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COMPARATIVE ANALYSIS OF CCUS CHAIN WITH DIFFERENT TYPES OF SOURCE AND SINK

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ABSTRACT

The economy of China is highly coal intensive. CO_2 Capture, utilization, and Storage (CCUS) is now the only available technology that can cut up to 90% of CO_2 emissions from power plants and large industrial processes fueled by coal or other fossil fuels. Without CCUS, the cost of meeting the anticipated long-term climate change mitigation objectives would be about 25% higher. For this reason, CCUS is recognized as the indispensable clean coal technologies in China. However, the progress of CCUS technology in the past several decades is rather behind that of the renewable energy, not only in China, but also in the world wide. The aim of this paper is to identify the critical gap interfering the deployment of CCUS technology from the level of whole CCUS chain, and then find the path for promoting CCUS development. In this paper, five CCUS cases with different combination of CO_2 sources and sinks, which including the one combining high purity source in coal chemical production industry with enhanced of oil recovery, and another one combining coal fired power plants with saline aquifer storage, are evaluated. The performance of different case like energy penalty, the economic cost and the environmental emission are compared. The results indicate that the CCUS case with high purity resources shows significant advantages in the energy penalty and the cost. On the basis of this result, the breakpoint for development of low cost CCUS technologies is indicated, and the recommendations are suggested.

Keywords: carbon capture and storage, CCUS cases study, energy penalty, economic cost, environmental emission

NOMENCLATURE

Abbreviations	
BECM	Enhanced coal bed mathane
CCUS	Carbon capture, utilization and storage
EOR	Enhanced oil recovery
EP	Energy penalty
GCCSI	Global CCS Institute
IGCC	Integrated gasification combined cycle power plant
REF	Reference plant
SAS	Saline aquifer storage
SCPC	Supercritical pulverized coal power plant
TPC	Total plant cost
USD	US dollars
WGS	Water gas shift
Symbols	
C_{OM}	Annual fixed operating and maintenance costs
C_{FUEL}	Fuel cost
C_{SNG}	Cost of SNG product
CF	Capacity factor
COE	Cost of electricity
CRF	Capital recovery factor
E	Energy consumption
K	Recovery rate
P_e	Annual electricity output
X	CO_2 concentration before separation
i	Discount rate
n	Plant life
η	Exergy efficiency

1. INTRODUCTION

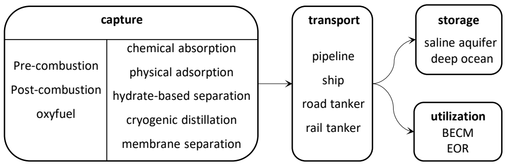
Since the rapid development of economic and high level industrialization, global emission of carbon dioxide (CO_2) has been increasing dramatically, reaching a historic high of 33.1 Gt in 2018 [1]. China alone is responsible for 9.5Gt (28.7%) of the total global emissions. Measures have to be taken to meet the mitigation objectives. There are many proposed options to deal with this problem, such as energy efficiency improvements, more use of renewable energy sources, implement of carbon capture, utilization and storage technology (CCUS), etc. Since China will be highly coal intensive in long-term and CCUS can reduce vast amount of CO_2 in a short time, it is recognized as the most practical and promising way to achieve large mitigation in recent future [2,3].

CCUS is a process consisting of the separation of CO_2 from industrial and energy-related sources, transport to a storage location and long-term isolation from atmosphere. Specifically, CO_2 were captured via separation technologies from large point sources, mainly including fossil fuel power plants, fuel processing plants and other industrial plants [2], then either transported to a storage site and permanently stored or transported for reutilization such as enhanced oil recovery (EOR).

CO_2 separation is the core process for capture technology, which mainly include chemical absorption, physical adsorption, cryogenic distillation and membrane separation, etc. After separation, captured CO_2 can be transported through pipelines, ships, road, rail tankers or other feasible options, then stored in geological formations such as saline aquifer, or can be used for enhanced coal bed methane (BECM), EOR, and other chemical process. There are about 800 sedimentary basins have been identified as suitable geological site for CO_2 storage [4], and some CCUS projects of different development stages have been established: CO_2SINK, In-Salah, RECOPOL, Sleipner and Otway, to name a few [4]. Although CCUS technology is in a constant development, it is still far from large scale commercial deployment. According to the 2018 summary report of the global status of CCS from GCCSI [5], only 43 large-scale facilities exist-18 in commercial operation, 5 under construction and 20 in various stages of development.

