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A New Integration System for Natural Gas Combined Cycle Power Plants with CO_2 Capture and Heat Supply

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Received: 11 October 2018; Accepted: 5 November 2018; Published: 7 November 2018

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Abstract: Although carbon mitigation in power industry is attracting more and more attention around the world, the large scale application of carbon capture technology is obstructed because of the enormous energy consumption and huge capital investment required. In this study, an integrated system with power generation, CO_2 capture and heat supply are proposed, which adopts three measures to reutilize the waste heat released from the CO_2 capture process, including extracted steam recirculation, a CO_2 Rankine cycle and a radiant floor heat subsystem. Amongst these measures, the radiant floor heat subsystem can efficiently reuse the relatively low temperature waste energy in the absorbent cooler. Through thermodynamic analysis, it is determined that the power output of the new integrated system is 19.48 MW higher compared with the decarbonization Natural Gas Combined Cycle (NGCC) power plant without system integration. On the other hand, 247.59 MW of heat can be recovered through the radiant floor heat subsystem, leading to an improved overall energy efficiency of 73.6%. In terms of the economic performance, the integration requires only 2.6% more capital investment than a decarbonization NGCC power plant without system integration and obtains extra revenue of 3.40 $/MWh from the simultaneous heat supply, which reduces the cost of CO_2 avoided by 22.3%. The results prove the economic and efficiency potential of a NGCC power plant integrated with carbon capture, which may promote the industrial demonstration of carbon capture theology.

Keywords: NGCC power plant; CO_2 capture and storage; CO_2 Rankine cycle; heat supply

1. Introduction

With the rapid development of the world's economy, the consumption of fossil fuels is expected to increase constantly in the short term future, which makes the environmental issues caused by anthropogenic atmospheric emissions more serious [1,2]. In 2015, a target was set at the Paris Agreement talks, to keep the Earth's temperature rise to only 1.5 degrees Celsius [3]. Therefore, how to meet the requirements of appropriate economic growth and environmentally sustainable fuel utilization have become an important topic at the present stage. As one of the largest CO_2 emitters, the power industry attracts great attention in this context. It is predicted that the world's electricity demand will increase continually up to 34,290 TWh by 2030, 20% of which will be generated from the Natural Gas Combined Cycle (NGCC) power plants [2]. Therefore, it is important to find an efficient approach to realize the carbon mitigation of NGCC power plants.

One potential solution for the carbon mitigation from fossil-fired power plants is the use of CO_2 capture technologies, which can be divided into three different categories: pre-combustion, oxy-fuel, and post-combustion CO_2 capture [1,4–6]. The post-combustion CO_2 capture based on monoethanolamine (MEA) is one of the most feasible approaches and recognized as the first choice for most demonstration projects due to its high technical maturity, large-scale applicability, and strong ability to remove CO_2 from low-CO_2-concentration flue gas [6–9].

Despite its advantages, post-combustion CO_2 capture based on MEA also has its own drawbacks. Firstly, the absorbent regeneration consumes large amounts of thermal energy, which is mainly supplied by steam extracted from the steam turbine in the decarbonization power plant, resulting in a considerable decrease of the net plant efficiency and causing safety and operation problems for low pressure turbines (LPTs). Secondly, the CO_2 capture process also requires a large amount of work, leading to a remarkable increase in auxiliary power. Specifically, the CO_2 separated by chemical absorption is nearly at ambient pressure, and must be compressed to a high pressure for transportation and storage, consuming substantial compression work. In addition, the absorbent circulation flowrate is relatively large and requires considerable pump work. The above characteristics of MEA-based CO_2 capture lead to a significant decrease in the net efficiency of power plants (by nearly 10–15 percentage points) [10–12].

