustion system with cryogenic O_2 storage for simultaneous flue gas decarbonization and peak shaving for a 1000 MW_e coal-fired power plant. The philosophy of this concept is that: 1) the boiler always operates at maximum continuous rating (MCR) to ensure the highest boiler efficiency; 2) during off-peak times, the excess energy output from coal combustion is used to provide heat for the calciner and produce pure oxygen for energy storage; 3) at peak times, the O_2 produced is used to capture CO_2 in the flue gas via the CaL process and reduce the CO_2 abatement penalty; and 4) any excess O_2 is treated as a by-product for commercial utilization. The whole system was simulated in Aspen Plus® which shows that the net electric efficiency of the proposed system without cryogenic O_2 storage system is 35.52%LHV (LHV, low heating value), while that of the conventional CaL system is 34.54%$_{LHV}$. The proposed system can reduce the methane consumption rate by 38.5 t/h when methane is used as fuel in the calciner. Including the cryogenic O_2 storage system, the peaking capability of the proposed system can range from 534.6

MW_e to 1041 MW_e. Correspondingly, the net electric efficiency is improved from 18.98%$_{LHV}$ to 36.97%$_{LHV}$. Increasing the rate of oxygen production can reduce the minimum net power output to lower than 534.6 MW_e. The peaking capability can be regulated by the rate of oxygen production where excess oxygen serves as a byproduct.

Highlights

• A calcium looping process with energy storage for peak shaving in a coal-fired power plant was proposed and assessed.
• The boiler always operates at MCR to ensure the highest boiler efficiency is achieved.
• The proposed system can reduce the net efficiency penalty from 6.96%LHV to 5.98%LHV.
• The proposed system with cryogenic O_2 storage has a wide peaking capability.

Keywords

CO_2 capture; Coal-fired power plants; Calcium looping; Cryogenic O_2 storage system; Peak shaving

1. Introduction

Global warming has gained extensive attention worldwide. The Paris Climate Agreement [1] aims to limit the rise in the global mean temperature, compared with pre-industrial times, to 2°C. As a developing country, China is now facing an onerous task of simultaneously protecting the environment and developing its economy. The 13th Five-year Plan [2] has set specific guidelines for saving energy and reducing carbon emissions. By 2020, carbon dioxide emission per unit of GDP should be 18% lower than that in 2015. By 2030, China's carbon dioxide emission per unit of GDP should fall 60% to 65% compared with that in 2005; meanwhile, the proportion of non-fossil energy in the total energy mix should increase to around 20%.

Utilization of renewable energy sources is a significant way to mitigate greenhouse gas emissions. It is predicted that the share of renewable energy sources in the energy portfolio for the power sector could increase to nearly 20% by 2035 worldwide [3]. Although the installed capacity of renewable energy power equipment has increased year by year, equipment utilization is extremely limited. For example, the average wind power curtailment rate was 12% with 1503 GW installed capacity of wind power equipment in China in 2017 [4]. The main reason for this is dealing with the largest challenge of renewable energy sources, namely their intermittence [5,6] which affects the operation of the electricity generation network [7,8]. What is worse, the increasing share of intermittent renewable energy sources in the energy portfolio will decrease the operating load and usable hours for coal-fired power plants. The profitability of the coal-fired power plant will fall because of the decreasing boiler efficiency when operating at lower loads. In addition, there are many other problems related to low-load operation, such as a reduction in equipment life, etc. Enhancing the peak-shaving capability of fossil-fuel power systems is an effective way to maintain the balance between renewable energy and traditional non-renewable energy for the power sector. Namely, the remaining power generation assets, mostly coal-fired power systems, would need to flexibly balance energy supply and demand, so that neither energy produced from renewable energy sources is wasted nor energy shortages occur [9].

Carbon capture and storage (CCS) technologies are expected to play a crucial role in greenhouse gas (GHG) emissions reduction from the power generation sector. Currently, CaL is regarded as one of the most important technologies for large-scale CO_2 capture and separation, along with mature chemical solvent scrubbing and oxy-fuel combustion [10–12] in coal-fired power plants. The CaL process was proposed by Shimizu et al. [13] for CO_2 capture, and typically comprises two interconnected fluidized bed reactors operating at atmospheric pressure. In the first reactor (carbonator), CO_2 is captured from the flue gas stream via a calcium-based sorbent. In the second reactor (calciner), the sorbent is regenerated at a high temperature, produced via oxy-combustion of fuel. To maintain the high temperature in the calciner, additional fuel such as methane is combusted simultaneously in an O_2-rich environment. There are many air separation technologies currently available including the adsorption process, chemical process, polymeric membrane, ion transport membrane and cryogenic separation [14, 15]. At present, the cryogenic air separation unit (ASU) is the main mature technology for high-purity O_2 production at a large scale [16]. The ASU and the CO_2 compression and purification unit (CPU), which is used to deliver CO_2 at desired pressure and purity, are highly energy intensive processes [17-21]. As such, the efficiency penalty associated with calcium looping has been shown to be between 6% and 8% [22,23].

Energy storage technologies can lead to superior energy utilization and enhanced flexibility of the whole system, offering more possibilities for peaking shaving. Thus, they should be widely deployed along with low-emission technologies [24]. At present, only a few research studies have been done on energy storage technologies combined with CCS. Criado et al. [25] designed a system for power plants operating with very low capacity factors and large load fluctuations, achieved by decoupling the operation of the carbonator and calciner reactors and connecting them to storage tanks filled with CaO or $CaCO_3$ periods. Hanak et al. [26] proposed three viable options for energy storage, including cryogenic O_2 storage, CaO/$CaCO_3$ solids storage, and CaO/$Ca(OH)_2$ solids storage coupling the calcium looping system. Electricity storage via a cryogenic liquid route was first proposed in the late 1970s [27]. It is based on the liquefaction of air by ASU, and a separation of O_2 simultaneously. Importantly, cryogenic O_2 can became an energy storage medium, and then utilized in the oxy-combustion process, unloading the ASU on demand [9, 26, 28]. However, the effect of the decreasing boiler efficiency when the system is operated at low-load condition, was not considered in these studies.

