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Cost of energy analysis of integrated gasification combined cycle (IGCC) power plant with respect to CO_2 capture ratio under climate change scenarios

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Abstract−This paper presents the results of the cost of energy (COE) analysis of an integrated gasification combined cycle (IGCC) power plant with respect to CO_2 capture ratio under the climate change scenarios. To obtain process data for a COE analysis, simulation models of IGCC power plants and an IGCC with carbon capture and sequestration (CCS) power plant, developed by the United States Department of Energy (DOE) and National Energy Technology Laboratory (NETL), have been adopted and simulated using Aspen Plus. The concept of 20-year levelized cost of energy (LCOE), and the climate change scenarios suggested by International Energy Agency (IEA) are also adopted to compare the COE of IGCC power plants with respect to CO_2 capture ratio more realistically. Since previous studies did not consider fuel price and CO_2 price changes, the reliability of previous results of LCOE is not good enough to be accepted for an economic comparison of IGCC power plants with respect to CO_2 capture ratio. In this study, LCOEs which consider price changes of fuel and CO_2 with respect to the climate change scenarios are proposed in order to increase the reliability of an economic comparison. And the results of proposed LCOEs of an IGCC without CCS power plant and IGCC with CCS (30%, 50%, 70% and 90% capture-mole basis- of CO_2 in syngas stream) power plants are presented.

Key words: Cost of Energy Analysis, IGCC, CO_2 Capture, Climate Change Scenario, Aspen Plus

INTRODUCTION

All around the world, there has been a growing consensus that limitation of CO_2 emissions is unavoidable due to global warming [1,2]. Consequently, various new technologies, so-called “renewable and sustainable energy,” which are concerned with the reduction of CO_2 emissions, have been introduced and developed during the decades. Since the power plant section is also affected by these new technologies, numerous researches [21-24] about the new power generation method such as geothermal power generation, wind power generation and tidal power generation etc., have been conducted in order to reduce CO_2 emissions which are caused by power plants. However, interest towards the modification of existing power generation system also has been increased since those new technologies are still developing or have regional limitations. Especially, the integrated gasification combined cycle (IGCC) has come into the spotlight as one of emerging technologies for the clean and more efficient use of coal for power generation due to its high thermal efficiency and low CO_2 emissions [3-8,25].

The United States Department of Energy (DOE) and National Energy Technology Laboratory (NETL) presented several IGCC models using Aspen Plus [3]. It provided simulation models and economic data of IGCC power plants with respect to its gasifier type such as GE Energy (GEE), ConocoPhillips (COP) and Shell. It also included simulation data of each IGCC power plant with/without carbon capture and sequestration (CCS). Before this work, the economic analysis of biomass IGCC with/without CCS power plant was performed [4] and the costs of energy (COE) of IGCC power plants were calculated with respect to various CO_2 capture options [5]. After that, the conceptual model of IGCC power plants based on the ELCOGAS power plant in Spain was provided, and the sensitivity analysis was performed with various feed stocks [6]. The optimization of IGCC power plant was also conducted by sensitivity analysis of combustion and gasification temperature [7] and the COE analysis of IGCC power plants with CCS was studied with respect to CO_2 prices [8].

Though all these researches provide proper simulation models and COE analyses of IGCC power plants, there are no researches which take the time dependency of CO_2 and fuel prices into account. Since CO_2 and fuel prices are continuously changing according to time, which will affect results of COE analyses significantly, it is required to reflect these changes in the COE calculation in order to perform COE analyses of IGCC power plants more precisely.

In this paper, to consider these situations, three different climate change scenarios suggested by the International Energy Agency (IEA) [1,2] were adopted to estimate price changes of fuel and CO_2 according to time. The concept of levelized cost of energy (LCOE) [9,10] was also adopted as an economic comparison tool in order to consider operation years of power plant. Simulation models of IGCC with/without CCS power plants were simulated using Aspen Plus, and an LCOE analysis of those models was done with respect to CO_2 capture ratio under climate change scenarios.

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METHODS

1. Description of the Climate Change Scenarios

According to the reports of the International Energy Agency (IEA), three different climate change scenarios are possible, such as the reference, the 450 ppm and the 550 ppm scenarios [1,2].

These are based on the assumption that the energy policy of each country in the world will play an important role in global warming. The reference scenario is possible when the current energy policy of all countries in the world will be continued in the future. Since the limitation of CO_2 emissions will not be restricted severely, demand for fossil fuels will be continuously increased. Consequently, CO_2 price will be lower, and coal price will be higher than those of other scenarios. Finally, the concentration of CO_2 in the air will rise up to 1,000 ppm by 2030.