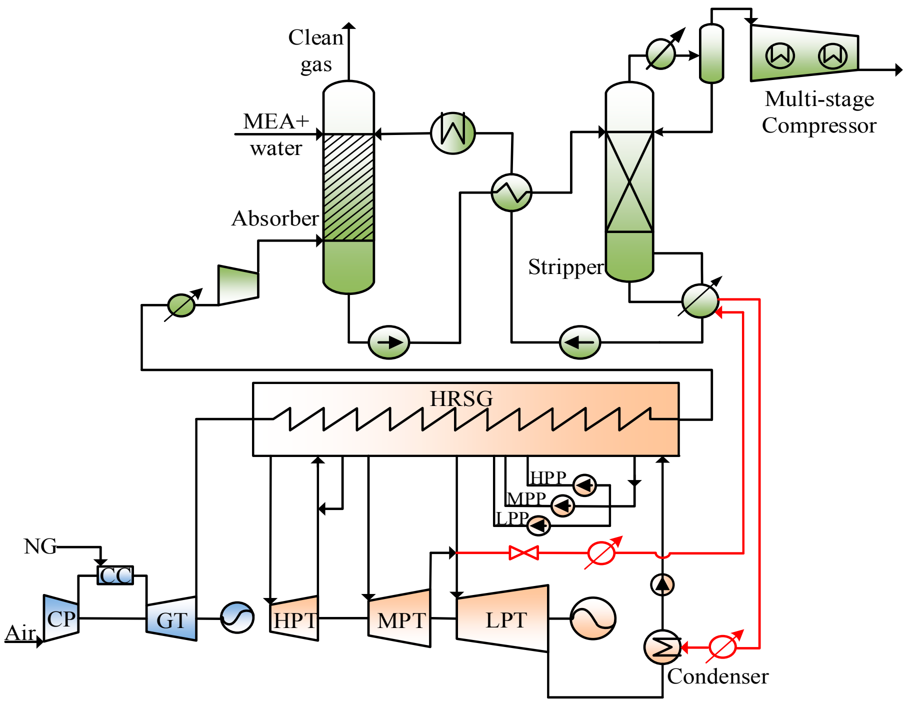
There are different ways to reduce the energy penalty of the power plant integrated with CO_2 capture, such as the development of new absorbents and the optimization of absorption flowsheets. Some researchers have focused on the system integration between the power plant and CO_2 capture process and considered it as an efficient strategy to improve the net efficiency [13–23]. For example, the temperature of the heat from multi-stages compression intercoolers is relatively high, which makes it feasible to recover and reuse this heat to heat up the water after the turbine condenser [13,14] or the rich amine solution [15], or even generate electricity through a supercritical CO_2 Rankine cycle [16,17]. The energy penalty of carbon capture is not only effected by the energy recovery from the CO_2 capture subsystem, but also the optimization of the steam extraction location [18]. Therefore a new design of a steam cycle using only three-stage LPTs is presented in order to match the temperature between the extracted steam and reboiler requirement while using the surplus heat of the reboiler condensate to increase the feedwater temperature [19]. In addition, the extracted steam flowrate from the steam turbine is generally enormous for CO_2 capture, which affects the operation safety and efficiency of the LPTs. On this account, Bonaventura et al. [20] proposed using medium temperature solar thermal power to supply the regeneration heat for a dry carbonate process, resulting in a fossil fuel energy penalty of 3–4% (including CO_2 compression). The studies mentioned above provide valuable ideas for the application of CO_2 capture processes, reveal the effect of system integration on the overall performance of decarbonization power plants and reduce the energy penalty of CO_2 capture to some extent. However, there are still some improvements which can be done in the system integration of power plants with CO_2 capture. For example, although the waste heat with relative high temperature in CO_2 capture subsystem is recovered efficiently by conventional measures, the wasted heat with relative low temperature and large flowrate cannot be utilized properly, such as absorbent cooling heat (40–65 °C). In addition, the flue gas temperature entering CO_2 capture subsystem in NGCC power plants is generally higher than that in coal-fired power plants, leading to an extra energy penalty of CO_2 capture in NGCC power plants.

Therefore, this study focuses on the relative low temperature heat released from a CO_2 capture subsystem and the sensible heat of flue gas which are always ignored by common heat integration measures. In terms of the above issue, a new integrated system of a NGCC power plant with CO_2 capture and heat supply is presented in this paper and three options are adopted to reduce the energy consumption of CO_2 capture. Specifically: (1) recirculating part of the reboiler condensate and mixing it with the extracted steam to fully utilize the surplus heat of the extracted steam; (2) employing a CO_2 Rankine cycle after the heat recovery steam generator (HRSG) to utilize the remarkable sensible heat in the flue gas; (3) integrating a radiant floor heat subsystem with the decarbonization NGCC power plant to reuse the relative low-temperature heat in the CO_2 capture subsystem. By these efforts, the energy penalty caused by CO_2 capture can be significantly reduced and the overall energy efficiency is greatly improved.

2. Concept Design of a NGCC Power Plant with CO_2 Capture and Heat Supply

2.1. Typical Configuration of a NGCC Power Plant with MEA-Based CO_2 Capture

A typical NGCC power plant integrated with post-combustion absorption CO_2 capture, as shown in Figure 1, includes three subsystems: a gas turbine (GT) subsystem, a steam turbine subsystem, and a CO_2 capture subsystem. In the GT subsystem, compressed air combusts with the natural gas (NG) at a combustion chamber (CC). The combustion flue gas then enters into a GT to generate electricity and the exhausted gas subsequently passes through a triple pressure HRSG to produce superheated steam for the steam turbine subsystem consisting of high pressure turbine (HPT), medium pressure turbine (MPT) and LPTs. After releasing heat, the flue gas enters a MEA-based CO_2 capture subsystem, where the absorber and stripper columns are interconnected by a cross-flow heat exchanger and the captured CO_2 stream from the top of stripper column is compressed by a multi-stage compressor. Enormous steam, accounting for more than 80% of the steam flow leaving MPT, is extracted from MPT/LPT crossover pipe in the steam turbine subsystem to meet the absorbent regeneration requirements, which implies a significant efficiency penalty for the whole power plant.