Considering the important role of CaL technology in the decarbonization portfolio and the fact that peak shaving is the main challenge for coal-fired power plants, this study aims to develop a CaL process for simultaneous CO_2 capture and peak shaving in a coal-fired power plant. The preliminary techno-economic feasibility of implementation of cryogenic O_2 storage in the coal-fired power plant is evaluated and the performance of such a system is benchmarked against a 1000 MWe coal-fired power plant without CO_2 capture and energy storage. The 1000MWe power plant represents the most advanced coal-fired power generation system all over the world, with high efficiency and large capacity. At the same time, it also has high demand for peak shaving. So it is meaningful to use the 1000MWe power plant as a reference plant. In order to quantify the characteristics of the system, the key performance indicators, such as auxiliary power consumption, net power output and net electric efficiency, are evaluated. Furthermore, the peaking capability of the proposed concept with cryogenic

O_2 storage system is quantified in terms of the peak-shaving coefficient. Finally, to demonstrate the feasibility of the system, the effect of the variation in the rate of excess oxygen production on the peak-shaving coefficient is evaluated.

2. Concept process description

2.1. Systematic hypotheses

Traditionally, the operating load of a power plant should be matched with the user demand because of the problems associated with large-scale electricity storage. In this work, to avoid loss of the net electric efficiency when the boiler operates at low load, several necessary hypotheses have been identified:

- The boiler always operates at MCR to ensure the highest boiler efficiency;
- At off-peak times, the excess energy output from coal combustion is used to provide heat for the calciner and produce pure oxygen for energy storage;
- At peak times, the produced oxygen is used to capture CO_2 in the flue gas via the calcium looping process and reduce the CO_2 abatement penalty; and
- Excess oxygen is treated as a by-product for commercial sale.

2.2. The new system concept

Fig. 1 presents the CaL combustion system with cryogenic O_2 storage for simultaneous flue gas decarbonization and peak shaving with a 1000 MW_e coal-fired power plant, as proposed here. It is based on a conventional CaL system that connects a CFB carbonator to an existing coal-fired power plant and combines an oxy-CFB calciner fired with methane using pure oxygen from an ASU.

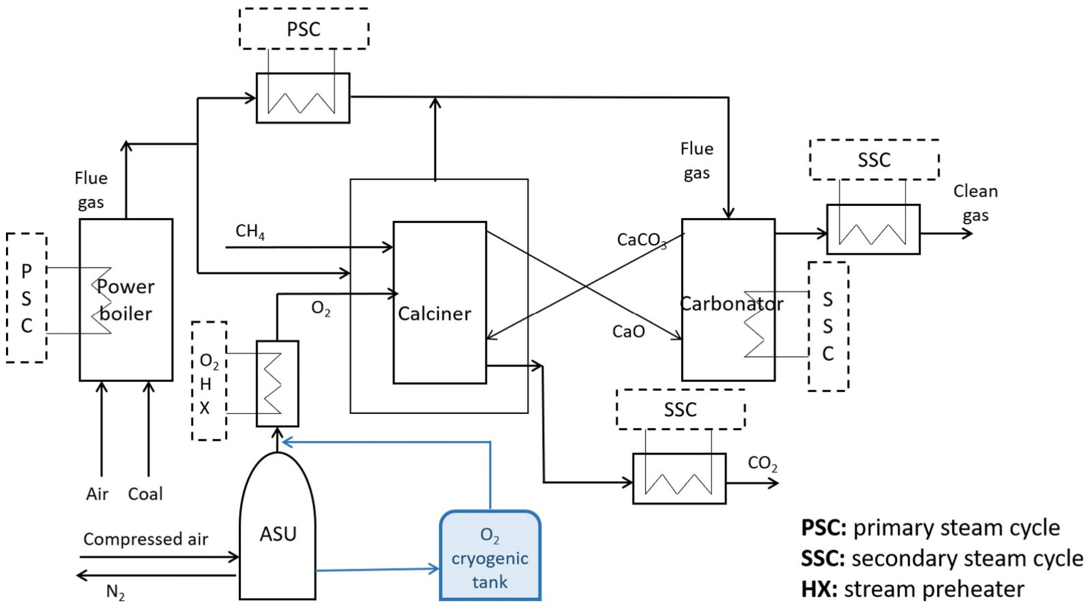


Fig. 1. Schematic diagram of 1000 MW_e coal-fired power plant modernized with a calcium looping process for CO_2 capture and energy storage.

In order to make best use of the heat after that the boiler operates at MCR, the flue gas is divided into two streams at the furnace outlet. The flue gas temperature at the furnace outlet is 1220°C. One stream goes to the boiler tail flue, and then transfers the heat to the steam-water side. The steam-water system can operate at part load of 50%. The other stream enters into a non-contact calciner, where the heat of the flue gas can be utilized to calcine limestone. Methane is burned in pure oxygen from the ASU to ensure full calcination. Details of the non-contact calciner used in the system are available in Supplementary Fig.1. The two flue gas streams recombine and enter into the carbonator for decarbonization. At the exit of both calciner and carbonator, the sensible heat from the CO_2-rich gas and from the clean flue gas now depleted in CO_2, is recovered through a secondary steam cycle (SSC). The SSC is designed to maximize the steam generation rate, and its characteristics are similar to the primary steam cycle (PSC), which is the steam-water system for the reference power plant. It is important to note that the SSC don’t share the same turbine with the PSC. After the heat is recovered, the CO2 gas stream leaving the calciner is delivered to the CPU. It is also important to mention that for simplify the whole system, the desulfurization process and the denitration process are not considered in this paper.

