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KEPCO-China Huaneng Post-combustion CO_2 Capture Pilot Test and Cost Evaluation

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Abstract – The proprietary post-combustion CO_2 solvent (KoSol) developed by the Korea Electric Power Research Institute (KEPRI) was applied at the Shanghai Shidongkou CO_2 Capture Pilot Plant (China Huaneng CERI, capacity: 120,000 ton CO_2/yr) of the China Huaneng Group (CHNG) for performance evaluation. The key results of the pilot test and data on the South Korean/Chinese electric power market were used to calculate the predicted cost of CO_2 avoided upon deployment of CO_2 capture technology in commercial-scale coal-fired power plants. Sensitivity analysis was performed for the key factors. It is estimated that, in the case of South Korea, the calculated cost of CO_2 avoided for an 960 MW ultra-supercritical (USC) coal-fired power plant is approximately 35~44 USD/tCO_2 (excluding CO_2 transportation and storage costs). Conversely, applying the same technology to a 1,000 MW USC coal-fired power plant in Shanghai, China, results in a slightly lower cost (32~42 USD/tCO_2). This study confirms the importance of international cooperation that takes into consideration the geographical locations and the performance of CO_2 capture technology for the involved countries in the process of advancing the economic efficiency of large-scale CCS technology aimed to reduce greenhouse gases.

Key words: CO_2 capture, Cost of CO_2 avoided, China, International collaboration

1. Introduction

China has many geographical advantages for CO_2 storage over other countries. According to a report by IEA [1], the operational coal-fired power plants that are able to access a CO_2 storage site within 250 km have a combined capacity of 385 GW. The power plants that meet the basic requirements for modifications have a combined capacity of 310 GW, and this value is forecasted to increase as new power plants with larger capacities and greater efficiency are completed in the future IEA [1].

Analysis also shows that China has an advantage in terms of costs for CO_2 reduction over other countries. A recent study on the cost of CO_2 captured in China showed that with the nominal assumptions made for the base case study, the cost of CO_2 avoided for 90% CO_2 capture was estimated as approximately 41 USD/tCO_2 [2], which is significantly lower than that of US coal-fired plants (approximately 60 USD/tCO_2 [3]. Many expert groups discussed such results and proposed that the low construction and labor costs in China compared to other major developed countries was a major factor [2,4].

This study presents a CCS cost analysis for the electricity environment of China, a nation with a high potential for large-scale CCS demonstration, based on a performance evaluation conducted at Asia's largest CO_2 capture pilot plant in terms of capacity. In addition, we analyzed the key factors that affect CCS cost according to the different electricity environments of Korea and China when a CO_2 solvent developed in Korea is applied to a coal-fired power plant in China with the goal of promoting future large-scale CCS demonstrations and proposing measures to decrease the overall CCS demonstration cost. For this purpose, the proprietary post-combustion CO_2 solvent (KoSol) developed by the Korea Electric Power Research Institute (KEPRI) was applied at the CO_2 capture pilot plant of the China Huaneng Group (CHNG) Shanghai Shidongkou for performance evaluation as shown in Fig. 1. With the key operation results, including solvent regeneration energy, CO_2 removal rate and solvent loss as a basis, the cost of CO_2 avoided was analyzed. In particular, cost analysis was conducted based on the continuous operation data of wet-amine CO_2 capture plants using CAPEX and OPEX related to power plants proposed in sources such as IEA reports [5-7].

According to the review on the cost analysis of CCS, the cost of CO_2 avoided is presented as 45~70 USD/tCO_2 for major CCS project reported between 2011 and 2013 [8]. In addition to the wet amine based post-combustion CO_2 capture process, the cost of CO_2 avoided of dry sorbent and membrane-based post-combustion CO_2 capture process is 45.8 €/t CO_2 (dry sorbent technology for a cement factory [9]), 45 USD/tCO_2 (membrane process, NETL 2010 baseline [10]). However, there is a difference in the size of the baseline plant compared to the wet amine process.

Whereas research results have been presented for key projects in Europe and Canada related to CCS cost analysis research based on

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CO_2 capture in the Boryeong power plant (KEPCO)

CO_2 capture in the Shanghai Shidongkou power plant (CHNG)

Fig. 1. Post-combustion CO_2 capture pilot plant of KEPCO & CHNG.

large-scale CO_2 capture plant performance evaluations [11-13], there have been a limited number of studies on CCS cost analysis research based on China, a nation with a high CCS market potential. In contrast, this research involved CCS cost analysis based on key performance data obtained from the operation of a pilot-scale CO_2 capture plant with consideration of the state of the electricity markets of different nations (Korea and China). In addition, this study has great implications as it analyzed how the cost of CO_2 avoided and the levelized cost of electricity (LCOE) are affected by the implementation of the same CO_2 capture technology in the electricity markets of different countries. Based on the analysis, we propose methods to minimize the cost of demonstrating future large-scale CCS technology through international cooperation.

2. Method

This paper describes the continuous operation tests conducted for the post-combustion CO_2 solvent (KoSol) that was applied at the CHNG Shanghai Shidongkou post-combustion CO_2 capture pilot plant and presents the related cost of CO_2 avoided. Performance tests were conducted over 1,000 hours and plant performance and cost evaluation models were developed.

The overall framework for the CCS cost analysis proposed in the CCS costing method task force is illustrated in Fig. 2 [14]. As shown in Fig. 2, to conduct CCS cost analysis, it is necessary to have a plant performance model capable of predicting the net output (or net plant efficiency) changes and CO_2 emissions of power plants before/after the installation of a CCS plant, as well as a plant cost model capable of calculating the costs of the power plant (amount of generated power, power generation unit price, etc.) based on the results of the plant performance model. Through the deep integration of the two models, it is possible to calculate the final desired results such as the amount of CO_2 reduction, the levelized cost of electricity (LCOE) increase, and the cost of CO_2 avoided resulting from the implementation of CCS technology.

In this study, a plant performance model and plant cost model are developed for the calculation of the cost of CO_2 avoided in accordance with the proposed framework. In this paper, the deployment of CO_2

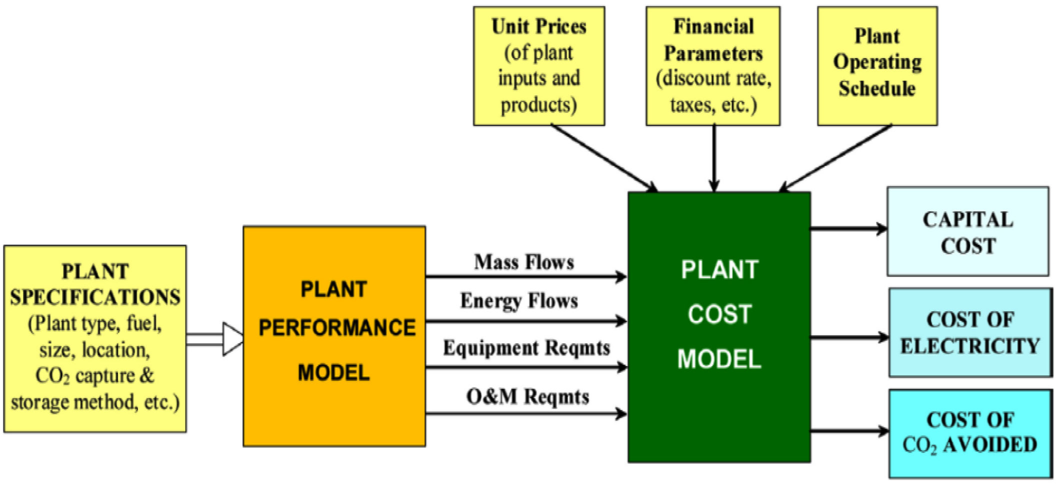

Fig. 2. CCS cost analysis framework [14].