CC	combustion chamber	LPP	low pressure pump
CP	compressor	LPT	low pressure steam turbine
GT	gas turbine	MEA	monoethanolamine
HPP	high pressure pump	MPP	medium pressure pump
HPT	high pressure steam turbine	MPT	medium pressure steam turbine
HRSG	heat recovery steam generator	NG	natural gas

Figure 1. Schematic of a typical NGCC power plant with CO_2 capture.

2.2. Energy Distribution Characteristics of the MEA-Based CO_2 Capture Process

A typical chemical absorption approach consumes enormous energy for absorbent regeneration and releases amounts of low-grade heat as the exhaust, which is quantitatively equal to the energy input, while its thermal parameters is much lower than that of the input energy [24–27]. This exhausted low-grade energy aggravates the energy penalty of CO_2 capture and reduces the economic performance of decarbonization NGCC power plant. As shown in Figure 2, there are three main energy loss sources in this CO_2 capture process, including extracted steam cooler, flue gas cooler and coolers in CO_2 capture subsystem. To be specific:

- Waste heat from extracted steam

The waste energy released by extracted steam cooler accounts for 15–20% of the total energy losses for CO_2 capture, which is attributed to the following two reasons: Firstly, in decarbonization power plants, the absorbent regeneration heat is generally supplied by the extracted steam, whose parameters are generally higher than the requirement of reboiler. Therefore, it must be throttled and cooled to some suitable temperature and pressure before entering into the reboiler, resulting in a large energy wastage. Secondly, the reboiler condensate should be cooled down before entering condenser to ensure the operation safety, which increases the energy penalty of CO_2 capture as well.

- Waste heat in flue gas

The cooling heat of the flue gas constitutes 15–20% of the total energy losses in a CO_2 capture process. It is because the flue gas in NGCC power plants doesn't need to pass through flue gas desulfurizer (FGD) to remove the SO_x before entering CO_2 capture subsystem, which leads to the flue gas temperature before entering CO_2 capture subsystem being higher than that in coal-fired power plants with FGD. In order to enhance the exothermic reaction in absorber, the flue gas should be cooled down firstly, which means a great deal of low-temperature heat (40.0–120.0 °C) is dissipated.

- Waste heat in the MEA-based CO_2 capture subsystem

The waste heat released by the CO_2 capture subsystem, which mainly comprises absorbent cooling heat (40.0–65.0 °C), CO_2 cooling heat (40.0–100.0 °C) and multi-stage compressor intercooler heat (40.0–165.0 °C), is approximately 55~70% of the total energy losses from CO_2 capture process and is difficult to utilize due to its relative low temperature and large flowrate. Especially, the absorbent cooling heat, accounting for 30–35% of the total energy losses, almost cannot be recovered through conventional integration measures because its temperature is slightly higher than the ambient temperature, resulting in an enormous energy waste.

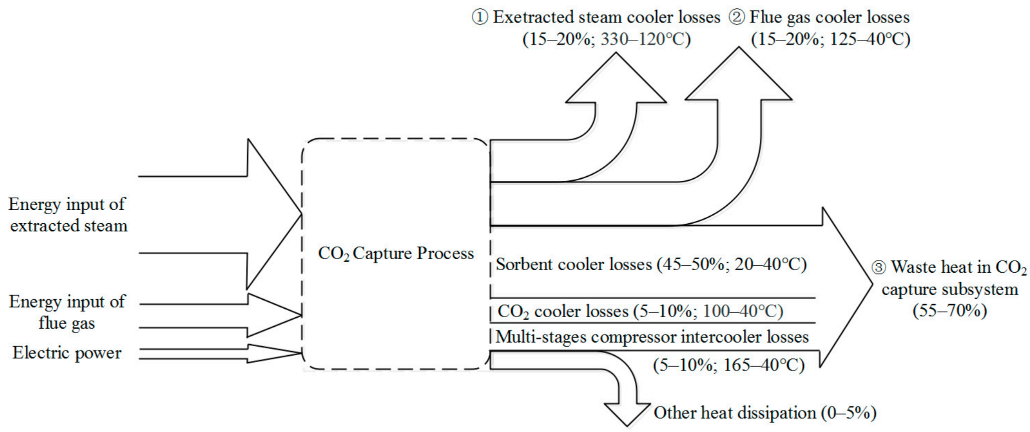


Figure 2. Energy flow schematic of a MEA-based CO_2 capture process.

In summary, when the NGCC power plant integrates with MEA-based CO_2 capture, huge low-temperature energy is exhausted in the extracted steam cooler, flue gas cooler and coolers in CO_2 capture subsystem, leading to remarkable energy penalty. Therefore, a new design concept of the de-carbonization NGCC power plants focusing on the low-temperature energy recovery should be paid special attention.

