Korean J. Chem. Eng., **29**(9), 1163-1170 (2012)
DOI: 10.1007/s11814-011-0302-3

Pinch based approach to estimate CO_2 capture and storage retrofit and compensatory renewable power for South Korean electricity sector

Muhammad Ilyas, Youngsub Lim, and Chonghun Han†

School of Chemical and Biological Engineering, Seoul National University, Seoul 151-744, Korea
(*Received 17 August 2011 • accepted 30 December 2011*)

Abstract−A pinch-based approach has been used to calculate optimum values of CO_2 capture and storage (CCS) retrofit and compensatory renewable power for the Korean electricity sector. Three cases are proposed. In the first case, KEPCO 2020 power generation forecast data were used to calculate CO_2 emissions and a 30% emission reduction target applied. For the second case, nuclear-free KEPCO 2020 forecast was used to calculate emissions along with 30% emissions reduction. In the third case, the emissions reduction target increased from 30% to 54.50% for case-2 scenario, in order to achieve 2005 emissions level. Results show that CCS retrofit and compensatory renewable power for case 3 is 2.6 times higher than case 1 and 1.8 times higher than case 2. According to sensitivity analysis results, CCS retrofit and compensatory renewable power for case 3 is more sensitive to CO_2 removal ratio and parasitic energy loss ratio, respectively, as compared to case 1 and case 2.

Key words: Pinch Analysis, Carbon Capture and Storage, Renewable Power, Electricity Sector Planning

INTRODUCTION

Growing environmental concerns due to carbon emissions have pushed governments to reduce CO_2 emissions. On a global scale, electricity generation by fossil fuels contributes a large part to total CO_2 emission. There is an augmented concern on efficiency improvements, fuel switching, and increased use of low-carbon or renewable energy for the generation of cleaner electricity to diminish climate change. Despite all these efforts, fossil fuels (especially coal) are still major contributors to the overall electricity generation mix in most regions of the world [1-3]. Furthermore, global electricity demand is increasing continuously. To meet this demand, more fossil fuel based power plants are being installed [3]. On the other hand, it is inappropriate to disrupt operations of existing fossil fuel based power plants before their expiry date. Therefore, retrofitting existing fossil fuel based power plants with carbon capture technology (pre/post combustion CO_2 capture or oxy-fuel combustion) is gaining more interest [4-6]. CO_2 capture technologies can be used to reduce 80-90% per kWh CO_2 emission from exhaust gases of power plants [2]. Once captured, CO_2 can be compressed and transported for sequestration to different sinks such as geological reservoirs, depleted oil wells and saline aquifers. There is still doubt about the feasibility of CO_2 capture and storage (CCS), but it is estimated that the CCS technology will be commercially available by the middle of next decade [5,7].

The CO_2 capture and storage (CCS) technology is an interim solution which can be used along with clean renewable sources. But CCS entails some drawbacks such as CCS process equipment incurs additional capital cost. In oxy-fuel combustion process, an air separation unit is used to provide pure oxygen [5,8]. The air separation unit requires 200 kWh/t CO_2 power input (six times the theoretical requirement) with existing technology [5]. Similarly, in post-combustion capture plants, flue gas scrubbers and solvent recovery systems are needed. According to Wall [5], 80% of the energy demand of scrubber systems is consumed by solvent recovery, and improvements in heat integration are expected to reduce energy requirements to 2 GJ/t CO_2 by 2015. Moreover, compressors are needed to compress CO_2 for transport and storage. Lee and Lim [9] recently estimated that 0.8kWh work is required to transport one ton of CO_2 liquid from CO_2 storage terminal to ship. Accordingly, Wall [5] estimated that capital costs of plants with CCS will be 25-50% higher than baseline plants. On the other hand, the CCS plant needs additional power; therefore, the overall thermal efficiency and power generation capacity of the plant will be reduced [2,5]. According to Andersson and Johnsson [8] estimates, a lignite-fired plant retrofit with oxy-fuel combustion process will reduce thermal efficiency from 42.6 to 33.5%. Moller [10] estimates that for a post-combustion capture system in a combined cycle plant, efficiency dropped from 54 to 46%. Wall [5] estimated 7-8% decrease in thermal efficiency for typical CCS systems. On average 15-20% reduction in power output can be envisaged after CCS retrofit. Because of additional capital cost and fuel consumption per unit of electricity output, power cost increases, with estimates ranging from 25 to 50% [5, 8,10]. Therefore, some researchers are working on developing cost-effective process alternatives for CO_2 capture process; such as Jung and Lim [11] have proposed flue gas split configuration for Monoethanolamine (MEA) based CO_2 Capture process, which provides 6.4% reduction of solvent flow rate and 5.8% reduction of absorbent regeneration energy.

