CHEMICAL ENGINEERING TRANSACTIONS

VOL. 81, 2020

A publication of

AIDIC

The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Qiuwang Wang, Min Zeng, Panos Seferlis, Ting Ma, Jiří J. Klemeš

ISBN 978-88-95608-79-2; **ISSN** 2283-9216

DOI: 10.3303/CET2081007

Emergy Evaluation of IGCC Power Generation with a Carbon Capture System

Siyue Ren[a], Xiao Feng[a,*], Yufei Wang[b]

[a]School of Chemical Engineering & Technology, Xi'an Jiaotong University, Xi'an 710049, Shaanxi Province, China
[b]State Key Laboratory of Heavy Oil Processing, China University of Petroleum (Beijing), Beijing 102249, China
xfeng@xjtu.edu.cn

IGCC (Integrated Gasification Combined Cycle) power generation system can improve the utilization efficiency of coal and has less impact on the environment. Carbon capture and storage system (CCS) is an essential way to control greenhouse gas emission. This paper aims to study the combination of IGCC and CCS systems from the perspective of sustainability (in terms of environment). The model of IGCC and CCS systems are built in Aspen plus. Based on the model, the impact of oxygen-coal ratio to the performance of IGCC power generation system is studied. The results show that the mole fraction of CO and H_2 could reach a relatively large value when the oxygen-coal ratio is in 0.7-0.8 and the net power of the system decreases with the oxygen-coal ratio. The emergy evaluation is performed by collecting the input and output data of the IGCC and IGCC-CCS systems under the oxygen-coal ratio of 0.8. The results show that the sustainability of the IGCC-CCS system is rising as the CO_2 tax increases and the order of the sustainability with different CCS scale is relative to the CO_2 tax. It indicates that the CCS system could improve the sustainability of the IGCC system under a certain CO_2 tax by reducing the CO_2 emission.

1. Introduction

Coal-fired power generation is currently the most important form of power generation in China. However, the burning of coal has caused problems such as energy shortage and the greenhouse gas emission. The development of new technology to make use of coal efficiently is crucial to solve energy and environmental problems. The IGCC (Integrated Gasification Combined Cycle) power generation system combines coal gasification and gas-steam combined cycle technologies. Compared with traditional coal-fired power stations, it improves the efficiency of coal resource use and has less impact on the environment. Kunze et al. (2011) performed a structured exergy analysis of an IGCC with carbon capture to identify exergy losses. The results show that the main unit causing exergy losses is the combined cycle, followed by the gas treatment section and the gasification island. In the gasification section, the oxygen-coal ratio is a significant factor to the efficiency of the coal gasification (Wang et al., 2015). Besides, the integration of IGCC and natural gas-fueled integrated intermittent chemical looping air separation is proved to have a promising economic potential (Shi et al., 2019).

CO_2 capture in IGCC systems is demonstrated to be an important factor which affects the power generation cost (Oh et al., 2019). Generally, in an IGCC power generation system, the method of solvent absorption is used to capture CO_2 (Moioli et al., 2016). However, the use of CCS systems is proved to be economically unreasonable under current technic and market conditions (Tola and Pettinau, 2014). For the progress of the CCS technology, Rosner et al. (2019) compared IGCC power plant with dual-stage Selexol for carbon capture with pressure swing adsorption-based warm gas CO_2 capture. The results showed that capture with Selexol was limited to 83.4 % due to high syngas CH_4 content while the efficiency was 31.11 % resulting in a 1st-year cost of electricity of 148.6 $/MWh. Carbon capture can be increased to 88.6 % and efficiency to 33.76 % with warm gas CO_2 removal.