2.3. Description of the Improved De-Carbonization NGCC Power Plant Integrated with Heat Supply

In view of the energy flow characteristics of CO_2 capture process, especially the three parts of energy loss as mentioned in Section 2.2, a new configuration of the decarbonization NGCC power plant is proposed as shown in Figure 3. In the new system, three targeted measures are adopted to reuse the surplus energy from extracted steam, flue gas and CO_2 capture subsystem, respectively.

- Extracted steam recirculation

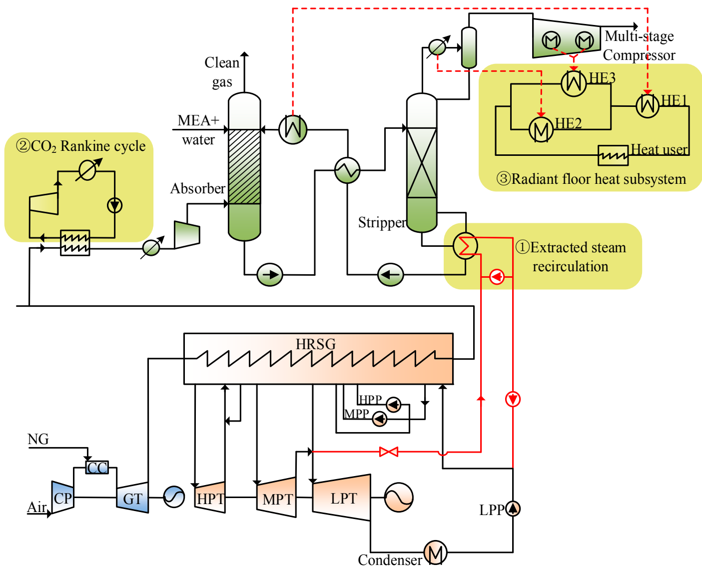
In the improved system, the steam extracted from the steam turbine for CO_2 capture is mixed with part of the reboiler condensate after going through the throttle to fully utilize the degree of superheating of the extracted steam and avoid absorbent degradation. Then the steam with suitable temperature and pressure subsequently releases the regeneration heat at the reboiler. The remainder of the condensate is recycled to the outlet of HRSG preheater, which further recovers the surplus heat of the extracted steam.

- CO_2 Rankine cycle

Aiming to reuse the cooling heat of flue gas whose temperature is relative high (~120 °C), a CO_2 Rankine cycle is introduced because of its lower critical parameters, making it suitable to recover the low-temperature sensible heat in the flue gas, as shown in Figure 3. In the CO_2 Rankine cycle, the working fluid is heated firstly to 148.0 °C by flue gas and then expands to 7.00 MPa in the turbine. The exhausted working fluid is cooled down to 26.0 °C and sequentially pumped to 12.00 MPa to finish the circulation.

- Radiant floor heat subsystem

A radiant floor heat subsystem is employed to utilize the low-grade and large flowrate heat in the CO_2 capture subsystem. Specifically, the heating water (40.0 °C) goes through heat exchanger 1 (HE1) to absorb the heat from the absorbent cooler and is then divided into two branches. One is heated by the captured CO_2 in HE2 and the other is heated by a multi-stage compressor intercooler in HE3. Afterwards, the heating water with proper temperature (70.0 °C) flows into the radiant floor system user releasing heat and then goes back to HE1 to finish the circulation.



CC	combustion chamber	LPP	low pressure pump
CP	compressor	LPT	low pressure steam turbine
GT	gas turbine	MEA	monoethanolamine
HPP	high pressure pump	MPP	medium pressure pump
HPT	high pressure steam turbine	MPT	medium pressure steam turbine
HRSG	heat recovery steam generator	NG	natural gas

Figure 3. Schematic of a new configuration of NGCC power plant with CO_2 capture.

3. Case Study

3.1. Main Assumptions and Case Description

To reveal the impacts of the three integration measures on the thermal performance of de-carbonization NGCC power plant, the following three cases are thoroughly simulated and thermodynamically analyzed in this section:

Base case: NGCC power plant without CO_2 capture
Case 1: De-carbonization NGCC power plant without system integration
Case 2: De-carbonization NGCC power plant with system integration

A 555 MW NGCC power plant is selected as the Base case in this study [28]. The pressure ratio of the gas turbine cycle and the flue gas temperature at GT inlet is set to 18.5 and 1371.0 °C, respectively. While the feed NG is formed primarily of methane (93.1 mol %), it also includes ethane (3.2 mol %), propane (0.7 mol %), *n*-butane (0.4 mol %), CO_2 (1.0 mol %) and nitrogen (1.6 mol %). Other parameters needed for the simulation are listed in Table 1.

Table 1. Main parameters for the case simulation.