capture plants to existing coal-fired power plants is considered to be unfeasible in practice due to the difficulties in the integration of the CO_2 capture plant and existing power blocks. Therefore, we selected deployment of CO_2 capture plants to upcoming new coal-fired power plants and assumed that the net output of power plants with CCS would be adjusted to match the net output of reference plant (without CCS).

The most important aspects to consider in the performance evaluation of power plants with CCS is the decrease in net efficiency of the power plant due to the CO_2 capture plant and the additional fuel (coal) consumption. CO_2 capture processes installed in coal-fired power plants require large amounts of electrical energy to operate the relevant processes (various pumps and fans, etc.), increase operating costs due to compression processes, and require large amounts of energy for steam used to regenerate the solvent in the stripper. The additional energy must be produced from the turbine block of the power plant, which results in a decrease in net plant efficiency. To predict the decrease in net plant efficiency due to the addition of a the CO_2 capture plant, integration between the CO_2 capture plant and the power block, which consists of components such as boilers, turbine systems, and feed water heaters, is necessary. Such integration requires highly complex thermodynamic calculations and is beyond the scope of this paper. Hence, we used the shortcut method proposed by Bolland et al. [15] to predict the decrease in plant net output due to the addition of CCS, considering the CO_2 capture pilot plant data of CHNG and KEPCO. The net efficiency of a power plant with CCS can be calculated using the following equation (1) [15].

2-1. Efficiency with CO_2 capture

$$\eta_{CCS} = \eta_{ref} - \frac{E^{CO_2}_{rem,mech}C}{LHV} - \frac{E^{CO_2}_{rem,heat}\alpha C_f}{LHV} - \frac{E^{CO_2}_{comp}C_f}{LHV} \qquad (1)$$

where η_{CCS} is the efficiency of the power plant with CCS, $\eta_{reference}$ is the efficiency of the reference power plant without CCS, $E^{CO_2}_{rem,mech}$ is the mechanical work required for the CCS plant, $E^{CO_2}_{rem,heat}$ is the heat required for stripping of CO_2 from the solvent, $E^{CO_2}_{comp}$ is the power requirement for compression of CO_2, f is the fraction of the CO_2 captured in the CO_2 capture process and LHV is the lower heating value for coal.

Following this, the cash flow during the power generation lifetime of the power plant was analyzed for plants with and without CCS. The cash flow analysis calculates the required amount of coal input to achieve the rated output of the power plant and the resulting CO_2 emission based on the carbon content and calorific value of the fuel (coal) used. In addition, the LCOE with and without CCS was calculated through cash flow analysis. The key metrics for the analysis of cost of CO_2 avoided detailed in this paper are as follows [14].

2-2. Levelized Cost of Electricity, LCOE

The levelized cost of electricity can be defined as follows:

$$\mathrm{LCOE} = \sum_t \frac{(\text{capital expenditure})_t + (\text{operating expenditure})_t + \mathrm{Fuel}_t}{(1+r)^t} \Big/ \sum_t \frac{(\text{electricity sold})_t}{(1+r)^t} \qquad (2)$$

where *electricity sold*$_t$ is the net electricity produced and sold in year t, r it the annual rate used to discount values usually taken to be a pre-defined rate of return required to cover equity and debt costs, *capital expenditure*$_t$ is the expenditure in year t associated with construction of the plant, *operating expenditure*$_t$ is the total non-fuel operating and maintenance costs in year t and *fuel*$_t$ is the total fuel costs in year t.

2-3. Cost of CO_2 avoided

Cost of CO_2 avoided compares a plant with CCS to a reference plant without CCS and quantifies the average cost of avoiding a unit of atmospheric CO_2 emissions. It is defined as follows [16]:

$$\text{Cost of } CO_2 \text{ avoided} = \frac{|(\mathrm{LCOE})_{ref} - (\mathrm{LCOE})_{CCS}|}{(tCO_2/MWh)_{ref} - (tCO_2/MWh)_{CCS}} \qquad (3)$$

where LCOE = levelized cost of electricity generation ($/MWh), tCO_2/MWh = CO_2 mass emission rate to the atmosphere in tons per MWh (based on the net output of each power plant), and the subscripts "ccs" and "ref" refer to plants with and without CCS, respectively.

3. Results

3-1. Technical evaluation

3-1-1. Solvent exchange test: CHNG CO_2 capture plant

The CHNG CO_2 capture plant is installed at the Shanghai Shidongkou No. 2 power plant and is installed in the process after SCR, ESP, and WFGD for flue gas treatment. A refining system (a CO_2 compression and liquefaction process) is installed after the CO_2 capture plant to produce food-grade high pure CO_2. The produced CO_2 is stored in a storage tank and is transported by trucks once sold to buyers. This revenue compensates for a proportion of the operating costs of the CO_2 capture plant. The specifications of the CHNG CO_2 capture plant are listed in Table 1. The flue gas that is supplied to the CO_2 capture process is obtained from the WFGD and is supplied at a constant gas flow rate (66,000 Nm^3/hr, based on normal operating condition). A simplified flow sheet of CHNG Shanghai Shidongkou CO_2 capture pilot plant is shown in Fig. 3.

The CO_2 capture plant consists of one absorber and one stripper in addition to other equipment, including a reboiler, a reclaimer, and various pumps, condensers, and coolers. Power consumption data of every equipment is monitored and collected in real time through distributed control system of the CO_2 capture plant and used to evaluate the operating costs. The absorber and stripper both contain structured packing materials. The flue gas that is supplied to the CO_2 capture process is supplied to the bottom section of the absorber by a

Table 1. Post-combustion CO_2 capture pilot plant specifications (design basis)

Component	Unit	Shidongkou, China	Boryeong, Korea
Absorber			
Column height	m	40	37
Column diameter	m	4.2	3.3
Stripper			
Column height	m	31	26
Column diameter	m	3.2	2.2
Power plant type	-	USC	USC
Flue gas flow rate	Nm^3/hr	66,000	35,000
CO_2 concentration of flue gas	vol.%	9~15	13~15
CO_2 removal rate	%	> 90%	> 90%