The 450 ppm scenario assumes that not only OECD countries but also non-OECD countries should participate in reduction of CO_2 emissions. As a result, the amount of CO_2 emissions will be reduced from 29 giga ton (2007) to 26.4 giga ton by 2030 and average global temperature will rise up by 2 °C. Due to strict limitation of CO_2 emissions, the demand for clean energy will increase. Consequently, the demand for fossil fuels will decrease and the CO_2 price will be higher than that of other scenarios.

The 550 ppm scenario is between the reference scenario and the 450 ppm scenario. According to this scenario, the amount of CO_2 emissions will increase from 29 giga ton (2007) to 33 giga ton by 2030 and the average global temperature will rise up by 3 °C. Prices of coal and CO_2 will be formulated between those of the reference scenario and the 450 ppm scenario.

Table 1 shows prices of coal and CO_2 for all scenarios. Due to lack of information, some values were estimated based on energy demand and scenarios. Prices in 2010 were from the Index Mundi [11]. CO_2 prices in 2010 were not considered since CO_2 trading markets were not activated until then.

2. Levelized Cost of Energy (LCOE)

The concept of levelized cost of energy (LCOE) is useful when an economic analysis is performed between power plants with different performance characteristics, since the LCOE accounts for a project's installation, financing, tax and operating costs and the quantity of electricity it produces over its life. In this study, a real LCOE which accounts for the effect of inflation over the life of project, was adopted as a comparison basis and calculated by Eq. (1) [9,10].

$$\text{real LCOE} = \frac{\sum_{n=0}^{N} \frac{c_n}{(1+d_{nominal})^n}}{\sum_{n=1}^{N} \frac{Q_n}{(1+d_{real})^n}}$$

where Q_n (kWh) is electricity generated by the project in year n
N is project life in years
C_n ($) is project net cost in year n
d_{real} is real discount rate
$d_{nominal}$ is nominal discount rate

IGCC MODELING AND SIMULATION RESULTS

In this section, IGCC with/without CCS power plant models will be presented. All models were simulated using Aspen Plus. In the case of IGCC with CCS power plants, four detailed cases were simulated with respect to CO_2 capture ratio such as 90% CO_2 capture, 70% CO_2 capture, 50% CO_2 capture and 30% CO_2 capture.

1. Modeling of IGCC Power Plants

IGCC power plants have been studied by various groups during past decade [3-8,12-15]. Generally, the thermal efficiency of IGCC power plants is known to be higher than that of existing coal power plants since IGCC power plants convert coal into the syngas and utilize the heat of the syngas by using the heat integrated system in order to generate the electricity. The IGCC without CCS model consists of several sections such as coal preparation, coal gasification, air separation unit (ASU), cleaning (H_2S removal), power generation and heat recovery steam generator (HRSG). In the case of IGCC with CCS model, the water gas shift (WGS) section and the CO_2 removal section are added.

For better understanding, the simulation models of IGCC power plant with/without CCS are shown in Figs. 1 and 2. The coal feed is mixed with water and undergoes crushing and screening in order to make coal-water slurry in the coal preparation section. The gasifier converts coal-water slurry into the syngas with 95 mol% pure oxygen which is supplied by the ASU. In the case of no CCS, the syngas directly goes to the cleaning section, and H_2S is removed from the syngas in the cleaning section. In the case of CCS, the WGS reactor converts most of CO which is contained in the syngas into CO_2 and H_2 in order to remove CO_2 in the cleaning section. After that, H_2S and CO_2 are removed from the syngas in the cleaning section. Then, the syngas goes to the syngas turbine and generates the electricity. Finally, the steam is generated by using the heat which is recovered from the syngas and goes to the steam turbine which generates the electricity in the HRSG section.