Because of the above-mentioned discrepancies, the CO_2 Capture and Storage (CCS) technology increases power cost. It can only become competitive if a carbon tax is introduced. The South Korean government has decided to pass an emission trade bill and start an

†To whom correspondence should be addressed.
E-mail: chhan@snu.ac.kr

emission trading scheme in 2015 [12]. As described above, the retrofit of existing plants with CCS technology will increase power generation cost; therefore, it is very important to estimate the minimum feasible amount of CCS retrofit, which needs to be installed in a country to achieve a particular target of carbon emissions level. Similarly, from the above discussion it is evident that the installation of CCS plants in existing electricity sectors of a country will result in loss of its power generation capacity. Therefore, this loss of power generation should be compensated by renewable power to meet the required CO_2 emissions target.

In the chemical engineering literature, pinch analysis techniques have been used for heat integration [13], pollution prevention through process integration and mass integration [14-16] of process plants. Pinch technology has also been used in the area of resource conservation such as the recovery of waste [15], water [17-23], hydrogen [24-26], utility gas [27], and property-based integration [28,29]. Mathematical programming approaches are also used for heat, and mass integration and resource conservation, but pinch techniques are still useful because of their graphical insight into the problem, which helps in later detail design stages of the problem.

In addition to classical application of pinch analysis in resource integration, the pinch technique was also used in targeting emissions for total sites [30-35]. Previous applications of pinch technology were on industrial plant scale. Tan and Foo [36] recently did carbon-constrained energy planning at regional/national energy sector level. They presented energy planning composite curves, based on pinch approach, to estimate minimal amount of zero-carbon sources to accomplish the energy demand and meeting emission level target. Later Lee, Tan and Foo [37] extended their carbon-constrained pinch based approach into the application of low-carbon energy source and segregated planning scenario. Tan and Foo [38] also applied a pinch-based carbon constrained approach for the allocation of different energy sources to different applications with specific carbon footprint limits. This carbon-constrained pinch-based approach has been successfully applied in the electricity sectors of Ireland [39] and New Zealand [40]. Tan and Foo [41] applied the pinch analysis methodology to Philippines power generation sector for carbon-constrained planning. Their technique is useful for planning of power generation sector to achieve a specific CO_2 emission level target. Their graphical approach also helps to optimize different tradeoffs involved in electricity generation sector with respect to carbon-constrained planning.

In this work, the pinch technique presented by Tan and Foo [41] to estimate CCS retrofit and compensatory renewable power has been applied to South Korean electricity generation sector. In addition, estimation of CO_2 emission limit, L, has been described in more detail, which the Tan and Foo [41] work lacks. For this purpose, three cases have been proposed to estimate CO_2 emission limit, L, in South Korean power generation sector. As the South Korean government has made a policy decision to cut carbon emissions by 30% till 2020 to attain the level of year 2005 CO_2 emissions [42], therefore, for the first case, 30% reduction in CO_2 emissions proposed, while total CO_2 emissions estimated from 2020 power generation data forecasted by Korea Electric Power Corporation (KEPCO) [43]. There are mounting concerns over nuclear energy security, but in the KEPCO 2020 forecast, the nuclear energy share has been almost doubled as compared to year 2005 share [43]. Therefore, the second case is based on the assumption that the nuclear energy share in the year 2020 KEPCO forecast [43] is substituted by coal, which is the cheapest source of fossil fuel. That's why total CO_2 emissions for second case were obtained from modified 2020 KEPCO power generation forecast in which nuclear energy share was replaced by coal and 30% reduction target for CO_2 emissions applied. As 30% carbon emissions reduction target is not feasible for case 2 to achieve CO_2 emissions level of year 2005, therefore a third case is proposed. In the third case, the CO_2 emissions reduction target increased from 30% to 54.50% to achieve CO_2 emissions level of year 2005, whereas total CO_2 emissions for case 3 were the same as case 2. Moreover, sensitivity analysis has been carried out in order to see the tradeoff between CO_2 emission limit, L, and required degree of CCS retrofit, R for CO_2 removal ratio (RR) changing from 0.85 to 0.95. Similarly, a sensitivity analysis was conducted for compensatory renewable power generation with respect to different CO_2 emission limits for parasitic energy loss ratio (EL) ranging from 15% to 25%.