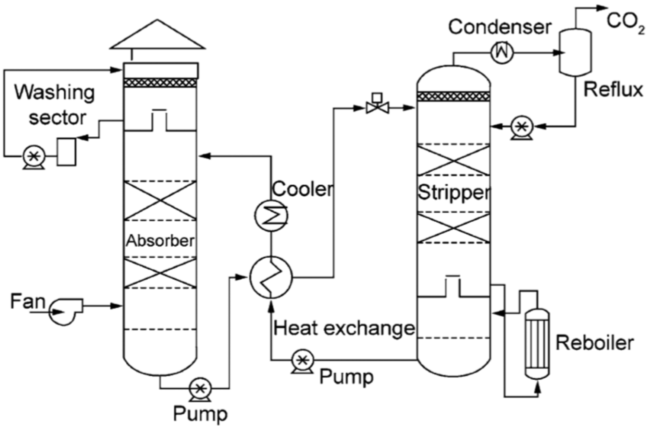

Fig. 3. Flowsheet of CHNG Shanghai Shidongkou CO_2 capture plant [17].

fan. CO_2 is removed from the flue gas through chemical reactions that occur between the flue gas and the lean solvent that is injected to the upper section of the absorber. During the continuous operation with CO_2 solvents developed by CHNG, the internal temperature of the absorber is maintained at approximately 50~60 °C, and a water washing system installed in the upper section of the absorber reduces the co-emission of the flue gas and solvent. The CO_2-rich solvent (rich amine) is transferred via pumps through a heat exchanger between the absorber and the stripper. Low-pressure steam is supplied to the stripper to separate CO_2 from the solvent. The stripper bottom temperature is maintained at 105~110 °C depending on the solvent characteristics. The regenerated CO_2 stream passes through a mist eliminator, condenser, and reflux drum to remove water and solvent, after which it is discharged with 99.5% to 99.7% purity. The discharged gas is utilized for food-grade purposes after separate refining processes (Fig. 4). Detailed specifications of the described post-combustion CO_2 capture pilot plant with comparison of the pilot plant at Boryeong in South Korea are as follows.

Table 2 shows the composition of the flue gas supplied to the post-combustion CO_2 capture plant. The CO_2 concentration and composition of other impurities in the flue gas is similar to the flue gas that is supplied to the Boryeong CO_2 capture plant of KEPCO. During operation of the CO_2 capture pilot plant of CHNG, the flue gas is subjected to a flue gas treating process before being supplied to the bottom of the absorber. During this process, the flue gas is cooled to below 50 °C. The solvent applied in the solvent exchange test is an

Table 2. Flue gas composition of CO_2 capture test

Description	Unit	Shidongkou, China	Boryeong, Korea [19]
CO_2	vol.%	13~15	13~15
H_2O	vol.%	4.6	11.0
SOx	ppm, vdry	2	< 5
Fly ash	mg/m^3	10	15

CO_2 capture plant

CO_2 storage TK(2 units)

Fig. 4. CHNG Shanghai Shidongkou CO_2 capture pilot plant.

Table 3. Operating conditions of CO_2 capture test

Description	Unit	Shidongkou, China	Boryeong, Korea
Solvent	-	KoSol-4	KoSol-4
Solvent initial charge	ton	90	57
L/G ratio	kg/Nm^3	3.0	2.0
Absorber			
- Feed gas temperature	^oC	38	46~48
Stripper			
- Pressure	barg	0.44	0.3
- Steam	barg	3.0	3.5

amine-based solvent (KoSol-4) developed by KEPRI for post-combustion CO_2 capture [18]. The CO_2 capture performance and reliability of the solvent has already been confirmed through over 10,000 hours of continuous operation at the Boryeong power plant prior to the exchange test at the CHNG Shanghai Shidongkou pilot plant.

3-1-2. Baseline operating conditions

Continuous operation is conducted with the above flue gas composition. Table 3 describes the operating conditions derived from initial trial operations. The initial operating conditions are set with reference to Boryeong pilot plant data and are adjusted accordingly during operation to identify the optimal operating conditions.

3-1-3. CO_2 capture pilot test results

The test campaign lasted two months, and the performance test results for the CHNG pilot plant with reference to the Boryeong pilot plant are summarized in Table 4. To accurately analyze solvent (KoSol-4) loss to the atmosphere during the long-term continuous operation of the pilot test of this study, the solvent was not replenished during the operation. As the CO_2 removal rate and solvent regeneration energy consumption gradually decreased due to solvent loss, we used the initial operation data, which had relatively lower solvent loss, for

Table 4. Key results of the solvent exchange test

Description	Unit	Shidongkou, China	Boryeong, Korea
Test campaign	-	'18.4~5	'17.2~6
Solvent	-	KoSol-4	KoSol-4[1)]
Lean amine temperature @ inlet to the absorber	^oC	33	40
Flue gas temperature @ inlet to the absorber	^oC	38	40
Rich amine temperature @ inlet to the stripper	^oC	93	105
Reboiler bottom temperature	^oC	108	110
Solvent make-up	$kg/tonCO_2$	1.6	0.72
Temperature difference	^oC	15	5
CO_2 removal rate	%	90	90
Reboiler heat duty (solvent regeneration energy)	GJ/tCO_2	3.1 / 2.8[2)]	2.8
Product CO_2 purity	%	> 99	> 99

[1)]KEPRI, as of 2019, is currently developing a KoSol-5 solvent that improves upon the performance of the KoSol-4 solvent and is conducting 5,000 hours of continuous operation performance evaluations at the Boryeong CO_2 capture pilot plant. Key performance details that have been obtained include an average CO_2 removal rate of 90% and solvent regeneration energy of 2.5~2.6 GJ/tCO_2.

[2)]Performance improvements to the CHNG lean/rich amine heat exchanger are expected to lower the value to 2.8 GJ/tCO_2.

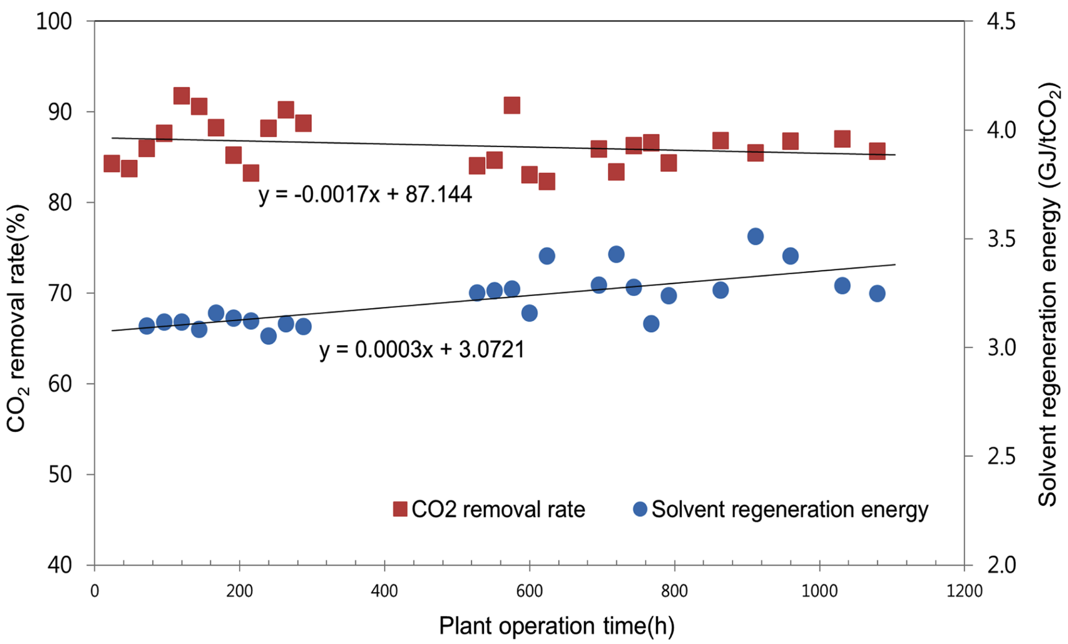

Fig. 5. CO_2 capture test results of the CHNG pilot plant.