In this research, models of IGCC power plants developed by DOE/NETL were adopted to conduct the LCOE analysis of IGCC power plants with respect to CO_2 capture ratio under the climate change scenarios. Each model included about 200 streams and 90 units, and simulated by Aspen Plus 7.1. The list of Aspen plus models which are used in simulations and references of each section are

Table 1. Possible outcomes for CO_2 and coal prices under climate change scenarios [1,2]

	Scenario 1 (the reference)			Scenario 2 (the 450 ppm)			Scenario 3 (the 550 ppm)		
	2010	2020	2030	2010	2020	2030	2010	2020	2030
Coal ($/ton)	100[a]	115[b]	110[b]	100[a]	105[c]	65[b]	100[a]	110[c]	85[b]
CO_2 ($/ton)	-	43[b]	54[b]	-	50[b]	110[b]	-	40[b]	90[b]

[a]Current prices as of Mar. 2010 [11]
[b]Values from World Energy Outlook 2008 and 2009
[c]Estimated values based on scenarios

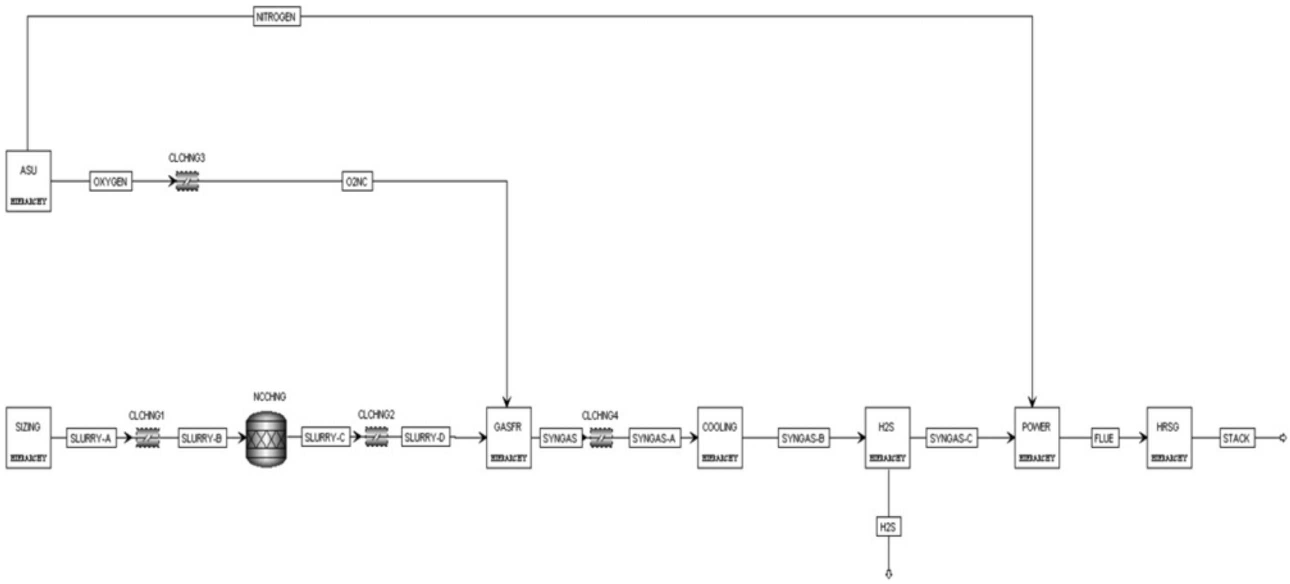

Fig. 1. A simulation model of IGCC power plant without CO_2 capture.