As Fig 1 shows, there are three main capture technologies: 1) Post-combustion. This process separates CO_2 from flue gas after fuel combustion, the CO_2 level in flue gas is quite low and ranges between 7%-14% for coal-fired power plants; 2) Pre-combustion. In pre-combustion process, coal will be converted to syngas through gasification, and syngas will enter water gas shift unit, forming a gas stream contains CO_2 more than 30% finally [6]. This technology can be used for integrated gasification combined cycle power plant (IGCC) and other chemical plants based on coal gasification; 3) Oxyfuel combustion. In this process, pure oxygen produced by air separation unit is used for combustion, which promises that the flue gas mainly consists of CO_2 and steam. CO_2 then can be easily removed after steam condensation. Air separation unit is energy intensive, thus high cost and energy consumption is needed in this capture process.

The leading obstacles interfering deployment of CCUS is its high costs. As Fig 1 (b) shows, capture section generally contributes to 70-80% of the total costs of a full CCUS chain [7]. With special focus on capture section, this paper will conduct a comparative analysis of CCUS chain cases with different types of source and sink first, and then develop systematic and quantitative analysis of the energy consumption and costs for carbon capture, aiming to identify the critical gap interfering the deployment of CCUS technology from the level of whole CCUS chain, and at the same time, point out the breakpoint for promoting CCUS development.



(a) Technologies of CCUS

(b) Distribution of CCUS full chain costs

Fig 1 Technical options for each sector and costs distribution of CCUS full chain

2. CASE DEFINITION

To investigate the energy consumption and economic effect of sources with different CO_2 concentration, a supercritical pulverized coal power plant (SCPC), which usually has a low CO_2 concentration in flue gas ranging from 10-15%, an IGCC power plant with a CO_2 molar fraction of 20-40% in gas mixture, and a coal-to-SNG chemical source (CO_2 concentration >90%) are chosen as three sources.

Pipeline is a mature commercial technology option and the most commonly used method for CO_2 transportation, thus is deployed for cases study. In general, transport section doesn't induce a significant cost on CCUS projects when distance between source and sink is less than 300 km [8]. It is estimated that transportation cost is around 1-8 USD/t CO_2 per 250 km pipeline [2], in this paper, transport distance and transport and storage cost (T&S) are assumed to be 150 km and 5$/t CO_2, respectively.

Existing typical sink can be divided into 2 types, including geological storage and utilization. Saline aquifer storage (SAS) is a representative geological storage method, whose cost is 7-13$/t CO_2 reported by U.S. DOE [8]. Geological storage can't bring any revenue stream while utilization like CO_2-EOR could. In EOR cases, each tonne of CO2 will lead to an increase in production of approximately 2.5-3.0 barrels of oil, which will generate around 200-270 dollars income for the whole chain [9].

2.1 Definition of CCUS cases with different sources and sinks

2.1.1 Cases 1&5: SCPC source

Traditional pulverized coal power plants with CCUS always adopt post-combustion technologies, as can be seen from Fig 2, it captures CO_2 from flue gas, where the concentration of CO_2 usually is between 10-15%, a relatively low value compared to other resources, amine-based chemical absorbent (MEA) is the most efficient technology, which has a high absorption efficiency over 90% [10], thus is usually adopted in post-combustion capture. In this case, the purity of captured CO_2 is over 98.98%, with the remaining 125ppmv of H_2S, thus satisfies the pipeline specification and 95% requirement of SAS and EOR. After being captured and compressed to 11-14 MPa (typically 14 MPa [2]), CO_2 at supercritical state will be sent to transport unit via pipelines and finally stored in SAS (case 1) or used for EOR (case 5).

2.1.2 Cases 2: IGCC source

In IGCC cases, a water gas shift unit (WGS) is located after quenching the syngas to convert 95% of CO to CO_2. Then CO_2 will be separated from shifted gas which contains about 30%-40% volume fraction of CO_2. The relatively high CO_2 concentration will reduce energy consumption compared with SCPC source. After Selexol capture process, CO_2 will transported through pipeline and used for EOR.