the performance comparison with the Boryeong pilot plant operation data and the following evaluation of the cost of CO_2 avoided.

According to the analysis conducted with the above conditions, the CHNG CO_2 capture pilot plant that applied the KEPCO's proprietary solvent (KoSol-4) had an average CO_2 removal rate of 90%, and the solvent regeneration energy consumption was 3.1 GJ/ tCO_2 as shown in Fig. 5.

Of these results, the solvent regeneration energy consumption value was slightly higher than the test results obtained from the Boryeong pilot plant in South Korea (2.8 GJ/tCO_2). The difference in solvent regeneration energy consumption of the Boryeong pilot plant and the CHNG pilot plant, despite the fact that both pilot plants used the same solvent (KoSol-4), seems mainly due to the lower efficiency of the lean/rich amine heat exchanger installed in the CHNG pilot plant. The temperature difference between the bottom section of the stripper and the rich amine that was fed into the top section of the stripper exceeded 15 ^oC during operation, and energy (sensible heat) consumption increased to adjust the temperature gap. Considering that the temperature difference of the Boryeong pilot plant, which applied the same solvent as the CHNG pilot plant, was maintained at 5 ^oC or lower during operation, the operating condition of the CHNG pilot plant was almost 10 ^oC higher.

Based on the above results, to analyze the effects of temperature difference during the operation of the lean/rich amine heat exchanger on solvent regeneration energy consumption, we divided the solvent regeneration energy into three components (reaction heat, sensible heat, and latent heat), as proposed by Chakma [20], and analyzed the sensible heat requirement according to decrease in temperature difference of the lean/rich amine heat exchanger. Using the analysis results, we calculated the predicted solvent regeneration energy consumption. According to the analysis, if the lean/rich amine heat exchanger of the CHNG pilot plant is improved to lower the temperature difference to 5 ^oC, the sensible heat element is decreased by approximately 0.3 GJ/tCO_2, which results in a decrease in solvent regeneration energy consumption from the current value of 3.1 GJ/ tCO_2 to 2.8 GJ/tCO_2. Based on the results, the key performance metrics of the CHNG pilot plant and the Boryeong pilot plant, both of which used the KEPCO's proprietary solvent (KoSol-4), are summarized in Table 4.

In addition to solvent regeneration energy and CO_2 removal rate, amine (solvent) loss is an important index of the key performance of CO_2 capture plants. Amine loss refers to the decrease in the total amount of the solvent as small amounts of the solvent are lost to the atmosphere due to the high vapor pressure [21]. High amounts of amine loss require operators to regularly make up the solvent, which increases the overall CO_2 capture plant operation costs. In the case of MEA (monoethanolamine, 30 wt%), a notable post-combustion CO_2 capture solvent, the amount of solvent make up due to amine loss has been reported to be 1.5 kg/tonCO_2 [22]. Compared to MEA, the proprietary solvent of KEPCO (KoSol-4) had a solvent make up amount of approximately 0.72 kg/ton CO_2, according to the operation results of the Boryeong CO_2 capture plant. However, according to the operation results from the CHNG pilot plant, the solvent make-up amount of the proprietary solvent of KEPCO (KoSol-4) was 1.6 kg/ton CO_2. This difference was due to the existence of a two-stage water washing section in the upper section of the absorber in the Boryeong CO_2 capture plant, which minimizes solvent loss better than the single-stage water washing section in the upper section of the absorber in the CHNG CO_2 capture pilot plant. For the CCS cost analysis, costs were calculated based on the solvent make up amount obtained from the Boryeong CO_2 capture plant (0.72 kg/ton CO_2) as the difference in solvent make-up amount is due to the design of the CO_2 capture pilot plants that were developed by KEPCO and the Huaneng Group with consideration of the inherent properties of the developed solvent.

3-2. Economic evaluation

Using the results of the solvent exchange test, we performed a CCS cost evaluation. This cost evaluation study estimated the cost of CO_2 avoided of the KEPRI-developed capture technology by analyzing the different power generation markets (South Korea and China) and exploring strategies for future large-scale CCS demonstrations and technology spin-offs. The CO_2 capture process is the main factor that affects the reliability of technology for CCS technology demonstration and the total costs for such projects. This is because the CO_2 capture process consumes a substantial amount of energy (such as steam consumption for solvent regeneration that is extracted from the turbine block of power plants) of all the processes in the CCS chain and constitutes for a large proportion of the total costs. In addition, the CO_2 capture process greatly affects post-capture processes (CO_2 compression, transportation, storage, etc.). Hence, many researchers are trying to develop high-efficiency CO_2 solvents and improve processes to reduce steam consumption (solvent regeneration energy) in the CO_2 capture process.

3-2-1. Key assumptions and input data

3-2-1-1. Key parameters

We used data proposed by IEA as a reference for the reference power plant [7]. Following the selection of the reference power plant, the plant lifetime, construction period, decommissioning costs and discount rate were considered for the cost analysis. The lifetime and construction period of the coal-fired power plant was set as 30 years and 4 years, respectively.

For the cash flow analysis, the baseline for the discount rate was assumed as 5.5% based on the recommended discount rate of public projects in Korea [23,24], and a sensitivity analysis was conducted for discount rates of 3~7% according to IEA guidelines [25]. In addition to CO_2 capture, the calculation of CO_2 transportation and storage costs is important for CCS cost evaluation. CO_2 transportation and storage costs are highly dependent on the geographical location. In particular, various transportation options (onshore/offshore pipeline, ship, truck) are available for CO_2 transportation, each of which has

Table 5. Key financial parameters (for baseline case)

Description	Unit	Value	Comments
Plant lifetime	yrs	30	[16]
Construction period	yrs	4	
Discount rate	%	5.5	[23]
Decommissioning cost	USD	0	[23]

different costs and may have issues in terms of public acceptance. Hence, standardized models are limited in calculating CO_2 transportation costs. For CO_2 storage, investment and operating costs vary greatly depending on the geographical environment for CO_2 storage. Due to such uncertainties, we did not consider CO_2 transportation and storage costs in this study. For CO_2 compression, the high-purity CO_2 was assumed to be compressed to 110 bar and the electricity power consumption due to compression was calculated using data proposed by Bolland et al. [15]. In addition to the parameters mentioned above, the fuel (coal) price greatly affects CCS cost. We conducted a cost analysis using the representative fuel costs of each country (Korea and China) as the baseline case and the effects of coal price on cost of CO_2 avoided and LCOE under the same conditions were analyzed through sensitivity analysis.