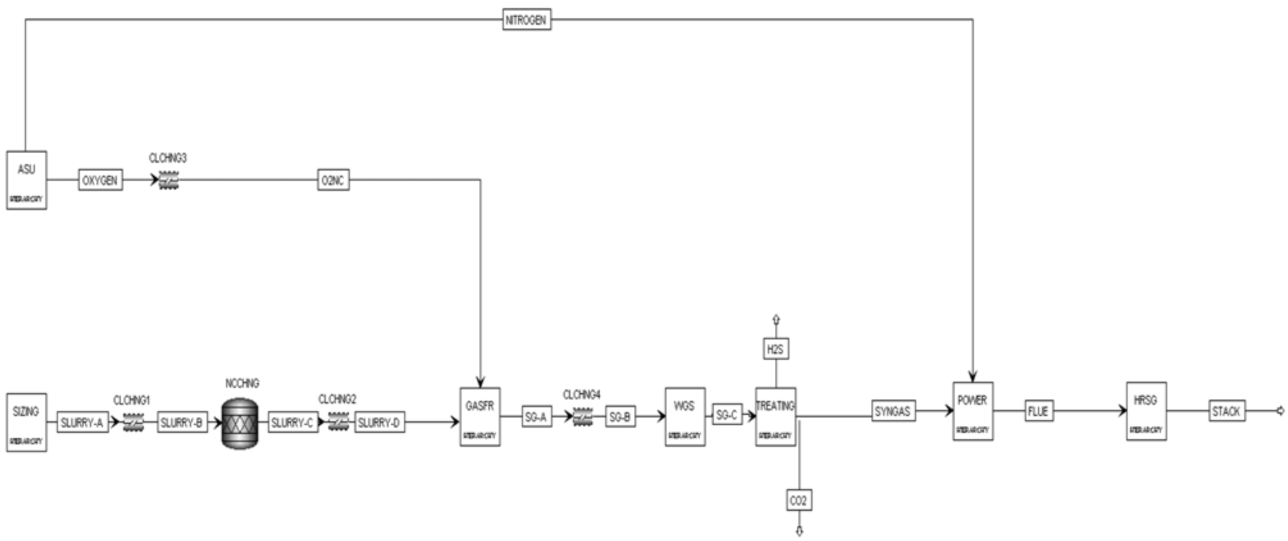

Fig. 2. A simulation model of IGCC power plant with CO_2 capture.

Table 2. Aspen model list and references of IGCC power plant simulations

Section	Aspen model list	References
Coal preparation	Mixer, Split, Crusher, Screen	[3], [16,17]
ASU	Mixer, Split, Valve, Flash2, HeatX, Compr, MHeatX, RadFrac	[3], [14], [16-19]
Gasifier	Split, Pump, RStoic, RGibbs, HeatX, Flash2	[3], [7,8], [12-17]
WGS	REquil, HeatX, Flash2	[3], [14], [16,17], [20]
Cleaning	Mixer, RadFrac, Compr, Flash2, Pump, Valve	[3-6], [14-17], [20]
Power generation and HRSG	Mixer, Split, Heater, Compr, Rstoic, HeatX, Flash2, Pump	[3], [14], [16,17]

also summarized in Table 2.

2. Simulation Results

Simulation input data and simulation results for all cases which are including no CCS case, 90%, 70%, 50% and 30% CO_2 capture (mole basis) cases are summarized in Table 3. Bitumus, Illinoi No. 6 is used as feed coal and the feed rate is fixed as 56.04 kg/sec for all cases. Total power generation has a range from 618.74 MWh to 678.79 MWh, and the net power generation has a range from 480.37 MWh to 585.06 MWh. The power consumption tends to increase as CO_2 capture ratio increases due to CO_2 capture and the com-

Table 3. Simulation input data and results

	IGCC without CCS	IGCC with CCS (90%)	IGCC with CCS (70%)	IGCC with CCS (50%)	IGCC with CCS (30%)
Coal type	Bitumus, Illinoi No. 6	Bitumus, Illinoi No. 6	Bitumus, Illinoi No. 6	Bitumus, Illinoi No. 6	Bitumus, Illinoi No. 6
Feed In (kg/sec)	56.04	56.04	56.04	56.04	56.04
Total power generation (MWh)	678.79	618.74	627.27	633.10	640.57
Power consumption (MWh)	93.73	138.37	132.21	126.06	119.90
Net power (MWh)	585.06	480.37	495.05	507.04	520.67
HHV efficiency (%)	38.45	31.57	32.54	33.32	34.22
CO_2 emission (kg/net-MWh)	757.33	109.44	280.73	444.45	598.73

Table 4. Averaged costs for IGCC power plants

	IGCC without CCS	IGCC with CCS (90%)	IGCC with CCS (70%)	IGCC with CCS (50%)	IGCC with CCS (30%)
Plant construction cost ($/net-KWh)	1954	2646	2567	2507	2442
Fixed operating cost ($/MWh-net)	4.32	5.40	5.24	5.12	4.98
Variable operating cost ($/MWh-net)	6.77	8.72	8.14	7.56	6.98

pression. Consequently, the high heating value (HHV) efficiency tends to decrease as CO_2 capture ratio increases.

LCOE CALCULATION AND COMPARISON FOR IGCC SIMULATION RESULTS

1. Cost Data for LCOE Calculation

To calculate LCOE of IGCC power plants, cost data are quoted from the reference [3]. Since all costs are estimated in 2006, the inflation rate 2% is assumed to reflect current costs. All averaged costs of IGCC power plants are summarized in Table 4. The plant construction cost includes all equipment costs, building costs, structure costs and site costs. The fixed operating cost includes labor costs and maintenance costs. And the variable operating cost includes utility costs and chemical costs etc. except for coal prices. In the case of IGCC power plants with CCS, all costs are varying with respect to CO_2 capture ratio since the net power generation, consumption of chemical solvents and utilities are varying with respect to CO_2 capture ratio.