The existing studies analyzed the IGCC-CCS power generation systems from the perspective of technology and economy. However, the scale of the carbon capture system on the overall performance of IGCC power generation systems has not been studied, and neither has the sustainability of the system. In this paper, the

Paper Received: 18/03/2020; Revised: 26/05/2020; Accepted: 26/05/2020
Please cite this article as: Ren S., Feng X., Wang Y., 2020, Emergy Evaluation of IGCC Power Generation with a Carbon Capture System, Chemical Engineering Transactions, 81, 37-42 DOI:10.3303/CET2081007

input of the IGCC-CCS system is studied by emergy analisis with the first time. The electricity output of the IGCC system with different CCS scale is simulated by Aspen plus. The sustainability of IGCC-CCS systems is evaluated by the emergy indexes. The aim is to obtain the impact of the carbon capture system on the performance and sustainability of IGCC power generation.

2. Method

The emergy evaluation is used to analyze the sustainability of IGCC-CCS power generation systems based on the model established in Aspen plus.

2.1 Simulation of the IGCC power generation system with carbon capture system

The IGCC-CCS system is simulated in Aspen plus based on the data of IGCC power generation systems performed by Black (2010). Figure 1a is the IGCC power generation system, in which the Texaco gasifier with the coal-water slurry feed is adopted in the coal gasification part and the MDEA is adopted as absorbent to absorb CO_2 and H_2S. Figure 1b is the IGCC-CCS system, in which the steam gas shift unit is added and the CO from the coal gasifier is shifted into CO_2 and H_2 by reacting with steam to achieve CO_2 absorption.

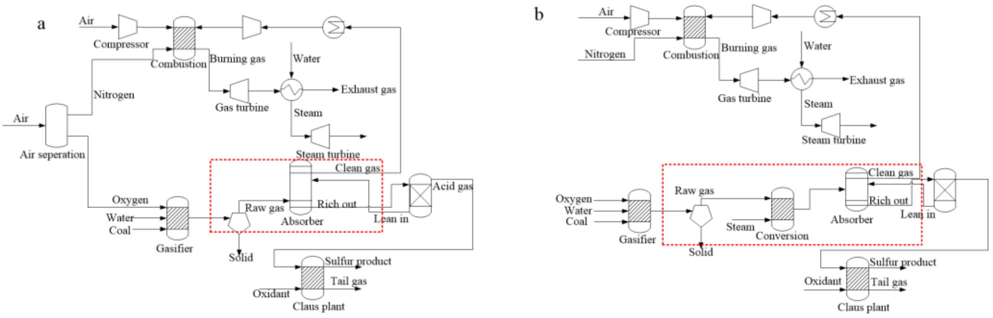


Figure 1: Simulation flow diagram of IGCC power generation system a: IGCC; b: IGCC-CCS

The power generated from simulation is compared with that from reference in Table 1 (Black, 2010), where the value of gas turbine is the net power after deducting the power consumed by air compressors, and the CCS scale is 90 %.

Table 1: Comparison of the power generated from simulation and literature

System	Data sources	Oxygen-coal ratio	P (gas turbine)×2 (MW)	P (Steam turbine) (MW)	Power loss (MW)	Net power (MW)
IGCC	Literature (Black, 2010)	0.8	464.0	276.3	117.4	622.0
	Simulation	0.8	463.9	275.5	117.4	622.1
IGCC – 40 % CCS	Simulation	0.8	462.9	265.9	184.1	544.8
IGCC – 60 % CCS	Simulation	0.8	463.2	265.1	184.1	544.2
IGCC – 80 % CCS	Simulation	0.8	463.5	264.3	184.1	543.7
IGCC – 90 % CCS	Literature (Black, 2010)	0.8	464. 0	263.5	184.1	543.3
	Simulation	0.8	463.8	263.5	184.1	543.3

2.2 Emergy analysis

Emergy is the amount of available energy that is directly or indirectly applied in the process of product or service formation. For the convenience of calculation, other forms of energy input are converted into solar emergy (sej) by multiplying their transformities (Odum, 1996). The emergy analysis considers both the resources in the market and environment. The economic and ecological cost of a system could be evaluated by emergy analysis to unveil the sustainability of the whole system.

The emergy evaluation of a system mainly includes determination of the research scale and the emergy baseline, organization of input and output data, and calculation of emergy indices. The research scale of this paper is the IGCC power generation system, which is shown in Figure 2.