Three viable operating modes for the proposed concept have been identified:

Off-peak mode: During the off-peak period, power generation from the PSC of this proposed system is sufficient to meet user demand. The extra power generation from the SSC is used to provide energy for the ASU. A part of the produced O_2 from the ASU can be used directly for the calcination process; the rest can be stored in the O_2 cryogenic tank for use in peak periods.

Peak mode: The power generation from the both PSC and SSC are used to maximize the steam generation rate. The ASU can be shut down during the peak period for maximum power output. The oxygen produced from the O_2 cryogenic tank is used to capture CO_2 in the flue gas via the CaL process and reduce the CO_2 abatement penalty. Furthermore, excess oxygen is treated as a by-product for commercial sale.

Daily variable-load-operation mode: over a 24-h day, the system operates in the part-load mode during the nightly off-peak period (12:00 midnight – 8:00 am), and full-load mode during the diurnal peak period (8:00 am – 12:00 midnight).

It should be highlighted that the liquid oxygen product can be stored at a low temperature and atmospheric pressure in an insulated storage tank [9,29]. It is assumed that liquid O_2 is stored in the cryogenic tank at 0.12MPa at around -182 °C, which is maintained by the waste N_2 leaving the ASU [9]. Heat losses are not expected to affect the process performance to any great extent and thus they are neglected in this concept study.

To evaluate performance of the proposed concept, a model of the entire process has been developed in Aspen Plus with the key assumptions presented in Table 1. The model comprises five sub-models: a supercritical coal-fired power plant model, a CaL system model, a secondary steam cycle model, an ASU model and a CPU model. The main model follows the work of Hanak et al [26], but has the additional features that the CO_2 capture system was scaled to remove 95% of the flue gas from the reference 1000 MW_e coal-fired power plant. In addition, the CaL-HYD system was not considered in this work. The thermodynamic model was based on the Peng-Robinson with Boston-Mathias modifications property method. Peng-Robinson equation of state was previously used by other authors [30] with positive results.

A core of the analyzed concept is the 1000 MW_e coal-fired power plant. The system comprises a once-through steam boiler with flue gas treatment train and a supercritical steam cycle with single steam reheating stage. The combustion is simulated as two parts: first, the coal is split into its composition elements in an RYIELD block. Then, the previously devolatilized components with preheated air stream enter into an RGIBBS block for oxidation reactions. At base load, the main steam at 603 °C and 26.07 MPa is sent to a high-pressure (HP) turbine cylinder, where it is expanded to 4.68 MPa. Steam is then returned to the boiler where it is reheated to 605 °C, before it is sent to an intermediate-pressure (IP) turbine and subsequently to the two low-pressure (LP) turbines. To enhance the overall power cycle efficiency, steam is extracted from the turbines for feedwater heating so that water is introduced to the boiler at 300 °C. A feedwater heating train consists of four LP feedwater heaters, the last of which is called a deaerator and is a mixed feedwater heater, and three HP feedwater heaters.

For the CaL system model, the flue gas enters into the carbonator at 650 °C, which is modelled using an RSTOIC block. Then, the sorbent is regenerated in the calciner at 850 °C, which is modelled by an RGIBBS block. The accuracy of this model had been demonstrated in many studies [31-33]. It should be highlighted that to simplify the model, the desulfurization efficiency of the CaL is not considered. The calciner is operated with a pure oxygen stream as oxidant.

The SSC model is similar to the PSC except for data presented in Table 1.

A cryogenic ASU is used to produce O_2 for the oxy-combustion in the calciner. The model has the standard double-column modelled by two Radfrac columns. Finally, N_2 and other gases are discharged to the environment. The 99 vol.% O_2 stream is collected for utilization directly or stored in the O_2 cryogenic tank. Something that should be mentioned is that the electric consumption of the ASU is higher when the system operates at part load because the product of the ASU is cryogenic O_2 which means more energy is needed to cool the air.

It is well established that the CO_2 stream pressure at ambient temperature for pipeline transport is 11 MPa [34]. To minimize the power requirement of the CPU, the CO_2 gas stream leaving the calciner is compressed to 9 MPa and cooled down to 25°C first. Then it is pumped to 11 MPa prior for transport.

The entire model and specific data have been shown in Supplementary data file (Fig. 2 – 6, Table 1 – 5).

Table 1. Key process model assumptions.

Blocks	Parameters	Value	
		Peak mode	Off-peak mode
Calciner	Temperature [°C]	850	850
	Fresh limestone/sorbent circulation rate [-]	0.04	0.04
	Gibbs reactor		
Carbonator	Temperature [°C]	650	650
	Carbonation extent [-]	0.65	0.65
	CO_2 capture efficiency [-]	0.95	0.95
	Stoichiometric reactor		
Secondary steam cycle	Design live/reheat steam temperature [°C]	605 / 603	605 / 603
	Design live/reheat steam pressure [MPa]	18.3 / 3.35	22.5 / 4.62
Air separation unit	Oxygen purity [%]	99.0	99.0
	Electric consumption [kWh/t_{O2}]	253	400
CO_2 compression and purification unit	Compressor isentropic efficiency [-]	0.85	0.85
	Compressor mechanical efficiency [-]	0.99	0.99
	CO_2 delivery pressure [MPa]	11	11

2.3. Considerations

The model is used to evaluate the performance of the following cases:

Case 1：The 1000 MW_e coal-fired power plant;

Case 2：The conventional CaL without energy storage system;

Case 3：The proposed CaL without energy storage system; and

Case 4：The proposed CaL with energy storage system.