3-2-1-2. CAPEX & OPEX

Based on the method proposed above, the developed CCS performance and cost model was used to calculate LCOE with and without CCS and the cost of CO_2 avoided with consideration of the power generation market. The key assumptions for the cost analysis are shown in Table 6. The reference power plant type was assumed as an USC coal-fired power plant, and the net output for the Chinese and Korean coal-fired power plants was assumed as 1,000 MW (net plant efficiency: 45%) and 960 MW (net plant efficiency: 43%), respectively. IEA reports that present the generating costs of major countries in the world, including South Korea and China, are referred to for the overnight cost and O&M costs of the reference power plant [7], and Fig. 6 shows the overnight costs for the construction of coal-

Table 6. CAPEX & OPEX of power plants with and without CCS

Description	Unit	Shidongkou, China	Boryeong, Korea	Comments
Power plant				
Plant type	-	USC	USC	
Reference plant net output	MW	1,000	960	[7]
Net plant efficiency	%	45	43	
Plant capacity factor	%	85	85	
Fuel				
Fuel type	-	Bituminous	Bituminous	
Fuel cost	USD/GJ	2.9	3.7	[2], [28]
Overnight cost w/o CCS	USD/kWe	817	1,225	[7]
Overnight cost w/ CCS	USD/kWe	1,430	2,143	
Overnight cost increase	%	75	75	[8]
O&M cost w/o CCS	USD/MWh	4.11	4.85	[7]
O&M cost w/ CCS	USD/MWh	6.93	8.17	

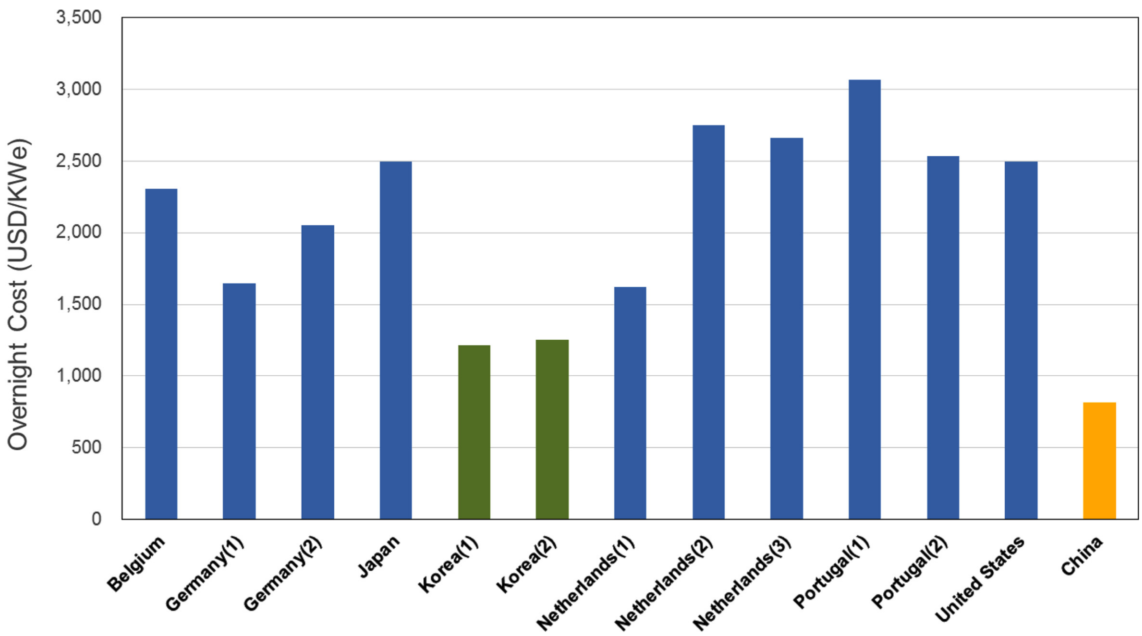

Fig. 6. Overnight cost of coal-fired power plants [7].

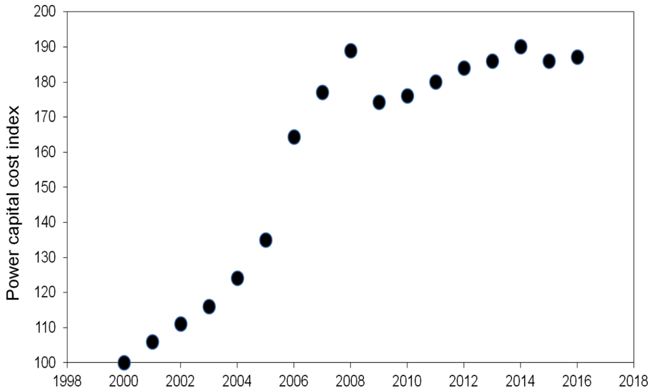

Fig. 7. Costs indices normalized to 100 in year 2000 [27].

Fig. 6, the overnight cost for the construction of power plants in South Korea is substantially lower than in other OECD countries. In addition, the overnight cost of power plants in China, a non-OECD country, is approximately half the average of OECD countries. This difference can also be seen through the comparison of the CAPEX of major pilot-scale CO_2 capture plants that are in operation. In particular, the construction costs of the Boryeong CO_2 capture plant (annual CO_2 capture capacity of 70,000 tons) and the CHNG CO_2 capture plant (annual CO_2 capture capacity of 120,000 tons), which were 22mUSD (Boryeong, 2013) and 16mUSD (CHNG, 2009), respectively, are substantially lower compared to the Shand Carbon Capture Test facility (70 mUSD for 43.8 ktCO_2/yr) and the European CO_2 Test Centre Mongstad (1.02 billion USD for 0.1 Mt CO_2/yr) [26] even after conversions into the same scale.

In addition, cost escalation, which used the power capital cost indices shown in Fig. 7, was considered for CAPEX and OPEX estimations of the proposed reference power plant.

In addition to the costs of the reference power plant, certain reports based on extensive research on costs of power plants with CCS have been released [5]. However, detailed cost calculations at the level of such reports are beyond the scope of this paper as substantial engineering is required to perform such calculations. Therefore, to estimate the cost of a power plant with CCS, we used the average increase rate of overnight cost and O&M cost of a power plant with CCS from the analysis of major OECD countries [8], which considered fact that most of the CO_2 capture technology applied at demonstration plants is similar to amine solvent-based post-combustion capture processes. In this study, the O&M costs w/ CCS were calculated based on the average O&M increase (68.5%) due to the conversion from w/o CCS to w/ CCS proposed in previous studies [5]. In addition, typical coal properties of the Chinese and Korean cases are shown below in Table 7. For cost analysis, the carbon content and heating value data of the fuel (coal) presented in Table 7 were used to calculate the total amount of coal used and the resulting amount of CO_2 emissions for the w/o CCS plant and w/ CCS plant.