Gas Turbine Cycle			
Gas turbine type		Advanced F Class	
Air mass flowrate (t/h)		3143.00	
Nature gas flowrate (kmol/h)		4380.00	
Low heat value (LHV) of NG (kJ/kmol)		817,955.00	
Steam Turbine Cycle			
	Temperature (°C)	Pressure (MPa)	Flowrate (t/h)
HPT inlet steam	560.0	16.65	392.50
MPT inlet steam	560.0	2.48	467.20
LPT inlet steam	329.7	0.52	509.30
HPT exhaust steam	304.1	2.69	392.50
MPT exhaust steam	334.2	0.52	467.20
Condensate water	38.8	0.90	514.20
CO_2 Capture Subsystem			
CO_2 recovery ratio (%)		90	
Absorber pressure (MPa)		0.10	
Reboiler pressure (MPa)		0.22	
Pressure drop in column (MPa)		0.01	
Multi-stage compressor			
1st stage outlet pressure (MPa)		0.60	
2nd stage outlet pressure (MPa)		1.70	
3rd stage outlet pressure (MPa)		5.10	
4th stage outlet pressure (MPa)		15.00	

3.2. Simulation Basis

In this study, three cases are simulated within UniSim Design R450, which can be used to determine energy-efficient solutions (including the identification of the most appropriate operating conditions) [9,29]. The relevant thermodynamic data for the CO_2 capture subsystem was calculated by using the Amine package/Li-Mather method. For the gas turbine subsystem and steam turbine subsystem, the Peng-Robinson package and ASME-Steam package were used respectively. Particularly, the block models "Conversion Reactor", "Expander", "Heat Exchanger", "Absorber Column" and "Distillation Column" are selected for establishing the combustion chamber, the steam/gas turbines, the HRSG, the absorber and the stripper. Meanwhile, some additional block model are adopted to finish the simulation, such as "Compressor," "Heat Exchanger", "Cooler", "Pump" and so on.

3.3. Evaluation Criteria

For the conventional power generation unit, the net efficiency is commonly considered to evaluate the thermal performance of the whole power plants, which is the ratio of the power output to the total energy input and can be calculated as follows:

$$\eta_e = \frac{3600 \times P_{gen}}{M \times Q_L} \tag{1}$$

Here, η_e is the net efficiency, P_{gen} is the net power output (MW), M is the total amount of fossil fuel input to the boiler per unit time (kmol/h), Q_L is the LHV of fuel (kJ/kmol), 3600 can be considered as 3600 s/h.

For the new system, it not only generates electric power, but also supplies heat for the radiant floor user. Therefore, the overall energy efficiency (η_f) is also adopted for comprehensive thermodynamic performance evaluation, which can be defined as follows [29–32]:

$$\eta_f = \frac{3600 \times \left(P_{gen} + E_q\right)}{M \times Q_L} \tag{2}$$

where, E_q is the valid heat supplied to the radiant floor heat subsystem (MW).

4. Results and Discussion

4.1. Thermodynamic Performance

Based on the simulation and calculation above, Table 2 shows the main thermodynamic analysis results of these three cases. The net power output of the NGCC power plant is reduced by 115.40 MW due to the implementation of CO_2 capture, which is about 21% of the net power output in NGCC power plant without CO_2 capture.

Table 2. Thermal performance comparison for Base case, Case 1 and Case 2.

Classified Performance	Base Case	Case 1	Case 2
Power consumed by air compressor (MW)	449.31	449.31	449.31
GT power output (MW)	823.26	823.26	823.26
HPT power output (MW)	48.33	48.33	48.33
MPT power output (MW)	59.76	59.76	59.76
LPT power output (MW)	95.15	3.72	14.15
Auxiliary power (MW)	9.57	34.55	39.08
Net power output (MW)	561.27	445.87	465.35
Fuel molar LHV (kJ/kmol)	817,955	817,955	817,955
Flowrate of NG (kmol/h)	4380	4380	4380
Flue gas outlet temperature of HRSG (°C)	122.4	122.3	161.1
CO_2 flowrate entering CO_2 capture subsystem (kg/s)	56.20	56.20	56.20
Specific regeneration heat (GJ/tCO_2)	——	5.18	5.18
Flowrate of extracted steam (kg/s)	——	130.56	111.94
Heat recovery in absorbent cooler (MW)	——	——	212.58
Heat recovery in extracted stream (MW)	——	——	23.65
Heat recovery in captured CO_2 (MW)	——	——	11.36
Power generated by CO_2 Rankin cycle (MW)	——	——	13.69
Pump power in CO_2 Rankin cycle (MW)	——	——	4.61
Heat recovery by CO_2 Rankin cycle (MW)	——	——	135.94
Net efficiency (%)	56.4	44.80	46.76
Overall energy efficiency (%)	56.4	44.80	71.64

Particularly, 130.56 kg/s of extracted steam is sent to the reboiler, which is ~90% of the total steam flowrate at MPT outlet, meaning a 91.43 MW decrease of the LPT power output; secondly, 24.98 MW extra electricity is consumed by auxiliary facilities in CO_2 capture subsystem, including the boost fan, circulating pumps and multi-stage compressor. Due to the above two aspects, the efficiency penalty of CO_2 capture reaches to 11.6 percentage points in the NGCC power plant.