It should be illustrated that the boiler always operates at MCR to ensure the highest boiler efficiency for the Case 3. As a result, the system does not have peak shaving capacity. Only implementation of energy storage can allow the system to benefit from peak shaving (Case 4).

The thermodynamic performance of the proposed cases needs to be characterized by the key performance indicators related to its power generation. The key performance indicators, such as fuel consumption rate, gross power output, water pump electricity consumption, total fan electricity consumption, ASU electricity consumption, CPU electricity consumption and net power output, are estimated. Net electric efficiency (η_e), which is defined in Eq. (1) as the ratio of the net power output (W_{net}) and the heat input from fuel combustion (Q_{fuel}), is also calculated.

$$\eta_e = \frac{W_{net}}{Q_{fuel}} \qquad (1)$$

To assess the peaking capability of the proposed concept with cryogenic O_2 storage system, the peak-shaving coefficient (ξ_{ps}) is defined. This is quantified in terms of Eq. (2) as the ratio of net power output at full-load mode (W_{netf}) and the net power output at part-load mode (W_{netp}).

$$\xi_{ps} = \frac{W_{netf}}{W_{netp}} \qquad (2)$$

3. Results and discussion

3.1. Proof of the reference power plant

An assessment of the model prediction accuracy should focus on the global performance indicators, such as the gross power output or the net thermal efficiency. Therefore, the global parameters are compared with operational data to assess the overall reliability of the coal-fired power plant model. The performance analysis conducted for the 1000 MW_e coal-fired power plant (case 1) is shown in Table 2. It can be seen that the model results matched well with those of the reference power plant. Under peak-mode conditions, the net electric efficiency of 41.5%$_{LHV}$ was estimated, which is only 0.2%$_{LHV}$ point higher than the reference operational value.

As mentioned above, prediction of the power plant models has mostly been validated at peak-mode condition, from which the off-peak mode condition ~~are~~ is then estimated. Here it was shown that the net coal consumption rate at peak mode was 0.296 tce/(h·MW_e). However, the net coal consumption rate at part-load mode was 0.312

tce/(h·MW_e). This means that the power plant would require more fuel and reduce profits when it operates at part-load condition. Finally, the net electric efficiency declines by 2.4% when it operates at off-peak mode.

Table 2. Energy balance and main performance results for the reference power plant.

Parameters	Peak mode (calculation)	Peak mode (reference)	Off-peak mode (calculation)
Coal consumption rate (t/h)	350	353	201
Gross power output (MW_e)	1000.6	1000	534.6
Net power output (MW_e)	945.7	949.2	512.1
Gross electric efficiency ($\%_{LHV}$)	43.9	43.5	40.8
Net electric efficiency ($\%_{LHV}$)	41.5	41.3	39.1

3.2. Comparison between the conventional CaL and the proposed CaL

To avoid loss of boiler efficiency when the boiler operates at low-load condition, a conceptual CaL system was proposed. The energy balance and main performance results for the conventional CaL system and the proposed CaL system without energy storage system are provided in Table 3, while the results for the proposed CaL system with energy storage are presented in Table 4. Modification of the reference air combustion coal-fired power plant to the CaL system would result in efficiency penalty of 6.96$\%_{LHV}$ points for case 2 and 5.98$\%_{LHV}$ for case 3 at peak mode. These values agree with those from earlier studies, i.e., between 6 and 8% points [22,23]. This is because of the auxiliary electricity consumption by the ASU and the CPU. Additionally, the oxy-CFB calciner fired with methane will increase the flow of flue gas, such that the total fan electricity consumption is increased. Both case 2 and case 3 can maximize the steam generation rate. As a result, the water pump electricity consumption is increased slightly.

Table 3. Energy balance and main performance results for the CaL without energy storage system.

Parameters	Case 2		Case 3
	Peak mode	Off-peak mode	Peak mode
Coal consumption rate (t/h)	350	201	350
Methane consumption rate (t/h)	77	44.3	38.5
Gross power output (MW_e)	1434.1	782	1199
Water pump electricity consumption (MW_e)	55.4	21.4	35.4
Total fan electricity consumption (MW_e)	27.3	18.1	22.9

ASU electricity consumption (MW_e)	80.2	46.2	40.8
CPU electricity consumption (MW_e)	113	62.4	99.7
Total auxiliary electricity consumption (MW_e)	275.9	148.1	198.8
Net power output (MW_e)	1158.2	633.9	1000.2
Gross electric efficiency ($\%_{LHV}$)	42.77	40.59	42.58
Net electric efficiency ($\%_{LHV}$)	34.54	32.90	35.52

It is important that the proposed CaL process can reduce the CO2 abatement penalty by 0.98% compared with the conventional CaL system for the same reference power plant. Interestingly, both the conventional CaL system and this CaL system can increase the system capacity to meet the increasing electricity demand due to the methane consumption in the calciner. In recent years, the usable hours of coal-fired power plants have been progressively decreasing, so the increased system capacity would not increase profitability for the power plant, particularly in the off-peak time. On the contrary, the methane consumption rate for the conventional CaL system was 77 t/h (case 2), higher than it was (38.5 t/h) for the proposed CaL system (case 3). This is mainly because part of the high-temperature flue gas enters into the calciner, to calcine the limestone. The methane consumption rate for the proposed CaL process can be reduced. The entropy loss of high-temperature flue gas is much lower than that of methane combustion. That means that the proposed CaL system can reduce the fuel cost for the power plant and increase its profitability potential. Because of the lower methane consumption rate for the proposed CaL system, the oxygen consumption for case 3 was found to reduce proportionally, so the ASU electricity consumption can also be reduced. Meanwhile the flow of flue gas from the calciner decreased. It can further decrease the total auxiliary electricity consumption including CPU and total fan electricity consumption compared with case 2. Therefore, such a result indicates that the proposed CaL system can be expected to ensure a greater profit compared with the conventional system.