METHODOLOGY

Salient features of the Tan and Foo [41] methodology to estimate CCS retrofit and compensatory renewable power are as follows:

- Total power output, P, of a country is composed of energy source, i, with carbon intensity C_i (kg CO_2 per kWh), contributing P_i to the total power out, P. As an approximation, carbon intensity of non-fossil sources is taken as zero.
- CO_2 emission limit, L, (mega tons (Mt) of CO_2) must be lower than the actual current emissions ($\Sigma_i C_i{*}P_i$).
- A fixed CO_2 removal ratio, RR, (fraction of CO_2 emissions removed from flue gases) and parasitic energy loss ratio, EL, (ratio of plant power output reduction after CCS retrofit to original output) has been assumed.
- As CCS retrofit incurs capital cost and loss of power output, the first objective is to determine minimum CCS retrofit (R, in TWh/y) for power generation sector.
- To compensate power loss incurred by CCS, the secondary objective is to estimate power generation from new non-fossil plants with near-zero carbon intensities, which is compensatory renewable power (R*EL, in TWh/y).

For more details Tan and Foo's [41] original work can be studied.

SOUTH KOREAN ELECTRICITY SECTOR

As per Korean government decision, 30% CO_2 emissions of year 2020 forecast (813 million tons) will be reduced to achieve CO_2 emission level of the year 2005 (594 million tons) [42]. Therefore, for this study, 2005 is selected as a base year. The objective of this work is to estimate how much CCS retrofit plants and compensatory renewable power generation should be installed in Korean electricity sector to achieve the 30% reduction target of year 2020 CO_2 emissions in South Korean electricity sector to achieve CO_2 emission level of year 2005. To calculate total CO_2 emissions in year 2005, carbon intensity (C_i, kg CO_2/kWh) data for year 2005 was required. This data was taken from Ministry of Education, Science and Technology, South Korea, Statistics ID TX_10506_A076. Table 1 shows this data. As Table 1 illustrated that carbon intensity of hydro power

Table 1. Carbon intensity of several power sources (Ministry of Education, Science and Technology, South Korea)

Power source	Carbon intensity (C_i) in year 2005 (kg CO_2/kWh)
Coal	0.97
Oil	0.80
Gas	0.44
Hydro power	0.01
Nuclear	0.02

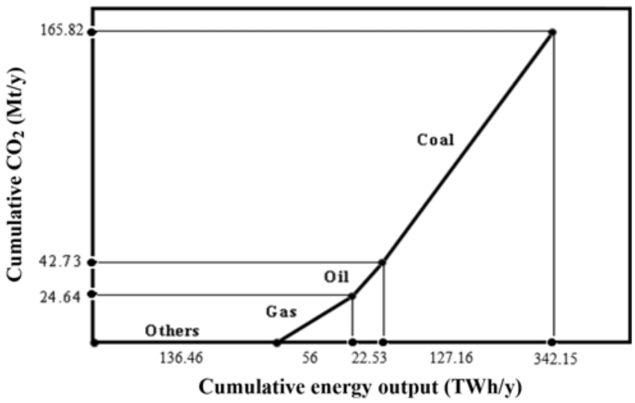

Fig. 1. Source composite curve for Korean electricity generation sector.

and nuclear energy was very low as compared to fossil fuel sources, therefore carbon intensity of hydro power and nuclear energy were approximated to zero.