2.1.3 Cases 3&4: Coal-to-SNG source

GCCSI reported the high purity sources account for 6% of global industrial emissions, high-purity CO_2 emissions from industry sector like ethanol production, ammonia production and natural gas process are of a great potential to result in less capture costs.

As a representative coal chemical process, coal-to SNG plant is chosen as the high purity point source for case 3&4. As shown in Fig 2, the WGS is used to convert partial CO to CO_2, leaving the gas product possess a ratio of H_2 to CO between 3.1-3.3 to satisfy the requirement of subsequent chemical synthesis. The concentration of CO_2 is usually greater than 90% for coal chemical process [11], thus a small quantity of energy consumption for CO_2

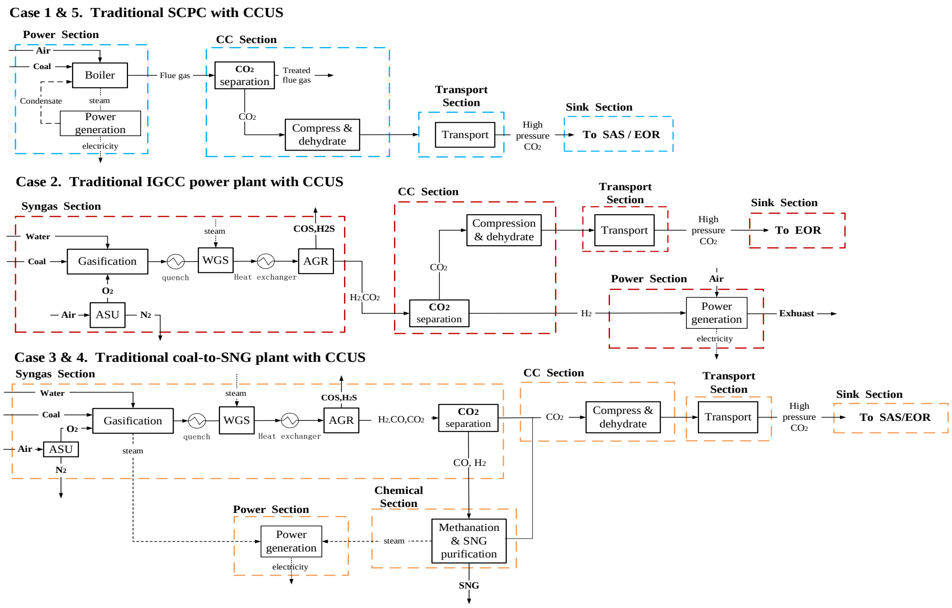


Fig 2 Simplified flowsheet of CCUS cases

compression can be expected. EOR and SAS are sinks of case 3 and case 4, respectively.

2.2 Methodology

In this paper, Integrated Environmental Control Model (IECM) software is employed to assist calculation of the case study. Since IECM is not designed for coal chemical process, the study done by U.S. National Energy Technology Laboratory (NETL) in 2008 is used to facilitate our analysis [12], with the help of US inflation rate (18.2% from 2007 to 2017), financial performance of the system will be adjusted to the same base year 2017 with other power plant cases. Detailed NETL work information see ref [9].

In this paper, the price of the oil is assumed to be 50.84$ per barrel, which is an average price of crude oil in 2017, and each ton of CO_2 will lead to an increase in production of 2.7 barrels of oil [9].

Other financial assumptions are given below:

(1) The steam and electricity needed for CCUS system are derived from the power section within the system;

(2) All the economic data are expressed in constant 2017 dollars, no carbon tax is considered, by products such as sulfur of each case isn't intended for sale.

(3) For cases with EOR sink, half of captured CO_2 are assumed to be stored while 50% are recycled through Selexol process, the recovery ratio is assumed to be 90%, thus a 5% escape rate can be obtained and lead to a decrease of avoided CO_2 in EOR cases;

3. ENERGY CONSUMPTION FOR CARBON CAPTURE

Carbon capture energy consumption related issues are quite complex, containing different levels, angles and boundary conditions. To better understand this, important concepts and the relationship between them should be clarified firstly.