It should be noted that the net electric efficiency declined by 1.64% when operating at off-peak mode for case 2. This can be attributed mainly to the effect of the decreasing boiler efficiency when the system is operated at low-load condition. For case 3, no off-peak-mode thermodynamic performance has been evaluated. The boiler always operates at MCR to ensure the highest boiler efficiency. As a result, only implementation of energy storage can allow the system to benefit from peak shaving.

3.3. Comparison between the proposed CaL with and without energy storage

The thermodynamic performance of the proposed CaL with energy storage (case 4) is presented in Table 4. In this case, two different conditions are discussed. First, in this condition, the O_2 stored in O_2 cryogenic tank can be used every day. For the purposes of discussion, superscript "*" is used for mark this condition in the sections below. In the second condition, the net power output is the same as it is when the 1000 MW_e coal-fired power plant operates at part load mode. Excess oxygen will be treated as a by-product for commercial utilization. Also, superscript "**" is used for mark this condition in the sections below.

Analysis of the energy storage system revealed that by unloading the ASU, the net electric efficiency can be increased to 36.97%$_{LHV}$ for case 4 at peak mode. However, this comes at the expense of a higher efficiency penalty during the off-peak periods, which has been estimated to be 30.95%$_{LHV}$ points, while the O_2 stored in cryogenic tank can be used completely every day. However, implementation of cryogenic O_2 storage can change the minimum net power output of the considered system. The minimum net power output of the proposed CaL system was 871.4 MW_e, which is higher than the electricity demand at off-peak time. The excess power output can be used to produce oxygen. Excess oxygen will be treated as a byproduct for commercial utilization. The minimum net power output can be regulated by the rate of oxygen production when excess oxygen as a byproduct is produced. When the net power output was the same as the base-case 1000 MW_e coal-fired power plant it operates at part load mode, the net electric efficiency was found to be 18.98%$_{LHV}$ points with 6592 t/d cryogenic O_2 produced for commercial utilization. The price of cryogenic O_2 is about 1200-2000 RMB/t in China [35], which is higher than the cost of electricity consumption to producing cryogenic O_2 (400 kwh/t_{O2} · 0.35 RMB/kwh). Oxygen has a wide range of industrial uses. For example, liquid oxygen can be used in the aerospace industry. Liquid oxygen fuel has also been widely used in the preparation and launch of binary propellant aircraft. Oxygen can be used as plasma cutting gas as well as laser cutting auxiliary gas. In the glass industry, oxygen can enhance glass furnace combustion and reduce nitrogen oxide emissions. In sewage treatment industry, oxygen is in great demand as feed gas for ozone. In addition, oxygen can also be used in the medical industry. So there is little doubt that the amount of O_2 discussed here can be absorbed by the market. That means excess oxygen as a byproduct can enhance the power plant profitability.

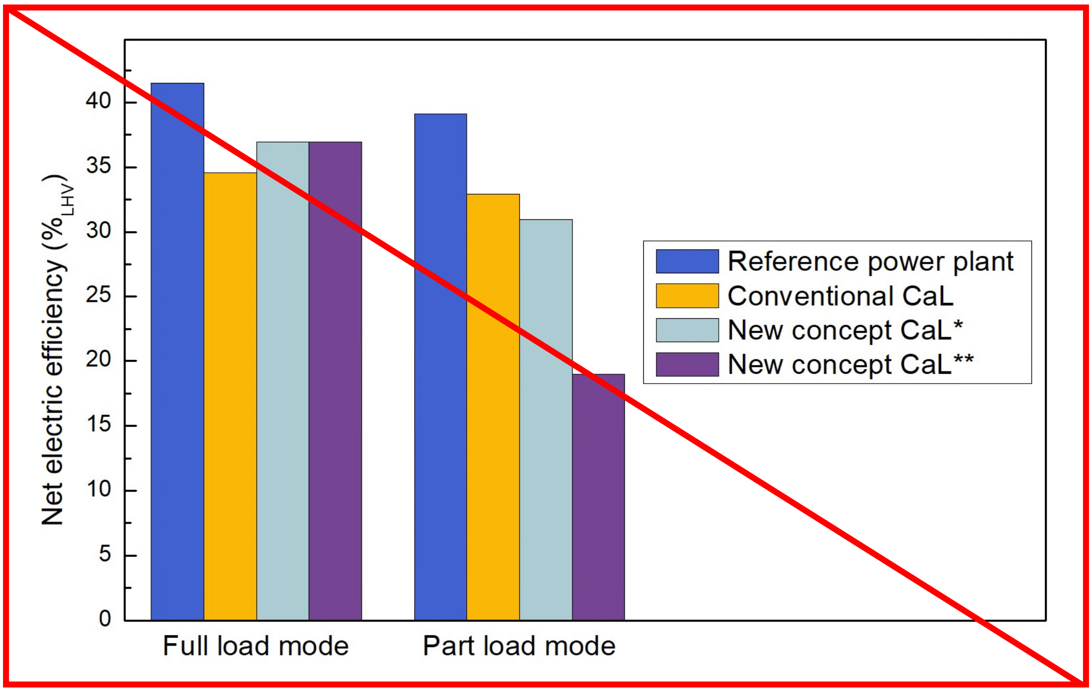
It also needs to be highlighted that the minimum net power output can be lower than 534.6 MW_e and this can be achieved by increasing the rate of oxygen production.

Table 4. Energy balance and main performance results for the proposed CaL with energy storage system.