To calculate CO_2 emission of Korean electricity sector in year 2005, electricity generation data was obtained from Korea Electric Power Corporation (KEPCO) 2005 annual report. In Table 2 this data is reported. Following the Tan and Foo [41] methodology, energy sources in Table 2 are rearranged in order of ascending carbon intensity. Then, a source composite curve for South Korean electricity sector was plotted on a cumulative energy output (TWh/y) vs. cumulative CO_2 emissions (Mt/y) diagram. Fig. 1 shows this composite curve. In Fig. 1, the slope of each energy source segment corresponds to its carbon intensity (C_i, kg CO_2/kWh). Moreover, terminal end points of source composite curve (Fig. 1) provide total power out ($\Sigma_i P_i$) 342.15 TWh/y and total CO_2 emissions ($\Sigma_i C_i$*P_i) 165.82 Mt/y in the year 2005.

ESTIMATION OF CO_2 EMISSIONS LIMIT, L

As the motivation of this work is Korean government's decision to cut 30% of year 2020 CO_2 emissions [42], therefore KEPCO electricity generation forecast data for year 2020 [43] has been used to calculate CO_2 emissions for the year 2020 in Korean power generation sector. Three cases have been proposed to calculate CO_2 emissions limit, L.

1. Case 1 CO_2 Emissions Limit, L

For the first case, actual KEPCO electricity generation forecast data for year 2020 [43] used to calculate CO_2 emissions in 2020. Table 3 presents this data. To calculate CO_2 emissions in Table 3, it is assumed that carbon intensity remains constant from year 2005 to 2020. Table 3 shows that CO_2 emissions in year 2020 from South Korean electricity generation will be 240.25 Mt CO_2/y. As per the government policy decision [42], after 30% of these emissions are reduced, 240.25−240.25*0.3=168.18 Mt CO_2/y will remain, which nearly meets the level of CO_2 emissions in 2005 (165.8 Mt CO_2/y). Fig. 2 shows these results.

From Fig. 2, it is estimated that to cut 30% CO_2 emissions within 15 years, (240.25−168.18)/15=4.80 Mt CO_2/y should be reduced from year 2005 to 2020. Therefore, 165.82−4.80=161.02 Mt/y CO_2 emission limit, L, applied for Case 1.

2. Case 2 CO_2 Emissions Limit, L

In the South Korean electricity generation sector, nuclear energy contributes a major part of the energy mix, and this share is increas-

Table 2. Fuel source wise power generation (power output, GWh, from KEPCO 2005 annual report)

Energy source	Power output (GWh)	Carbon intensity, C_i (kgCO_2/kWh)	Power output, P_i (TWh/y)	CO_2 emissions, $\Sigma_i C_i$*P_i (Mt/yr)
Coal	127159	0.97	127.16	123.09
Gas	55999	0.44	56.00	24.64
Oil	22532	0.80	22.53	18.09
Hydro	5744	0.00	5.74	0.00
Nuclear	130715	0.00	130.72	0.00
Total	342149		342.15	165.82

Table 3. Source wise power generation forecast for year 2020 (power output, GWh, from KEPCO 2020 forecast [43])

Energy source	Power output (GWh)	Carbon intensity, C_i (kgCO_2/kWh)	Power output, P_i (TWh/y)	CO_2 emissions, $\Sigma_i C_i$*P_i (Mt/yr)
Coal	217454	0.97	217.45	210.50
Gas	62081	0.44	62.08	27.32
Oil	3039	0.80	3.04	2.44
Hydro	6256	0.00	6.26	0.00
Nuclear	259378	0.00	259.38	0.00
Renewable	40648	0.00	40.65	0.00
Total	588856		588.86	240.25

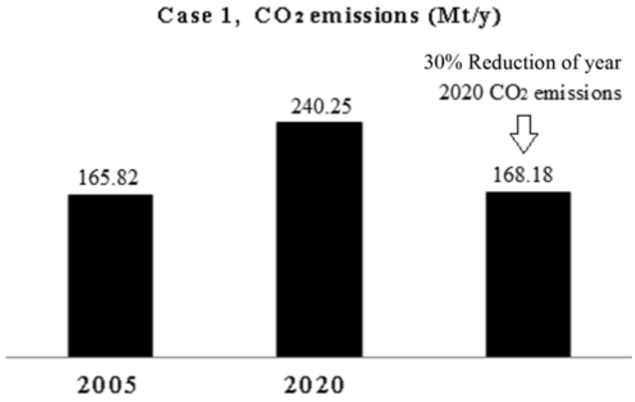

Fig. 2. Expected CO_2 emissions after 30% reduction of year 2020 emissions.