2. Results of LCOE Analysis for IGCC Power Plants Based on Scenarios

In this section, the results of LCOE calculation are presented for all cases. For the purpose of comparison, two types of LCOE are calculated. LCOEs excluding CO_2 cost and LCOEs which are reflecting price changes of CO_2 and coal with respect to the climate change scenarios are shown in Figs. 3 and 4. Fig. 5 shows the amount of LCOE changes from no CCS case with respect to the CO_2 capture ratio. In the case of LCOEs excluding CO_2 costs are based on current coal and natural gas costs with 2% general inflation rate. Project periods are assumed as 20 years for all cases.

3. Discussion

In the case of LCOEs excluding CO_2 costs, the LCOE of IGCC is the lowest [Fig. 3] due to the high HHV efficiency and low construction and operating costs. However, this type of LCOE has a problem in the aspect of reliability since it does not consider CO_2 cost properly. As mentioned before, there has been a growing consensus that carbon regulation is inevitable. If the "cap-and-trade" system is activated in the near future, CO_2 emitters will be allowed to

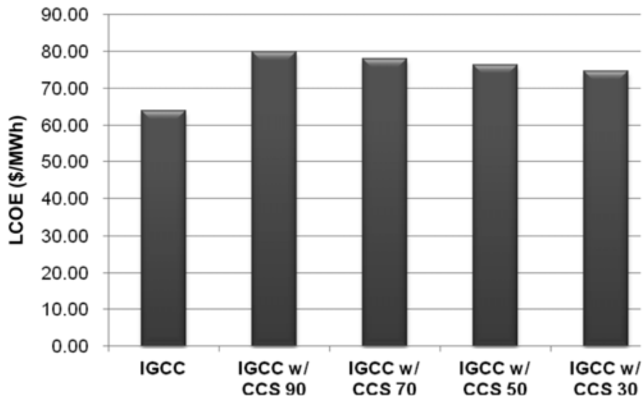

Fig. 3. 20 Year-LCOE excluding CO_2 cost for IGCC power plants.

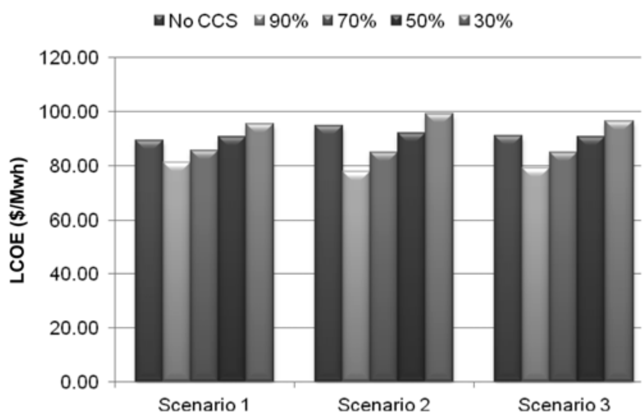

Fig. 4. 20 Year-LCOE which are reflecting price changes of CO_2 and coal with respect to scenarios.

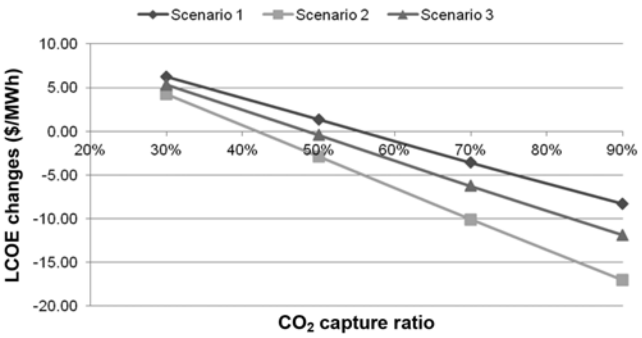

Fig. 5. The amount of LCOE changes from no CCS case with respect to CO_2 capture ratio.

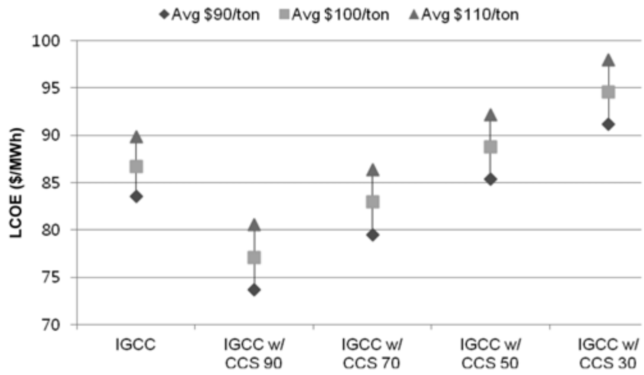

Fig. 7. Sensitivity analysis of the effect of coal price on LCOE.

buy and sell their emission allowances to meet their targets. Therefore, for the sake of reliability, the CO_2 price should be considered when CO_2 emitters perform the economic analysis of power plants.