Parameters	Peak mode	Off-peak mode *	Off-peak mode **
Coal consumption rate (t/h)	350	350	350
Methane consumption rate (t/h)	38.5	38.5	38.5
Gross power output (MW_e)	1199	1199	1199
Water pump electricity consumption (MW_e)	35.4	35.4	35.4
Total fan electricity consumption (MW_e)	22.9	22.9	22.9
ASU electricity consumption (MW_e)	0	169.6	506.4
CPU electricity consumption (MW_e)	99.7	99.7	99.7
Total auxiliary electricity consumption (MW_e)	158	327.6	664.4
Net power output (MW_e)	1041	871.4	534.6
Gross electric efficiency ($\%_{LHV}$)	42.58	42.58	42.58
Net electric efficiency ($\%_{LHV}$)	36.97	30.95	18.98

3.4. Key performance indicators for the considered cases

The net electric efficiency for different modes for the considered cases is shown in Fig. 2. It should be noted that the net electric efficiency at off-peak mode for the proposed system was lower than for the other cases. However, the profitability of the power plant is not reduced. This is because the energy exists as chemical energy in the O_2 cryogenic tank. On the other hand, the net electric efficiency at peak mode for the proposed system was higher than for the other cases. That means the proposed system can be expected to provide higher flexibility.



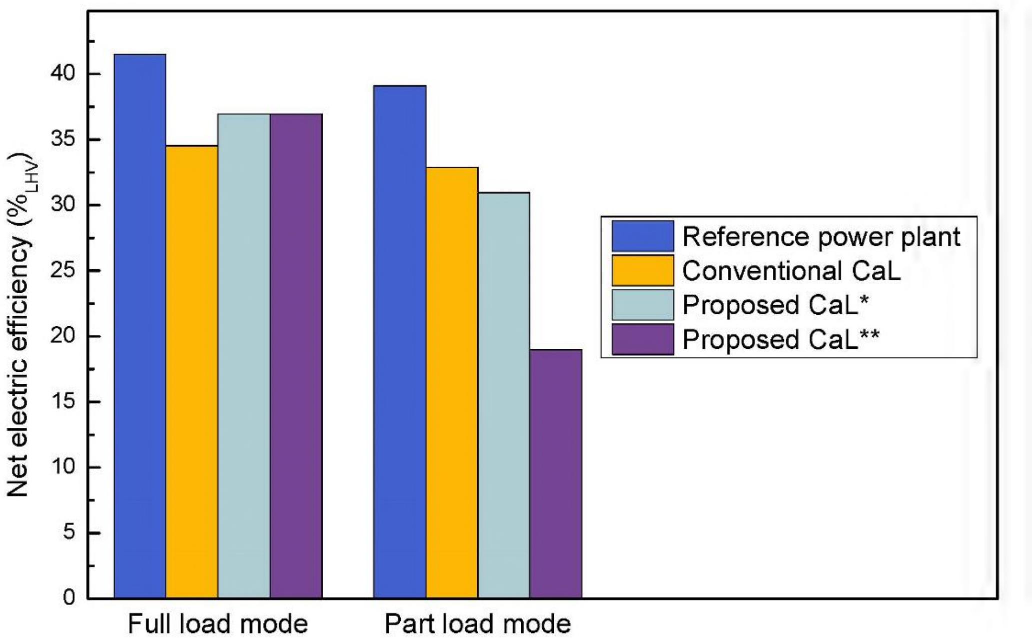
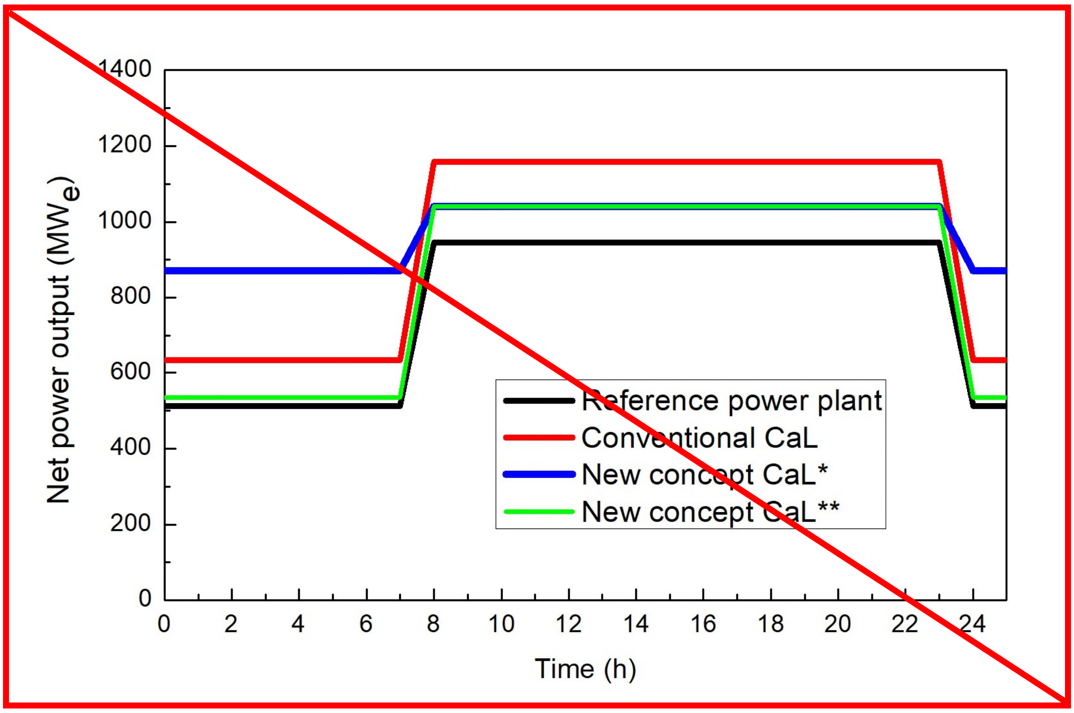


Fig. 2. The net electric efficiency of different modes for the considered cases.