3-2-2. CO_2 Capture cost evaluation

3-2-2-1. Baseline case

Table 8 shows the evaluation results of the baseline case based on the above key data. According to the analysis, the addition of a CCS plant to the Korean 960 MW USC coal-fired power plant results in a 10.1% decrease in net plant efficiency from 43% (without CCS) to 32.9% (with CCS), and LCOE increased from 47.96 USD/MWh (without CCS) to 74.06 USD/MWh (with CCS) due to the increase in coal consumption to meet the reference plant net output. The resulting cost of CO_2 avoided was calculated as 37.6 USD/tCO_2. On the other hand, when CCS technology that reflects the performance evaluation results of the CHNG pilot plant was applied to the Chinese 1000 MW USC coal-fired power plant, the net plant efficiency decreased by approximately 11.7% from 45% (without CCS) to 33.3% (with CCS), LCOE increased from 40.13 USD/MWh (without CCS) to 65.44 USD/MWh (with CCS), and the resulting cost of CO_2 avoided was calculated as 34.9 USD/tCO_2.

From the analysis of the Korean and Chinese cases, the calculated cost of CO_2 avoided of the Chinese coal-fired power plant case was lower than the Korean case. This was due to the lower cost index of China. On the other hand, the energy penalty of power plants due to the addition of CCS technology was calculated as 11.7% for the Chinese case in contrast to the 10.1% for the Korean case, which was due to the solvent regeneration energy consumption being set as 3.1 GJ/tCO_2 for the Chinese case according to the operation results obtained for the CHNG CO_2 capture pilot plant. Therefore, for subsequent sensitivity analysis, a range of values was used for solvent regeneration energy consumption (2.8~3.3 GJ/tCO_2) to analyze the effect of solvent regeneration energy consumption on CCS cost evaluations.

The key results of this study were compared to recent CCS cost

Table 7. Typical coal properties of Chinese and Korean cases

Description	Unit	Shidongkou, China [29]	Boryeong, Korea [19]
Higher Heating Value HHV			
As received	MJ/kg	23.89	26.8
Ultimate Analysis (Dry Ash Free basis)			
Carbon	wt.%	80.44	82.0
Hydrogen	wt.%	4.83	5.1
Nitrogen	wt.%	0.92	1.7
Sulphur	wt.%	0.55	10.3
Oxygen	wt.%	13.27	0.9
Total	wt.%	100.0	100.0

Table 8. Cost evaluation results of the baseline case

Regional Focus	Unit	Shidongkou, China	Boryeong, Korea	Comments Range / Rep value [8]
Year of the cost basis		2016	2016	
Organization		CHNG	KEPCO	
Region		Shanghai, China	Boryeong, South Korea	
Coal type		Bituminous	Bituminous	
Power plant type		USC	USC	
Net power output w/o CCS	MW	1,000	960	550-1030 / 837
Net power output w/ CCS	MW	1,000	960	
Net plant efficiency w/o CCS, HHV	%	45	43	39.0-44.4 / 44.4
Net plant efficiency w/ CCS, HHV	%	33.3	32.9	27.2-36.5 / 36.1
Energy penalty w/ CCS	%	11.7	10.1	
CO_2 emission w/o CCS	kg/MWh	840	799	
CO_2 emission w/ CCS	kg/MWh	114	104	
Relative decrease in net plant efficiency	%	26.0	23.5	
Overnight cost w/o CCS	USD/kW	817	1,225	2,313-2,990 / 2,630
Overnight cost w/ CCS	USD/kW	1,430	2,143	4,091-5,252 / 4,497
LCOE w/o CCS	USD/MWh	40.13	47.96	61-79 / 61.5
LCOE w/ CCS	USD/MWh	65.44	74.06	94-130 / 100.4
Cost of CO_2 avoided	USD/tCO_2	34.9	37.6	45-70 / 57
Relative increase in overnight cost	%	75.0	75.0	58-91 / 71
Relative increase in LCOE	%	63.1	54.4	46-69 / 63

evaluation research [8]. For the reference case for cost analysis, we referred to research conducted by Alstom in 2011 [30] on a coal-fired power plant with a net plant efficiency similar to the plant in this study (44.4%). The overnight costs of reference power plants and power plants with CCS were significantly low for both the Korean and Chinese cases. In addition, in contrast to the average cost of CO_2 avoided of the reference case, which was calculated as 57 USD/tCO_2, the cost of CO_2 avoided for the Chinese power plant in this study was almost 35 USD/tCO_2. This difference is attributed to the low CAPEX and OPEX of China compared to OECD nations. For more accurate analysis, further studies were required to estimate the detailed costs of power plants with CCS. To analyze the key factors that affect CCS cost, we broke down the LCOE of the Korean and Chinses cases and the reference case [30] of this study for w/o CCS power plants and w/CCS power plants. The analysis results are presented in Fig. 8. According to the analysis results, the cost of fuel constituted at least 50% of the LCOE data of the w/o CCS and w/ CCS power plants for the Korean and Chinese cases, which was at least 10% greater than the reference case data (w/o CCS: 40%, w/ CCS: 30%). The high impact of fuel cost on LCOE was due to the lower plant CAPEX and OPEX in China and South Korea compared to the reference case.

3-2-2-2. Sensitivity analysis

Following the analysis of the baseline case, we conducted a sensitivity analysis to analyze the effects of various variables on CCS cost for Korean and Chinese power plants, and the results are shown

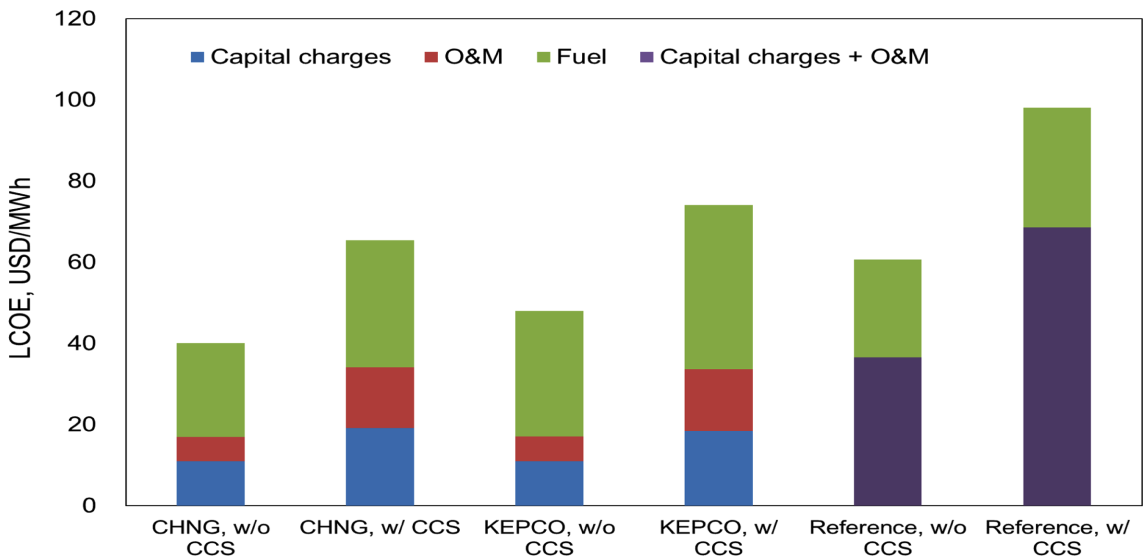

Fig. 8. Cost breakdown of various cases.