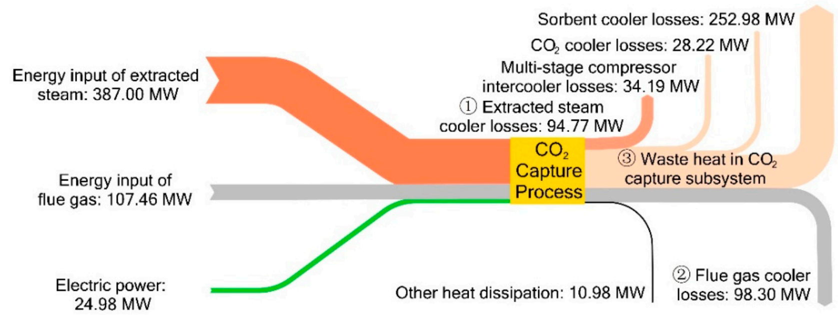
In the proposed system, the net power output increases from 445.87 to 465.35 MW by adopting three measures, resulting in 2.0 percentage points reduction in the efficiency penalty of CO_2 capture compared with Case 1.

Specifically, the degree of superheating of the extracted steam is fully utilized through extracted steam recirculation, which reduces the extracted steam flowrate by 18.61 kg/s and simultaneously increases the LPT power output by 10.44 MW. In addition, the rest reboiler condensate is injected into the HRSG preheater outlet to further utilize the surplus heat of extracted steam, increasing the flue gas temperature at HRSG outlet from 122.3 to 161.1 °C. All these waste heat in the flue gas (161.1–40.0 °C) can be recovered to generate electricity in the CO_2 Rankine cycle, which makes the net power output of NGCC increases by 9.09 MW. Therefore, the net power plant efficiency improves from 44.8% to 46.8% without consideration of heat supply.

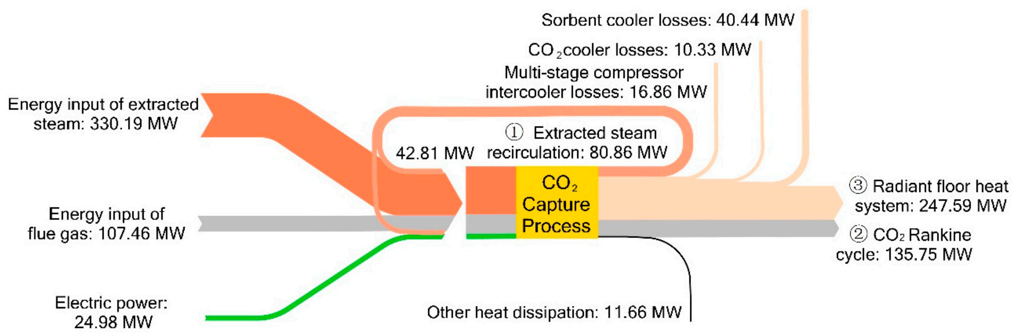
Moreover, in the heating season, most of the low-grade waste heat in CO_2 capture subsystem can be utilized by the radiant floor heat subsystem. As shown in Figure 3, the energy for the radiant floor heat subsystem includes three parts. Specifically, the heating water flows through HE1 and absorbs 212.58 MW heat from the absorbent cooler, then it is divided into two branches. 76% is delivered to HE2 and absorbs 23.65MW heat from the captured CO_2 stream with the temperature range of 94.7 to 71.0 °C and the rest enters HE3 to recover 11.36 MW heat from the multi-stage compressor intercooler. In this way, 247.59 MW heat can be supplied to the radiant floor users, which could increase the overall energy efficiency from 44.8% to 71.6%.

4.2. Energy Analysis for the CO_2 Capture Process

The energy flow diagrams of CO_2 capture process in Case 1 and Case 2 are shown in Figure 4 to reveal the essence of energy saving in the integrated system.



(**a**) Case 1.



(**b**) Case 2

Figure 4. Energy flow diagram of the CO_2 capture process in (**a**) Case 1 and (**b**) Case 2.

The energy input of Case 1 reaches 519.44 MW, including thermal energy brought by extracted steam (387.00 MW), sensible heat brought by flue gas (107.46 MW) and the electric power consumption (24.98 MW). These energy drives the process of CO_2 capture and absorbent regeneration, then degrades into low-temperature waste heat, which is quantitatively equal of the energy input and generally taken away by cooling water in the extracted steam cooler, flue gas cooler and the coolers in CO_2 capture subsystem, leading to a huge energy penalty, remarkable cooling water requirement and potential thermal pollution.