The daily variable-load operation mode was taken into consideration and is shown in Fig. 3. It was shown that both the conventional CaL system and the proposed CaL system would increase the average daily power output compared with the reference power plant. At the same time, it would demand more methane in the calciner. It should be highlighted again that increasing the system capacity would not increase profitability for the power plant during the off-peak time. But increasing system net power output in the peak time can better meet the demand of the user. Therefore, the proposed CaL** system can be expected to improve the profitability compared with the conventional CaL system.



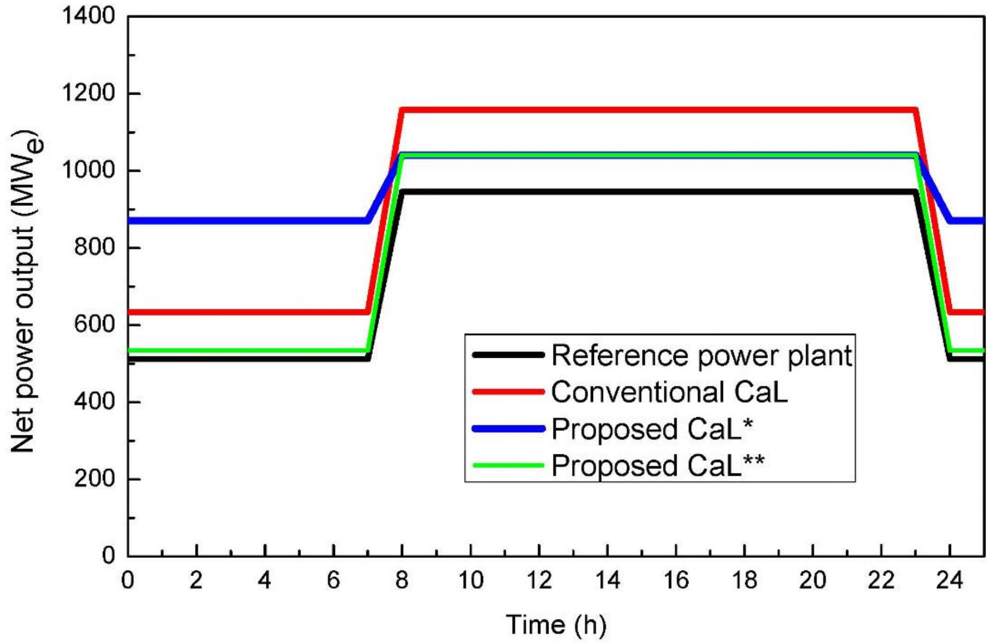


Fig. 3. Daily net power output for the considered cases.

Finally, the peak-shaving coefficient of each case is presented in Table 5. The results show that the peaking capability of the conventional CaL system was slightly reduced from 1.8467 (case 1) to 1.8271 (case 2). This is because integration of the conventional CaL system resulted not only in increasing of the maximum net output by 22.47%, but also caused increases in the minimum net power output of 23.78%. The proposed CaL system with cryogenic O_2 storage has good capability and flexibility for peak shaving. The peak-shaving coefficient can be regulated by the rate of oxygen production from 1.1946 to 1.9473 when excess oxygen as a byproduct is produced.

Table 5. The peak-shaving coefficient for considered cases.

Parameters	ξ_{ps}
Reference power plant	1.8467
Conventional CaL	1.8271
Proposed CaL*	1.1946
Proposed CaL**	1.9473

4. Conclusions

In this study, a concept for the CO_2 capture plant based on CaL with cryogenic O_2 storage is proposed and evaluated in a 1000 MW_e coal-fired power plant retrofit scenario. The thermodynamic performance analysis shows that the net electric efficiency of the proposed system without cryogenic O_2 storage system is 35.52%$_{LHV}$, while that of the conventional CaL system is 34.54%$_{LHV}$. The proposed CaL process can reduce the CO_2 abatement penalty. Secondly, the proposed system can substantially reduce the methane consumption rate when methane is used as fuel in the calciner. Considering the cryogenic O_2 storage system, the peaking capability of the proposed system can increase from 534.6 MW_e to 1041 MW_e. Correspondingly, the net electric efficiency is improved from 18.98%$_{LHV}$ to 36.97%$_{LHV}$. Increasing the rate of oxygen production can ensure that the minimum net power output is lower than 534.6 MW_e. Implementation of cryogenic O_2 storage was found to have a positive effect on the peak-shaving coefficient, which is defined as the ratio of the maximum and minimum net power output of the considered system. Finally, and importantly, the peaking capability can be regulated by the rate of oxygen production when excess oxygen as a by-product is produced.

Conflict of interest

There are no conflicts to declare.

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References

[1] IEA, Energy technology perspectives 2012: pathways to a clean energy system, IEA Publications, Paris, France, 2012.

[2] The "13th Five-Year" work plan for controlling greenhouse gas emissions. (in Chinese) http://www.gov.cn/zhengce/content/2016-11/04/content_5128619.htm/; 2016 [accessed 4 November 2016].

[3] IEA. Energy technology perspectives 2017: Pathways to a clean energy system. Paris, France: IEA Publications; 2017.

[4] National Energy Administration. (in Chinese) http://www.nea.gov.cn/2018-02/01/c_136942234.htm/; 2018 [accessed 1 February 2018].

[5] Twidell J, Weir T. Renewable energy resources, vol. 2. London, UK and New York, USA: Taylor & Francis; 2006.

[6] Pardo P, Deydier A, Anxionnaz-Minvielle Z, et al. A review on high temperature thermochemical heat energy storage. Renewable & Sustainable Energy Reviews, 2014, 32(5):591-610.