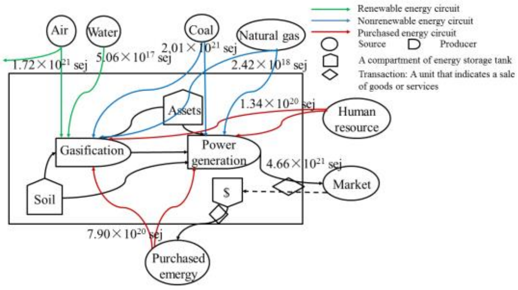


Figure 2: Emergy flow of the IGCC power generation system

According to Figure 2, the emergy input of the system is devided into three types, including the renewable emergy, nonrewable emergy and the purchased emergy. The output of the IGCC system is electricity, which is delivered to the market. The emergy baseline is 12.1×10^{24} sej/y in this paper (Brown and Ulgiati, 2016).

2.2.1 Emergy indices

The emergy indices of the system mainly include emergy transformity (Tr), emergy yield ratio (EYR), environmental loading rate (ELR) and sustainability index (ESI).The emergy transformity (Tr) of a product is the ratio of the total emergy input to the amount of the product. The product in a power generation system is electricity, the emergy transformity could be presented as

$$Tr = \frac{Y}{E_{\text{electricity}}} \tag{1}$$

where E is the output of the system, Y is the total emergy input. Emergy transformity indicates how much input is required to obtain the product.

The emergy yield ratio (EYR) represents the ratio of the total emergy output to the purchased emergy of the system, as shown in Eq(2).

$$EYR = \frac{Y}{F} = \frac{R+N+F}{F} \tag{2}$$

where R, N, F represent the renewable, nonrenewable and purchased emergy.

The environmental loading rate (ELR) indicates the degree to which the system influence on the environment. The traditional expression for ELR is

$$ELR = \frac{N+F}{R} \tag{3}$$

However, in most industrial cases the majority of the input resources are nonrenewable and the renewable resources is very small. Wang et al. (Wang et al., 2006) presented an improved emergy environment loading rate, which is expressed as:

$$ELR = \sum_{i=1}^{6} \frac{F_i}{F_t} = \sum_{i=1}^{6} \frac{F_i}{F_{cr} + F_{cn}} \tag{4}$$

where F_{cr} is the improved benefit by material circular and energy cascade utilization; F_{cn} is the improved benefit by using clean energy technologies.

Based on Eq(4), the ELR for an IGCC power generation system could be represented as

$$ELR = \frac{F}{F_E + F_N + F_R} \tag{5}$$

where F_E is the emergy of the amount of electricity generated resulting from the raised efficiency comparing to traditional coal-fired power generation system, F_N is the emergy of the coal saved, and F_R is the emergy of the emission cost saved.

The sustainability index (ESI) as shown in Eq(6) indicates that if a system has better production efficiency and less environmental pressure, there will be a higher ESI. Generally, the system will be sustainable when the ESI value is higher than 1, but it will be insufficient in the utilization of ecosystem service when the ESI value is higher than 10.

$$ESI = \frac{EYR}{ELR} \tag{6}$$

2.2.2 Emergy data of IGCC power generation systems

Table 2 is the emergy data of the IGCC and IGCC-100 % CCS power generation systems, in which the investment costs refer to the economic analysis of the IGCC power generation system by Skone and James (2010) for the system studied by (Black, 2010) and other data come from Black (2010).