3.1 Theoretical minimum energy consumption

Based on thermodynamics, theoretical minimum energy consumption (E_{theo}) to separate CO_2 from gas mixture can be expressed as Eq. (1) [13,14].

$$E_{theo} = RT_0 \frac{X(1-K)\ln\left[X(1-K)\right]-(1-XK)\ln(1-XK)-X\ln X}{XK} \tag{1}$$

Where R is the gas constant, 8.314 J/(mol K) , T_0 is reference temperature, usually assumed to be 298.15K. X is the CO_2 concentration before separation, K is the recovery ratio.

The utilization way of fuel chemical energy (e.g., combustion in boiler or gas turbine, gasification) will result in different CO_2 concentration in gas mixture, thus is a determinant of E_{theo}. Also, capture technology is of great importance, for pre-combustion capture, E_{theo} is usually less than post-combustion capture basically due to relatively high CO_2 molar concentration in gas mixture. When K is set to be 90%, the effect of X on E_{theo} is shown in Fig 3, E_{theo} sharply decreases with increasing X, when X is over 30%, the minimum energy consumption decreases significantly slower.

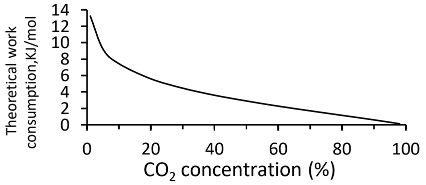


Fig 3 Theoretical minimum energy consumption for CO_2 separation from gas mixture

3.2 Direct and indirect energy consumption

Direct energy consumption of carbon capture (E_{direct}) is only separation and purification process related, considering different separation and purification technologies, it can be calculated by Eq. (2):

$$E_{direct} = \sum_{j=i}^{k} \frac{E_{theo,j}}{\eta_j} \tag{2}$$

where η_j represents the exergy efficiency of the separation or purification technology j, usually ranges between 10-30% [15].

Besides energy consumption related to separation and purification process, deploying carbon capture also leads to extra system energy consumption. For example, when add pre-combustion capture technology to IGCC system like case 2, steam and WGS unit is needed, which is not a necessary portion in reference plant without CCUS. Since this supplementary equipment and energy consumption are not caused by separation process directly, it is termed as indirect energy consumption ($E_{indirect}$). $E_{indirect}$ has a strong relationship with system form: for post-combustion system, higher heat integration level will result in less of E_{direct}, for pre-combustion system employing physical adsorption, change in fuel heating value and the steam consumption in shift reaction will all bring about different $E_{indirect}$. Also, as part of the overall energy consumption about which carbon capture brings, energy required for CO_2 compression (E_{compre}) can be calculated by Eq. (3):

$$E_{compre} = RT_0 \ln \frac{P}{P_0} \qquad (3)$$

Where P_0 and P are the pressure before and after compression, respectively.

Based on analysis above, energy consumption for carbon capture (E_{cap}) can be expressed as Eq. (4):

$$E_{cap} = E_{direct} + E_{indirect} + E_{compre} \qquad (4)$$

3.3 *Efficiency penalty*

E_{cap} will result in a system efficiency penalty (EP), it shows the decrease in plant efficiency percentage points due to capture [13]. Energy system form, capture technology, fuel type, separation technology and system integration level will all have an influence on system EP. On the whole, EP can be expressed by Eq. (5):

$$EP = Efficiency\ without\ CCUS\,(\%) - Efficiency\ with\ CCUS\,(\%) \qquad (5)$$

4. RESULTS AND DISCUSSIONS

Table 1 provides major performance and cost results for each case.