In the case of LCOEs which are reflecting price changes of CO_2 and coal with respect to scenarios, three different climate change scenarios suggested by IEA are adopted for the LCOE calculating in order to increase reliability of economic comparison. Since IEA predicts cost changes of coal and CO_2, considering the law of supply and demand, population growth and technology development with respect to the scenario, if LCOEs reflect these cost changes, more reliable cost comparison can be possible. The result of LCOEs which are reflecting price changes of CO_2 and coal with respect to scenarios shown in Fig. 4, IGCC with CCS (90%) shows the lowest LCOEs since the amount of CO_2 emissions is smaller than that of other cases for all scenarios. Overall, it tends to increase LCOE as the CO_2 capture ratio is decreased [Fig. 5]. If the CO_2 capture ratio is above 60%, CCS cases are more economical than no CCS case for all scenarios.

To analyze the effect of price changes of coal and CO_2 on LCOE, sensitivity analyses are performed. Fig. 6 presents the result of sensitivity analysis of the effect of CO_2 price on LCOE. In the case of IGCC without CCS case, the deviation of LCOE with respect to the average CO_2 price is the largest and in the case of IGCC with CCS case (90%), the deviation of LCOE with respect to the average CO_2 price is the smallest. On the other hand, the result of sensitivity analysis of the effect of coal price on LCOE [Fig. 7] shows almost the same deviation with respect to the average coal price regardless of cases. These results represent that LCOE has a greater sensitivity with the CO_2 price rather than the coal price since the coal price also affects results of LCOE calculation but it does not change the overall tendency of the results.

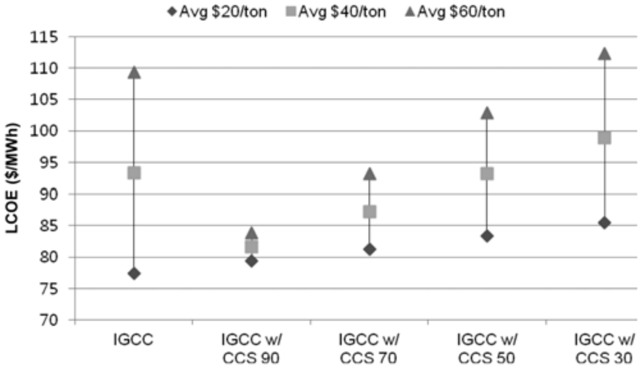

Fig. 6. Sensitivity analysis of the effect of CO_2 price on LCOE.

CONCLUSION

In this research, simulations and the economic analysis of the IGCC power plant with/without CCS have been performed with respect to the CO_2 capture ratio. To increase the reliability of the economic analysis, price changes of coal and CO_2 based on three different climate change scenarios suggested by IEA are reflected in the LCOE calculation. As a result, LCOEs of IGCC with CCS (90%) power plant are always the lowest since the amount of CO_2 emissions is always smaller than that of other case. And according to results of sensitivity analysis, LCOE has a great sensitivity with the CO_2 price rather than the coal price. LCOE also affected by the coal price change, but it seems to be not critical since it cannot change the overall tendency of LCOEs of IGCC power plants.

The results obtained in this study present a more realistic economical comparison between an IGCC power plant with the CCS and IGCC power plant without CCS than the existing LCOE which does not consider price changes of coal and CO_2. And it also can be of value to decision makers who are planning energy system including CCS. Based on this study, the research can be extended to compare LCOEs of whole energy generation systems including fossil fuel power plants and renewable energy power plants.

ACKNOWLEDGEMENT

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NOMENCLATURE

ASU : air separation unit
CCS : carbon capture and sequestration
COE : cost of energy
COP : ConocoPhillips
DOE : the united states department of energy
GEE : GE energy
HHV : high heating value
HRSG: heat recovery steam generator
IEA : international energy agency

IGCC : integrated gasification combined cycle
LCOE: levelized cost of energy
NETL: national energy technology laboratory
WGS : water gas shift

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