Table 2: Emergy data of IGCC and IGCC-100 % CCS power generation systems

Items	Unit	IGCC system (unit/y)	IGCC-90 % CCS system (unit/y)	Transformities (sej/unit)	Emergy of IGCC system (sej/y)	Emergy of IGCC-90 %CCS system (sej/y)
Renewable emergy (*R*)						
Process water	t/y	7.62×10^{5}	7.95×10^{5}	6.64×10^{11} (Odum, 1996)	5.06×10^{17}	5.28×10^{17}
Air	t/y	3.34×10^{7}	3.48×10^{7}	5.16×10^{13} (Odum, 1996)	1.72×10^{21}	1.80×10^{21}
Nonrenewable emergy (*N*)						
Coal	J/y	5.03×10^{16}	5.25×10^{16}	4.00×10^{4} (Odum, 1996)	2.01×10^{21}	2.10×10^{21}
Nature gas	J/y	5.04×10^{13}	5.04×10^{13}	4.80×10^{4} (Odum, 1996)	2.42×10^{18}	2.42×10^{18}
Purchased emergy (*F*)						
Capital costs	$/y	3.75×10^{8}	4.64×10^{8}	1.42×10^{12} (Yang et al., 2010)	5.33×10^{20}	6.59×10^{20}
Utility cost	$/y	1.20×10^{8}	1.25×10^{8}	1.42×10^{12}	1.70×10^{20}	1.78×10^{20}
Labor costs	$/y	9.42×10^{7}	1.08×10^{8}	1.42×10^{12}	1.34×10^{20}	1.54×10^{20}
Variable O&M cost	$/y	6.10×10^{7}	7.32×10^{7}	1.42×10^{12}	8.66×10^{19}	1.04×10^{20}
Emergy yield (*Y*)						
Electricity	J/y	1.96×10^{16}	1.71×10^{16}	2.38×10^{5}	4.66×10^{21}	4.99×10^{21}

The amount of electricity output refer to the simulation results, which is supplied by the net power of gas turbine and steam turbine. The emergy transformities from other literatures are converted to the baseline in this paper, which is 12.1×10^{24} sej/y.

3. Results and discussion

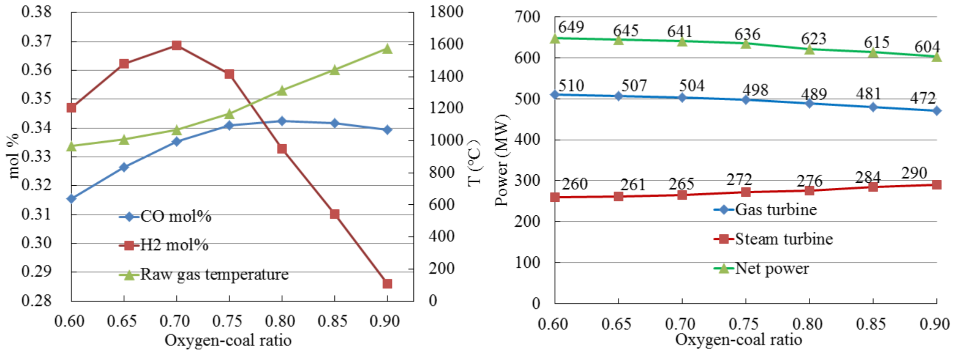
The impact of operation parameters to the performance of the IGCC power generation system is studied in this section. IGCC power generation systems with different scale of CCS systems are compared.

3.1 Impact of operation parameters to the system performance

In the coal gasification part of the IGCC power generation system, the oxygen-coal ratio has a great impact on the composition and temperature of the raw gas and efficiency of power generation, which is firstly studied in this article. Figure 3a shows the mole fraction of CO and H_2 in the raw gas, and the temperature of the raw gas changes with the oxygen-coal ratio. The mole fraction of H_2 in the raw gas reaches the maximum value when the oxygen-coal ratio is 0.7, and that of CO in the raw gas reaches the maximum when the oxygen-coal ratio is 0.8. The actual oxygen-coal ratio should be in this range to ensure a good efficiency of coal gasification. With the rises in oxygen-coal ratio, the temperature of the raw gas increases, because with the ratio of oxygen increase, the oxidation reaction of CO, H_2 and O_2 will occur, which will gradually increase the temperature of the raw gas.

Figure 3b shows that the power of gas turbine, steam turbine and the net power of the system change with the oxygen-coal ratio. According to Figure 3b, the power of the gas turbine decreases with the oxygen-coal ratio. The reason is that with the increasing of the mole fraction of oxygen, the CO and H_2 from the coal gasification unit will be consumed due to the oxidant reaction. The decrease of the CO and H_2 will cause the temperature of the combustion chamber to decrease and the power of the gas turbine will decrease. However, for rising the oxygen ratio will augment the flow rate of the raw gas, the temperature of the generated steam will increase.