Table 1

Performance and cost results of CCUS cases

Source & Sink	SCPC			IGCC		Coal-to-SNG			Units for SNG plant
	ref	SAS	EOR	ref	EOR	ref	SAS	EOR	
Thermodynamic performance									
Fuel input, 10^6 t/yr	1.44	1.81	1.81	1.57	1.78	3.26	3.26	3.26	10^6 t/yr
Plant output									
Plant net power output, MWe	559.6	461.9	461.9	594.3	547.2	91.7	48.5	48.5	MWe
SNG output 10^9 m^3/yr						15.2	14.9	14.9	
Plant net power efficiency (HHV basis, %)	38.3	25.2	25.2	37.3	30.5	2.8	1.5	1.5	%
SNG conversion efficiency (HHV basis, %)						61.4	61.3	61.3	%
CO_2 concentration before capture,%		11.8			37.57		99.02		%
EP,%		13.1			6.8		1.4		%
E_{direct}, KJ/mol		36.79			20.65		0.77		KJ/mol
Economic and environmental performance									
Emission rate (kg CO_2 net MWh^{-1})	818.1	174.5	228.1	804.5	209.9	84.4	10.2	13.9	kg GJ^{-1}
TPC (Million $)	1108	1823	1823	1451	1997	2629	2693	2693	M$
Fixed O&M cost (M$/yr)	40.44	66.60	66.60	53.01	72.97	95.62	97.36	97.36	M$
COE ($ MWh^{-1})	58.1	108.8	-38.5	68.6	-14.0	10.1	10.3	-1.7	$ GJ^{-1}
% increase in COE		87.3	-166.3		-120.4		2.0	-116.8	%
Cost of CO_2 avoided ($/t CO_2)		78.8	-163.8		-138.8		2.2	-143.4	$/t CO_2
Cost of CO_2 captured ($/t CO_2)		47.3	-90.1		-100.9		2.1	-142.2	$/t CO_2

4.1 *CO_2 emissions*

CO_2 emission results are shown in Fig 4. CO_2 avoided for different CCUS cases is of great importance from environmental perspective, it represents the overall CO_2 mitigation considering the additional CO_2 emissions stem from additional equipment required to implement CCUS technology.

As Fig 4 shows, avoided CO_2 of each case with SAS is a little more than corresponding EOR cases, this is because when CO_2 is used for EOR, part of captured CO_2 will escape to atmosphere from recycle process, which is intended to recover CO_2 for next injection. For SCPC + SAS, the 2.03kg/kg avoided CO_2 is equivalent to 86.0% of total CO_2 produced, while 81.8% for corresponding EOR case, and the avoidance rate are 78.4%, 79.2% and 75.4% for IGCC+EOR, Coal-to-SNG+SAS and Coal-to-SNG+EOR, respectively.

4.2 *Energy consumption*

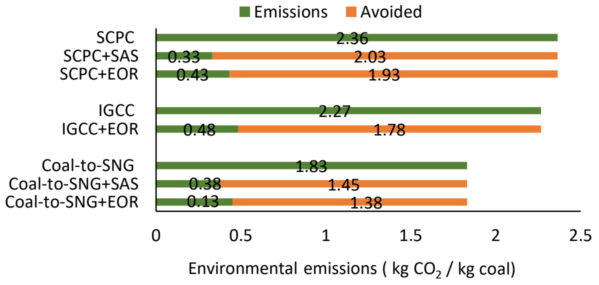


Fig 4 Environmental performance of different cases

Fig 5 shows separation process related actual energy consumption E_{direct} for CCUS cases, E_{direct} for SCPC+MEA absorbent, IGCC+Selexol, and Coal-to-SNG are 36.79 kJ/mol, 20.65 kJ/mol, 0.77KJ/mol, respectively. The vertical distance between E_{direct} and E_{theo} represents unideal degree of corresponding separation process, the less distance between E_{direct} and E_{theo}, the more efficient the separation technology is. To simplify analysis, energy consumption of impurity removal for power plant cases is not considered in this paper due to its very low share of E_{direct} compared to separation process, but for coal-to-SNG cases, since the purity of CO_2 source is over 98%, E_{direct} mainly includes energy consumption of impurity removal, thus this part can't be ignored. Calculated by Eq. (2), η_j are 18.65%, 17.77% and 7.79% for MEA chemical absorption technology, Selexol technology, purification process used by SCPC, IGCC and Coal-to-SNG, respectively. It also can be seen from Fig 5, the higher CO_2 concentration before separation is, the lower E_{direct} is, which is the same trend with the relationship between CO_2 concentration and E_{theo}. This idicates that compared to separation technology, CO_2 concentration is a more important factor determining E_{direct}.