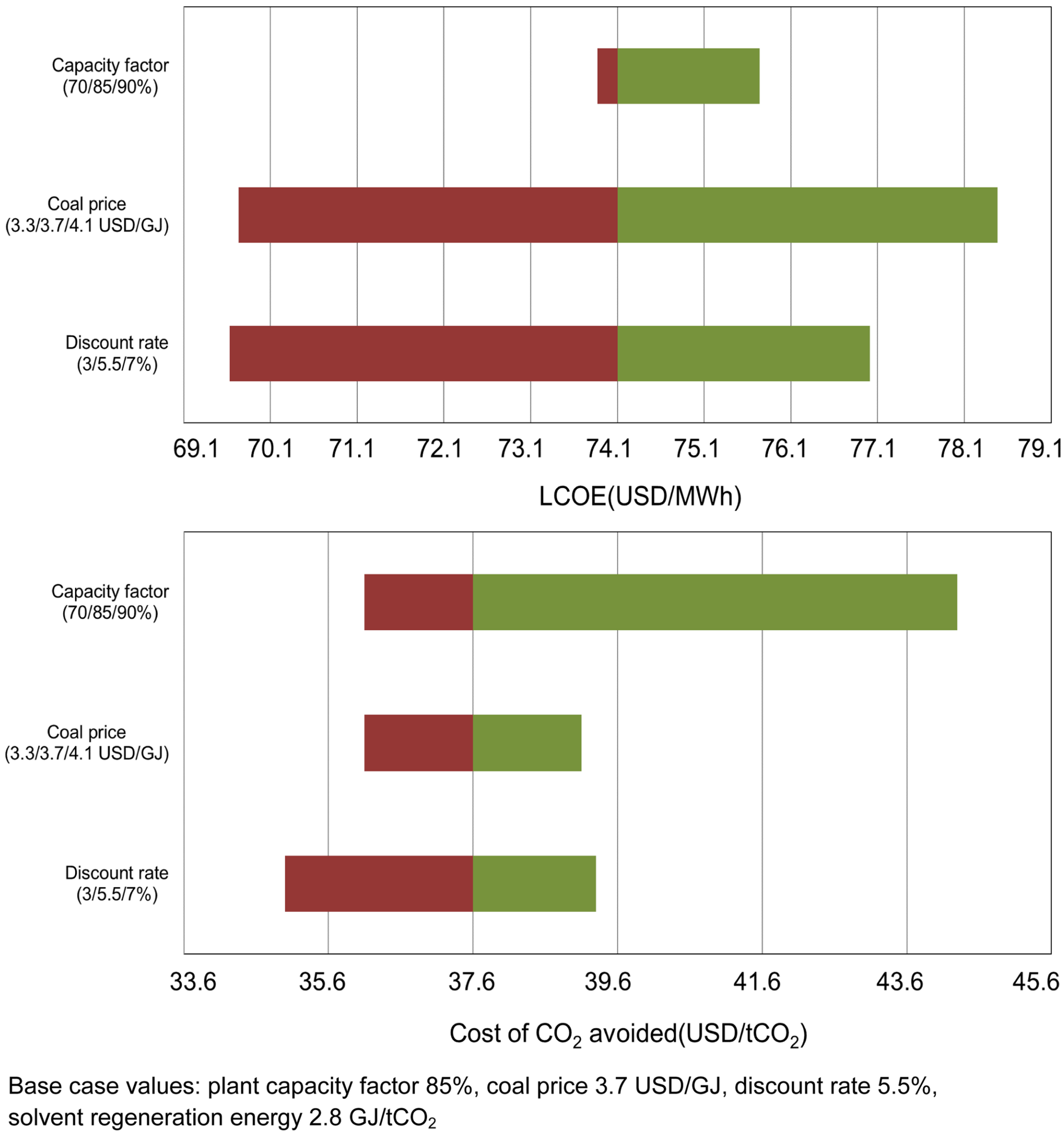

Fig. 9. Sensitivity analysis of LCOE and cost of CO_2 avoided (Korean case).

in Figs. 9 and 10. The key factors affecting CCS costs include coal price, plant capacity factor, and CO_2 capture performance, including CO_2 removal rate and solvent regeneration energy [31,32]. When one parameter was analyzed, other parameters were held constant at the baseline case.

Fuel cost directly influences the cost of electricity generation. Sensitivity analysis was conducted to analyze the effects of fuel cost on the cost of CO_2 avoided and LCOE by setting the representative fuel costs of Korea and China as the baseline. In the case of Korea, coal price was found to have the greatest impact on the LCOE of power plants with CCS. In contrast to the baseline case, in which the LCOE of power plants with CCS was evaluated as 74.1 USD/MWh, the LCOE of the Korean case varied according to the coal price from a minimum of 69.7 USD/MWh to a maximum of 78.4 USD/MWh, and the corresponding cost of CO_2 avoided ranged from 36.1 USD/tCO_2 to 39.1 USD/tCO_2, as shown in Fig. 8. As the current state of large-scale CCS plants is still in the initial stages of commercialization, substantial disparities are expected in terms of plant operation and financing [32]. To analyze the effects of such variations, the influences of plant capacity factor and discount rate were analyzed. Various literature sources were referenced to set the scope of the sensitivity analysis [2,25]. According to the analysis results, cost of CO_2 avoided significantly decreased as the plant capacity factor increased: under a discount rate of 5.5%, an increase in plant capacity factor from 70% to 90% resulted in a substantial decrease in cost of CO_2 avoided from 44.3 USD/tCO_2 to 36.1 USD/tCO_2. For the discount rate, under a plant capacity factor of 85%, an increase in the discount rate from 3% to 7% resulted in an increase in the cost of CO_2 avoided from 35.0 USD/tCO_2 to 39.3 USD/tCO_2.