Through system integration, a large amount of waste energy, originally taken away by cooling water in Case 1, can be efficiently recovered and effectively utilized. Firstly, 42.81 MW waste heat of extracted steam is recovered by the extracted steam recirculation, decreasing the extracted steam energy input from 387.00 to 330.19 MW with constant regeneration heat (292.23 MW). Secondly, the waste energy in flue gas cooler (135.75 MW) is utilized to generate electric power by the CO_2 Rankine cycle. It is noted that the exhausted heat from flue gas cooler in the Case 2 is greater than that in Case 1, due to the increase of the inlet temperature of the flue gas cooler. This is because part of the condensate from reboiler is injected to the outlet of HRSG preheater, which means less condensed water is available to recover the heat from the flue gas in preheater of HRSG, leading to an increase of flue gas temperature at HRSG outlet (i.e., the temperature at the inlet of the flue gas cooler). Thirdly, 247.59 MW waste heat from CO_2 capture subsystem is recovered by radiant floor heat subsystem, resulting in ~80% reduction in the total cooling heat losses of CO_2 capture subsystem as compared with the Case 1. By utilizing the above three measures, the total energy losses of the CO_2 capture process decrease from 519.44 to 79.29 MW with a reduced energy input by 56.82 MW and the overall energy efficiency of the new system can be improved significantly to 71.6%.

4.3. Techno-Economic Analysis

4.3.1. Techno-Economic Criteria

Techno-economic analysis is conducted to reveal the comprehensive performance of these three systems. The cost of electricity (*COE*) and the cost of CO_2 avoided (*COA*) are selected as the evaluation criteria. The *COE* (\$/MWh) is calculated as follows:

$$COE = \left(\beta \times C_0 + C_f + C_v \times CF - H \times C_H\right) / (P \times CF) \quad (3)$$

where β is the capital recovery factor; C_0 is the total overnight cost (*TOC*) (\$); C_f is the fixed Operation & Maintenance (OM) cost (\$); C_v is the variable OM cost (\$); H is the annual heat supply capacity (GJ); C_H is the heat price (\$/GJ); P is the annual net power output (kW); CF is the capacity factor.

The *COA* (\$/tCO_2) is defined by Kreutz et al. [33] as follows:

$$COA = \left(COE_{cap} - COE_{ref}\right) / \left(Er_{ref} - Er_{cap}\right) \quad (4)$$

where COE_{cap} is the *COE* of the system with CO_2 capture (\$/kWh); COE_{ref} is the *COE* of the system without CO_2 capture (\$/kWh); Er_{cap} is the CO_2 emission rate of the system with CO_2 capture (kg/kWh); Er_{ref} is the CO_2 emission rate of the system without CO_2 capture (kg/kWh).

To get the *TOC* of the new system, every added equipment cost should be estimated by utilizing the actual cost and the proper scaling factors, which can be calculated as follows [34]:

$$C_E = C_B \times (Q/Q_B)^M \quad (5)$$

where Q is the scaling parameter; Q_B is the reference parameter; C_E is the estimated equipment cost with capacity Q; C_B is the known equipment cost with capacity Q_B; M is the scale factor, which is constant specific to unit type.

4.3.2. Techno-Economic Assumptions

In this study, some economic assumptions are adopted. Specifically, (1) the NG price is 6.89 $/GJ LHV; (2) the OM costs are fixed at 4% of the *TOC*; (3) *CF* is assumed to be 85%; (4) the specific overnight cost of NGCC power plant is 718 $/kW [28]; (5) the CO_2 capture subsystem cost of a 555 MW NGCC power plant with 90% CO_2 capture efficiency is 311 M$ [28]; (6) the heat price is 5.32 $/GJ [35]; (7) the capital recovery factor is 0.105 [28]; and (8) the equipment lifespan is 30 years. Other parameters needed for estimating the added equipment costs of the integration measures are listed in Table 3.

Table 3. Main data for equipment cost estimation.

Component	Scaling Parameter	C_B (M$)	Q_B	M	Q
		Heat exchanger			
HE1	Heat transferred (MW)	1.64 [a]	57.20 [a]	0.90 [a]	212.58
HE2	Heat transferred (MW)	1.64 [a]	57.20 [a]	0.90 [a]	23.65
HE3	Heat transferred (MW)	1.64 [a]	57.20 [a]	0.90 [a]	7.93
		CO_2 Rankine cycle			
Turbine	Power output (MW)	30.77 [a]	200.00 [a]	0.67 [a]	13.69
Pump	Volume flow (m^3/h)	0.02 [b]	250.00 [b]	0.14 [b]	2487.10
HE	Heat transferred (MW)	1.64 [a]	57.20 [a]	0.90 [a]	135.94
Condenser	Heat transferred (MW)	1.64 [a]	57.20 [a]	0.90 [a]	126.85
		Extracted stem pretreatment			
Pump	Volume flow (m^3/h)	0.02 [b]	250 [b]	0.140 [b]	74.26

[a] Cost is taken from Campanari et al. [36]; [b] Cost is quoted from Guo et al. [37].