The power of the steam turbine gradually increases as the oxygen-coal ratio rises. The net power of the system decreases slowly as the oxygen-coal ratio rises. The effect of the oxygen-coal ratio on the net power is weak.



a b

Figure 3: Impact of the oxygen-coal ratio on system parameters a：Composition and temperature of raw gas; b: Power of gas turbine, steam turbine and net power of the system

3.2 Impact of CCS system scale on sustainability of IGCC power generation system

Based on the emergy data in Table 2, the emergy indices of IGCC and IGCC-CCS power generation systems under the CO_2 tax of 0.1 \$/kg (Zechter et al., 2017) are shown in Table 3. The oxygen-coal ratio is taken as 0.8. The investment costs and CO_2 emissions at different CCS scales are assumed to change linearly. The power of gas turbine, steam turbine and the air compressor is obtained by simulation.

Table 3: Emergy indices of IGCC power generation systems with different scales of CCS

Items	Without CCS	40 % CCS	60 % CCS	80 % CCS	90 % CCS
Electricity (J)	1.962×10^{16}	1.718×10^{16}	1.716×10^{16}	1.715×10^{16}	1.713×10^{16}
CO_2 emission (g/kWh)	905.32	591.14	434.04	276.95	119.86
EYR	5.05	4.78	4.69	4.62	4.56
ELR	1.00	1.52	1.51	1.50	1.48
ESI	5.06	3.15	3.10	3.08	3.08

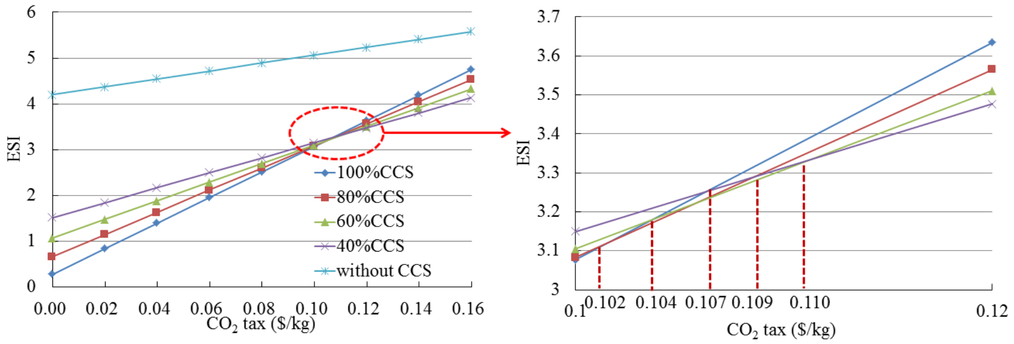


Figure 4: Sustainability index of IGCC power systems with different CCS scale changing with CO_2 tax

Figure 4 shows the sustainability index of the IGCC-CCS power generation system changing with CO_2 tax. The *ESI*s of IGCC-80 % CCS and IGCC-100 % CCS are less than 1 when the CO_2 tax is 0 \$/kg, which means unsustainable. The system is sustainable when the CO_2 tax reaches 0.026 \$/kg. According to Figure 4, with the scale of the CCS increasing, the sustainabilities of IGCC power generation systems will decrease when the CO_2 tax is less than 0.10 \$/kg. However, the ESI of the IGCC-100 % CCS gradually surpasses other cases and the order of the ESIs will be reversed when the CO_2 tax is greater than 0.11 \$/kg, which demonstrates the advantages of large-scale carbon capture systems. Due to the investment costs required for a carbon capture system, the ESI of the IGCC-CCS power generation system is always less than the IGCC power generation system when the CO_2 tax is lower. However, as can be seen from Figure 4, the ESI of the IGCC-CCS power generation system will surpass that of the IGCC power generation system when the CO_2 tax reaches a certain value.

The CCS system could reduce the CO_2 emission of the IGCC systems to improve its sustainability. However, the investment cost of the system will rise with the scale of the CCS system increasing, which will decrease the sustainability. These two factors should be balanced under a certain CO_2 tax.