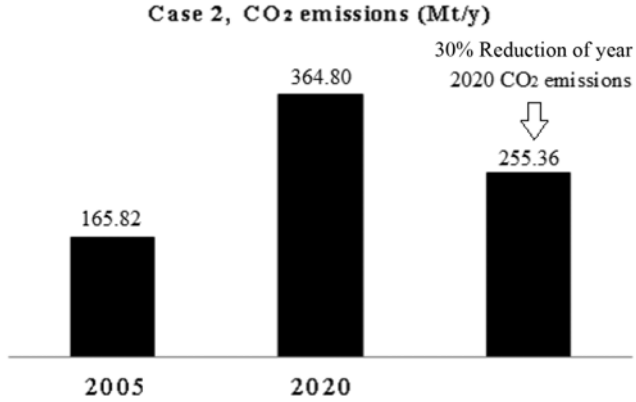

Fig. 4. Expected CO_2 emissions after 30% reduction of year 2020 emissions.

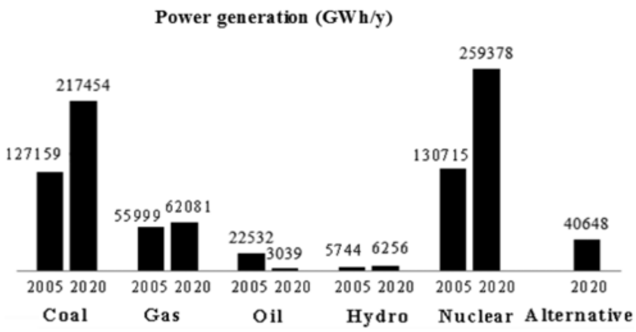

Fig. 3. Source-wise comparison of year 2005 and 2020 power generation.

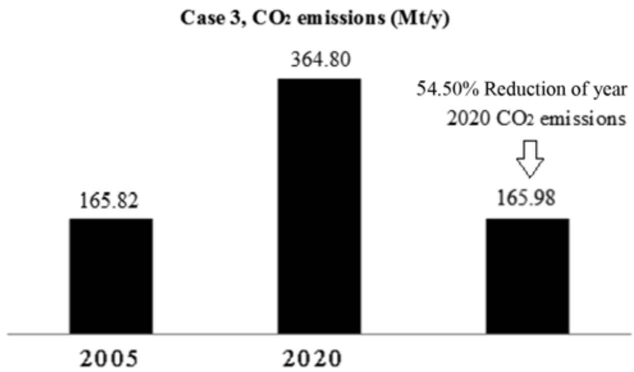

Fig. 5. Expected CO_2 emissions after 54.50% reduction of year 2020 emissions.

ing more and more because of growing electricity demand. Fig. 3 shows that as per KEPCO forecast [43], the share of nuclear energy will almost be doubled in year 2020 with respect to 2005, as 259.38–130.72=128.66 TWh nuclear energy will be added until 2020 in South Korean power generation mix. In the wake of Fukushima, the Japan nuclear disaster [44], a policy shift can be seen around the world against nuclear energy [45]. Therefore, in second case, it is assumed that after year 2005, no additional nuclear power will be installed in South Korea. Table 4 shows KEPCO year 2020 power generation forecast in which additional nuclear energy after 2005 has been replaced by coal, as coal is considered one of the cheapest sources of fossil fuel based energy. Table 4 shows that after replacing additional 346.12 TWh/y nuclear energy-based electricity with coal, total CO_2 emission increases to 364.80 Mt/y for year 2020. Fig. 4 describes that for case 2, after 30% reduction, 364.80−364.80*0.3=255.36 Mt/y CO_2 emissions will remain. From Fig. 4, it is estimated that to cut 30% CO_2 emissions within 15 years, (364.80−255.36)/15=7.29 Mt CO_2/y should be reduced from year 2005 to 2020. Therefore, 165.82−7.29=158.53 Mt/y CO_2 emission limit, L, applied for Case 2.