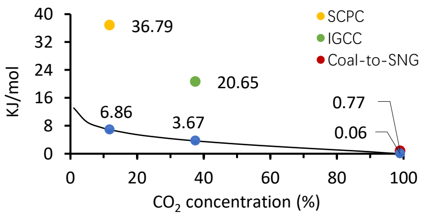
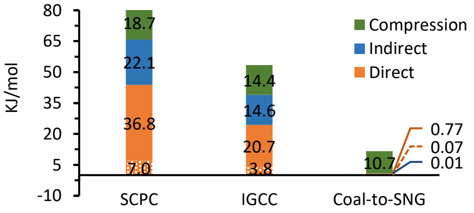
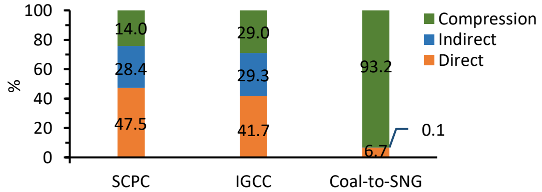


Fig 5 Actual and theoretical exergy consumption for carbon separation process

A particular breakdown of energy consumption that CCUS brings to the system are shown in Fig 6, SCPC+CCUS has the highest energy consumption, followed by IGCC+CCUS and Coal-to-SNG+CCUS. Since traditional coal-to-SNG plant separates CO_2 before adding CCUS system, resulting in high purity CO_2 source, E_{direct} and $E_{indirect}$ are significantly small, only accounting for 6.7% and 0.1% of the total energy consumption, respectively.



(a) Energy consumption for different CCUS cases



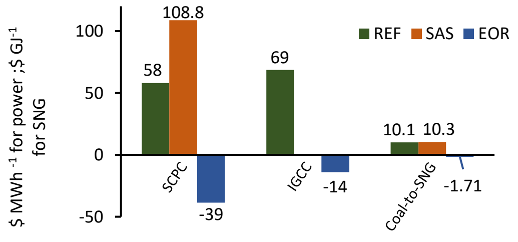
(b) Energy consumption percentage for different CCUS cases

Fig 6 Break down of energy consumption for CCUS cases

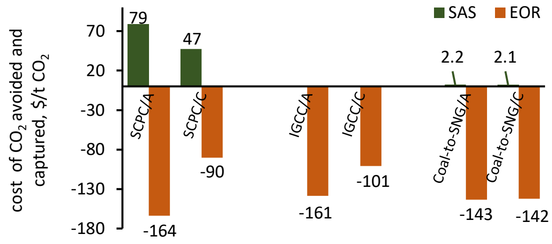
While for power plant cases, E_{direct} accounts for more than 40% of the total extra energy consumption. View from system level, the EP of SCPC+CCUS, IGCC+CCUS and Coal-to-SNG+CCUS are 13.2%, 6.8% and 1.4%, respectively. Based on results and analysis above, minimizing E_{direct} is a vital direction in making a breakthrough in CCUS development.

4.3 Cost results

Fig 7 sums up the cost results of CCUS cases, negative numbers represent financial gains. As expected, while SAS cases always add the cost of product and cost of mitigation, EOR cases can significantly offset the cost for deploying CCUS, even can generate benefits with higher oil price. Among SAS and EOR cases, Coal-to-SNG case has the lowest mitigation cost and the highest EOR benefit, respectively, which could attribute to both lower capture energy consumption.



(a) COE and C_{SNG} results



(b) cost of CO_2 avoided(A) and captured(C)

Fig 7 Cost results for CCUS cases

5. CONCLUSIONS

This paper conducts 5 CCUS cases study of different sources and sinks. From the aspects of energy consumption and cost for CO_2 emission reduction, these 5 cases were compared. With a EP of 1.4%, the least energy consumption (11.52 kJ/mol CO_2) and maximum financial benefit, it is concluded that Coal-to-SNG+EOR case has the best performance.

The results indicate that: 1) the combination of high purity resources with EOR can provide the best economic performance, due to low cost of capture unit, and extra benefit generated by EOR; 2) the concentration of CO2 before separation is the key parameter of separation processes; 3) there exists the great potential of saving energy consumption for CO2 capture not only from the improvement of separation process, but also from the increment of CO2 concentration.

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