4. Conclusions

In this paper, an IGCC-CCS power generation system is studied from the perspective of emergy. According to the analysis of oxygen-coal ratio, the mole fraction of H_2 and CO reaches a large value when the oxygen-coal ratio is in 0.7-0.8, and the net power of the system decreases with the oxygen-coal ratio. The results of emergy evaluation show that the sustainability index of the IGCC-CCS systems decreases with the scale of CCS increasing when the CO_2 tax is less than 0.10 $/kg. However, when the CO_2 tax is higher than 0.12 $/kg, the sustainability index of the IGCC-CCS system increases as the scale of CCS rises, which demonstrates the advantages of large-scale carbon capture systems. It could be obtained that the sustainability index of the IGCC-CCS system is less than the IGCC system within current CO_2 tax. The sustainability of the IGCC-CCS systems could be improved by improving the power generation efficiency and with CO_2 tax.

Acknowledgements

Financial support from the National Natural Science Foundation of China (21736008) is gratefully acknowledged.

References

Black J., 2010, Cost and performance baseline for fossil energy plants, Volume 1: Bituminous coal and natural gas to electricity, National Energy Technology Laboratory, Albany, OR, USA, 98-136.

Brown M.T., Ulgiati S., 2016, Assessing the global environmental sources driving the geobiosphere: A revised emergy baseline, Ecological Modelling, 339, 126–132.

Kunze C., Riedl K., Spliethoff H., 2011, Structured exergy analysis of an integrated gasification combined cycle (IGCC) plant with carbon capture, Energy, 36, 1480-1487.

Moioli S., Giuffrida A., Romano M.C., Pellegrini L.A., Lozza G., 2016, Assessment of MDEA absorption process for sequential H2S removal and CO2 capture in air-blown IGCC plants, Applied Energy, 183, 1452–1470.

Odum H.T., 1996, Environmental Accounting--Emergy and Environmental Decision Making, John Wiley & Sons, New York, USA.

Oh H.-T., Lee W.-S., Ju Y., Lee C.-H., 2019, Performance evaluation and carbon assessment of IGCC power plant with coal quality, Energy, 188, 116063.

Rosner F., Chen Q., Rao A., Samuelsen S., Jayaraman A., Alptekin G., 2019, Thermo-economic analyses of IGCC power plants employing warm gas CO_2 separation technology, Energy, 185, 541-553.

Shi B., Xu W., Wu W., Kuo P.-C., 2019, Techno-economic analysis of oxy-fuel IGCC power plants using integrated intermittent chemical looping air separation, Energy Conversion and Management 195, 290-301.

Skone T., James R., 2010, Life Cycle Analysis: Integrated Gasification Combined Cycle (IGCC) Power Plant, National Energy Technology Laboratory, 38-51.

Tola V., Pettinau A., 2014, Power generation plants with carbon capture and storage: A techno-economic comparison between coal combustion and gasification technologies, Applied Energy, 113, 1461–1474.

Wang L., Ni W., Li Z., 2006, Emergy evaluation of combined heat and power plant eco-industrial park (CHP plant EIP), Resources, Conservation and Recycling, 48, 56–70.

Wang Y., Wang J., Luo X., Guo S., Lv J., Gao Q., 2015, Dynamic modelling and simulation of IGCC process with Texaco gasifier using different coal, Systems Science & Control Engineering, 3(1), 198-210.

Yang Z.F., Jiang M.M., Chen B., Zhou J.B., Chen G.Q., Li S.C., 2010, Solar emergy evaluation for Chinese economy, Energy Policy, 38(2), 875-886.

Zechter R., Kossoy A., Oppermann K., Ramstein C., Lam L., Klein N., Wong L., Zhang J., Quant M., Neelis M., Nierop S., Ward J., Kansy T., Evans S., Child A., 2017, State and Trends of Carbon Pricing 2017, World Bank Group, Climate Change, Washington DC, USA, DOI: 10.1596/ 978-1-4648-1218-7.