[7] Jiang R, Wang J, Guan Y. Robust Unit Commitment with Wind Power and Pumped Storage Hydro. IEEE Transactions on Power Systems, 2012, 27(2):800-810.

[8] Singh M, Khadkikar V, Chandra A, et al. Grid Interconnection of Renewable Energy Sources at the Distribution Level With Power-Quality Improvement Features. IEEE Transactions on Power Delivery, 2010, 26(1):307-315.

[9] Hu Y, Li X, Li H, et al. Peak and off-peak operations of the air separation unit in oxy-coal combustion power generation systems. Applied Energy, 2013, 112(16):747-754.

[10] Mac Dowell N, Florin N, Buchard A, et al. An overview of CO_2 capture technologies. Energy & Environmental Science, 2010, 3(11):1645-1669.

[11] Li H, Yan J, Yan J, et al. Impurity impacts on the purification process in oxy-fuel combustion-based CO_2, capture and storage system. Applied Energy, 2009, 86(2):202-213.

[12] Yin C, Yan J. Oxy-fuel combustion of pulverized fuels: Combustion fundamentals and modeling. Applied Energy, 2016, 162:742-762.

[13] Shimizu, T., Hirama, T., Hosoda, H., Kitano, K., Inagaki, M., Tejima, K., 1999. A Twin Fluid-Bed Reactor for Removal of CO_2 from Combustion Processes. Chem. Eng. Res. Des. 77, 62–68.

[14] Jin B, Su M, Zhao H, et al. Plantwide control and operating strategy for air separation unit in oxy-combustion power plants. Energy Conversion & Management, 2015, 106(2015):782-792.

[15] Smith A R, Klosek J. A review of air separation technologies and their integration with energy conversion processes. Fuel Processing Technology, 2001, 70(2):115-134.

[16] Buhre B J P, Elliott L K, Sheng C D, et al. Oxy-fuel combustion technology for coal-fired power generation. Progress in Energy & Combustion Science, 2005, 31(4):283-307.

[17] Hu Y, Li X, Li H, et al. Peak and off-peak operations of the air separation unit in oxy-coal combustion power generation systems. Applied Energy, 2013, 112(16):747-754.

[18] Perrin N, Dubettier R, Lockwood F, et al. Oxycombustion for coal power plants: Advantages, solutions and projects. Applied Thermal Engineering, 2015, 74:75-82.

[19] Romeo L M, Abanades J C, Escosa J M, et al. Oxyfuel carbonation/calcination cycle for low cost CO_2 capture in existing power plants. Energy Conversion & Management, 2008, 49(10):2809-2814.

[20] J. Ströhle, A. Lasheras, A. Galloy, et al. Simulation of the Carbonate Looping Process for Post- Combustion CO_2 Capture from a Coal- Fired Power Plant. Chemical Engineering & Technology, 2009, 32(3):435-442.

[21] Darde A, Prabhakar R, Tranier J P, et al. Air separation and flue gas compression and purification units for oxy-coal combustion systems. Energy Procedia, 2009, 1(1):527-534.

[22] Boot-Handford M E, Abanades J C, Anthony E J, et al. Carbon capture and storage update. Energy & Environmental Science, 2013, 7(1):130-189.

[23] Perejon A, Romeo L M, Lara Y, et al. ChemInform Abstract: The Calcium-Looping Technology for CO_2, Capture: On the Important Roles of Energy Integration and Sorbent Behavior. Cheminform, 2016, 47(15):787-807.

[24] Antonelli M, Barsali S, Desideri U, et al. Liquid air energy storage: Potential and challenges of hybrid power plants. Applied Energy, 2016, 194.

[25] Criado Y A, Arias B, Abanades J C. Calcium looping CO_2 capture system for back-up power plants. Energy & Environmental Science, 2017, 10(Part 2).

[26] Hanak D P, Biliyok C, Manovic V. Calcium looping with inherent energy storage for decarbonisation of coal-fired power plant. Energy & Environmental Science, 2016, 9(3):971-983.

[27] Smith E M. Storage of Electrical Energy Using Supercritical Liquid Air. ARCHIVE Proceedings of the Institution of Mechanical Engineers 1847-1982 (vols 1-196), 1977, 191(1977):289-298.

[28] Hanak D P, Powell D, Manovic V. Techno-economic analysis of oxy-combustion coal-fired power plant with cryogenic oxygen storage. Applied Energy, 2017, 191:193-203.

[29] Kantharaj B, Garvey S, Pimm A. Compressed air energy storage with liquid air capacity extension. Applied Energy, 2015, 157:152-164.

[30] Porter R, Fairweather M, Kolster C, et al. Cost and performance of some carbon capture technology options for producing different quality CO_2 product streams. International Journal of Greenhouse Gas Control, 2017, 57.

[31] Lu D Y, Hughes R W, Anthony E J. Ca-based sorbent looping combustion for CO_2, capture in pilot-scale dual fluidized beds. Fuel Processing Technology, 2008, 89(12):1386-1395.

[32] Valverde J M. A model on the CaO multicyclic conversion in the Ca-looping process. Chemical Engineering Journal, 2013, 228(28):1195-1206.

[33] Martínez I, Murillo R, Grasa G, et al. Integration of a Ca-looping system for CO_2 capture in an existing power plant. AIChE Journal, 2011, 57(9):2599-2607.

[34] Hanak D P, Biliyok C, Anthony E J, et al. Modelling and comparison of calcium looping and

chemical solvent scrubbing retrofits for CO_2 capture from coal-fired power plant. International Journal of Greenhouse Gas Control, 2015, 42:226-236.
[35] Business Sohu. （in Chinese） http://www.sohu.com/a/238394508_780457/; 2018 [accessed 29 June 2018].

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