4.3.3. Techno-Economic Results

The techno-economic performances are shown in Figure 5, including the changes of the *TOC*, net power output, *COE*, and *COA* of these three cases. As the results show, the *TOC* of the NGCC power plant increases by ~80% due to the implementation of carbon capture and the net power output of Case 1 is reduced by 115.40 MW because of the extracted steam for absorbent regeneration and the auxiliary power consumption in CO_2 capture subsystem. These two effects result in a 28.54 $/MWh increase of the *COE*, which is 49% higher than that of the NGCC power plant without CO_2 capture.

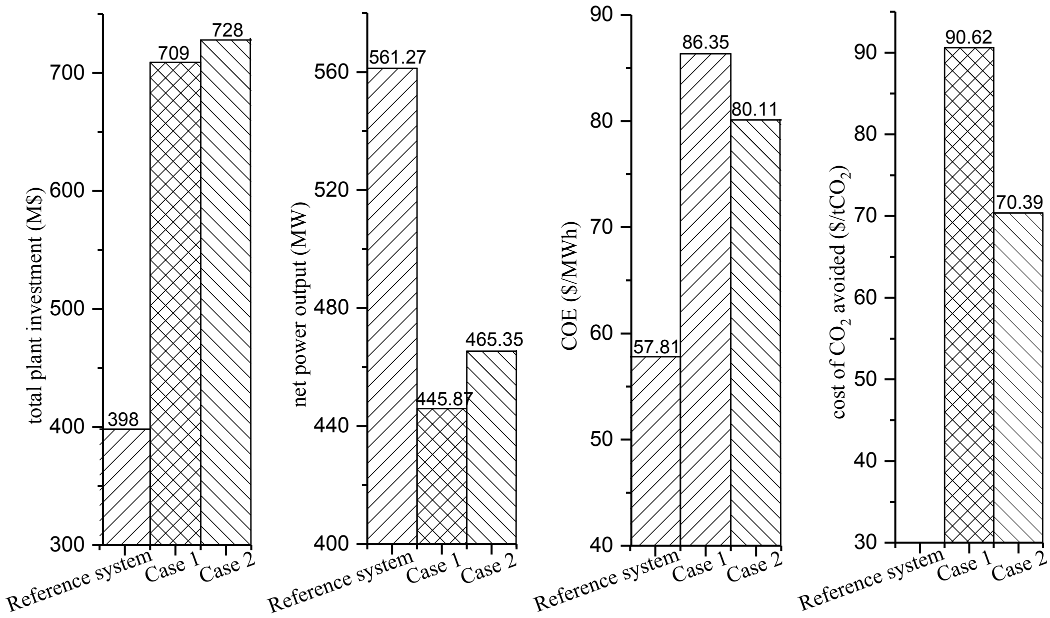


Figure 5. Techno-economic performance graph.

In the improved system, three measures are adopted to alleviate the energy consumption for CO_2 capture, causing \$19.00 M increase of the *TOC*. The power output of the new integration system is19.48 MW higher than the power output of Case 1. Moreover, in the heating period, 247.59 MW heat is recovered for the radiant floor heat subsystem, which brings extra benefit for NGCC power plant. Therefore, the *COE* and *COA* of the new system decreases to 80.11 \$/MWh and 70.39 \$/t CO_2, which are 7.2% and 22.3% lower than that of Case 1 respectively.

5. Conclusions

With the continuing concern about carbon emissions around the world, CO_2 capture technologies have attracted more and more attention. Not only are large amounts of energy consumed for absorbent regeneration, but the process also causes some operation and safety issues, which hinder its large scale application. Therefore, it is important to pay attention to the system integration between the energy utilization system and CO_2 capture process aiming to recover the low-grade energy and reduce the energy penalty.

In this study, an improved system of NGCC power plant with CO_2 capture and heat supply was developed, which recovers the sensible heat of flue gas to generate electricity through a CO_2 Rankine cycle and reutilizes the relative low heat released from the CO_2 capture subsystem for a radiant floor heating subsystem. Through thermodynamic and techno-economic analysis, the integrated measures cause only 2.6% enhancement of the total investment, but the power output is 4.4% higher than that for the decarbonization NGCC power plant without integration and 247.59 MW heat can be supplied to the radiant floor users as well. Therefore, the *COE* and *COA* of the new system are much lower than that of the decarbonization NGCC power plant without integration.

In summary, the integration measures proposed in this study are effective in enhancing the net efficiency of power plants with a reasonable increment of investment, which provides an efficient and economic option for CO_2 removal from NGCC power plants.

Author Contributions: Y.H. and Y.G. designed the models and wrote the paper. G.X. gave the conceptualization of the new system. H.L. and S.D. reviewed and improved the manuscript.

Funding: This research was funded by the National Key R&D Program of China (No. 2017YFB0603300), the International Science & Technology Cooperation Program of China (No. 2016YFE0124300), the International Science and technology cooperation project of Wuhan science and Technology Bureau (No. 2017030209020254), and the young talents program of Hubei provincial education department (No. Q20181402).

Conflicts of Interest: The authors declare no conflicts of interest.

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