Fig. 10 shows the key results of the sensitivity analysis for CCS

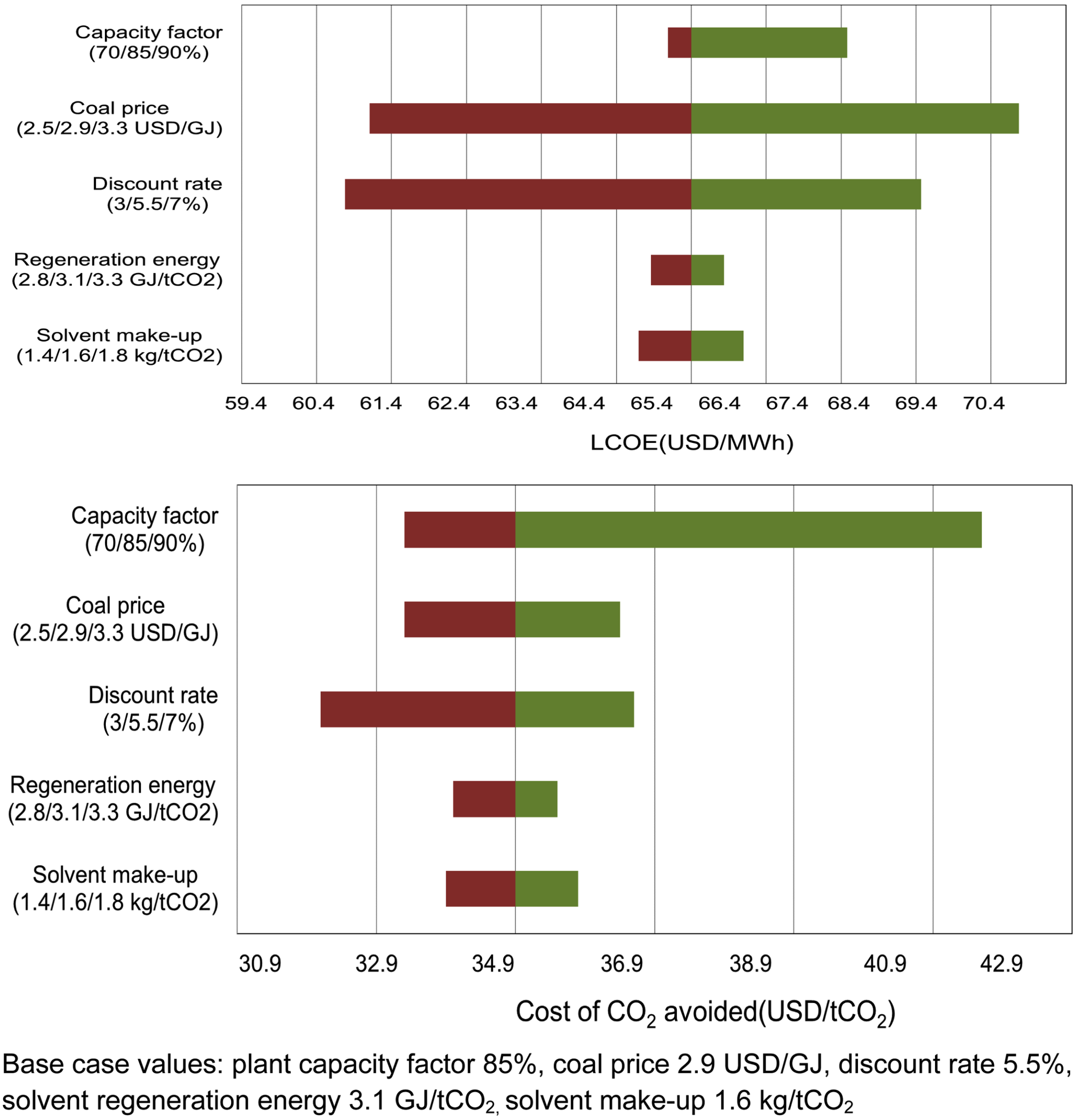

Fig. 10. Sensitivity analysis of LCOE and cost of CO_2 avoided (Chinese case).

costs for the Chinese power plant that applied the same CCS technology as the Korean plant.

The sensitivity analysis for the Chinese electricity market analyzed the ways in which LCOE and cost of CO_2 avoided were affected by changes in solvent make-up according to capacity factor, coal price, discount rate, solvent regeneration energy, and amine loss, as presented in the Korean case. As a result of the sensitivity analysis, solvent regeneration energy was found to have limited effects on the cost of CO_2 avoided compared to the capacity factor and coal price, despite being a core performance index of CO_2 capture technology with the CO_2 removal rate. Make-up costs due to solvent loss contribute to a sizeable proportion of the overall CO_2 capture plant operating costs. In particular, the sensitivity analysis for the pilot plant performance evaluation found that a 10% reduction in solvent loss results in a 1 USD/tCO_2 reduction in cost of CO_2 avoided due to reduced solvent make-up costs. Therefore, when developing CO_2 solvents, it is important to establish strategies to reduce solvent regeneration energy and reduce the unit prices of the solvent through the use of raw materials of low volatility and cost as well as through cooperation with CO_2 solvent chemical manufacturers.

Outside of these details, the trends for other factors, such as the capacity factor, coal price, and discount rate, were similar to the Korean case. The analysis results showed an overall trend similar to the Korean case. In particular, although LCOE of the power plant with CCS was evaluated as 65.4 USD/MWh for the baseline case, the value varied according to the coal price from a minimum of 61.1 USD/MWh to a maximum of 69.8 USD/MWh, and the corresponding cost of CO_2 avoided ranged from 33.3 USD/tCO_2 to 36.4 USD/tCO_2. Similar to the Korean case, the factors that followed coal price in terms of influence on LCOE and cost of CO_2 avoided were the discount rate and plant capacity factor, in that order.

4. Conclusion

The KEPRI-developed proprietary post-combustion CO_2 solvent (KoSol) was applied at the Shanghai Shidongkou pilot plant (Huaneng CERI, China: 120,000 tonCO_2/yr) of CHNG for performance tests, and the key performance data was analyzed. In addition, based on the main results of the pilot test and data on the Korean/Chinese power generation markets, we made calculations for the predicted cost of CO_2 avoided resulting from applying CO_2 capture technology to commercial-scale coal-fired power plants. In addition, we performed sensitivity analysis for the key factors. In the case of Korea, the cost of CO_2 avoided was analyzed as 35~44 USD/tCO_2 (excluding CO_2 transportation and storage costs) for a 960 MW scale USC power plant. On the other hand, application of the same technology to a 1000 MW USC power plant in China resulted in a slightly lower cost of CO_2 avoided of 32~42 USD/tCO_2 (excluding CO_2 transportation and storage costs). The difference despite the same applied technology was mainly attributed to the decrease in CAPEX and OPEX due to the low prices of the country (China) in which the capture technology was applied. This indicates the importance of various international cooperation methods that consider the geographical location and the level of technology of the country involved in realizing economic efficiency improvements for large-scale CCS technology.

Wet amine-based post-combustion CO_2 capture technology has already been technically proven as demonstration plants with capacities of at least 1 million tons per year are in operation in countries such as the US and Canada. Therefore, future research and development should focus on minimizing loss in efficiency resulting from CO_2 capture and decreasing investment costs such as operating and construction costs. In this regard, the cooperation between China, which has great potential and cost competitiveness for future CCS markets, and South Korea, which possesses superior engineering and design technology for post-combustion CO_2 capture processes, is expected to produce synergistic effects in the CCS technology field for both countries as well as to have a great ripple effect on related research around the world.

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