3. Case 3 CO_2 Emissions Limit, L

From Fig. 4, it can be observed that after 30% reduction, 255.36 TWh/y CO_2 emission will remain which is far higher than the CO_2 emission level of year 2005 (165.8 Mt CO_2/y). Therefore, for case 3, the CO_2 emission reduction target increased from 30% to 54.50% (See Fig. 5). As per above procedure, 152.57 Mt CO_2/y limit, L, applied for case 3 to achieve 54.50% reduction target, which fulfils

Table 4. Source wise power generation forecast for year 2020 after replacing additional nuclear energy with coal

Energy source	Power output (GWh)	Carbon intensity, C_i (kgCO_2/kWh)	Power output, P_i (TWh/y)	CO_2 emissions, $\Sigma_i C_i*P_i$ (Mt/yr)
Coal	346117	0.97	346.12	335.04
Gas	62081	0.44	62.08	27.32
Oil	3039	0.80	3.04	2.44
Hydro	6256	0.00	6.26	0.00
Nuclear	130715	0.00	130.72	0.00
Renewable	40648	0.00	40.65	0.00
Total	588856		588.86	364.80

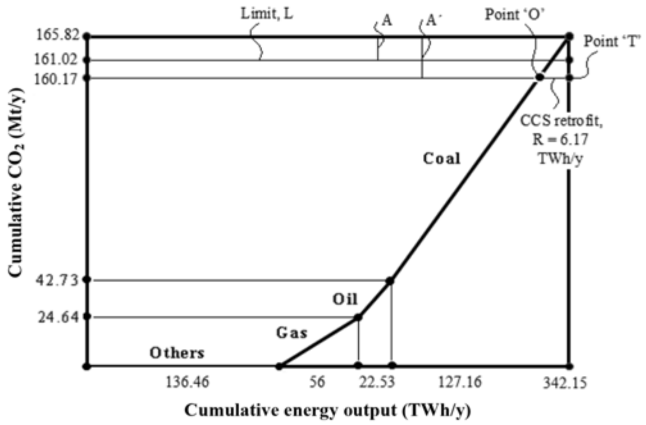

Fig. 6. Estimating minimum CCS retrofit, R, for case 1.

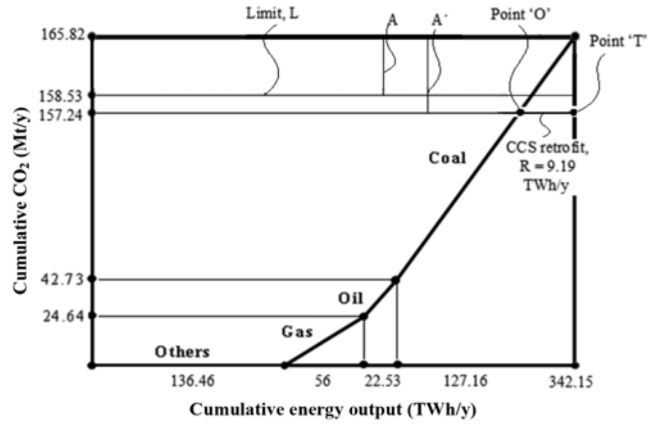

Fig. 7. Estimating minimum CCS retrofit, R, for case 2.

the South Korean government policy objective achieve the CO_2 emission level of year 2005.

CCS RETROFIT AND COMPENSATORY RENEWABLE POWER ESTIMATION

1. CCS Retrofit and Compensatory Renewable Power for Case 1

Fig. 6 helps in estimating CCS retrofit, R. Following the Tan and Foo [41] technique, the CO_2 emission limit, L, 161.02 Mt/y for case 1 has been plotted as a horizontal line on the source composite curve. As the objective is to minimize CCS retrofit, therefore, coal power plants, having highest carbon intensity, should be preferred for CCS retrofit. A fixed removal ratio (RR) of 0.85 was assumed for estimations in Fig. 6. In Fig. 6 the vertical distance $A=\Sigma_i C_i P_i - L=4.8$. As RR is equal to 0.85, therefore to find actual retrofit value vertical distance A´ is determined by

$$A'=A/RR=5.65$$

Minimum CCS retrofit, R in Fig. 6, is the horizontal distance from the point of intersection of A′ line with source composite curve (point 'O') to terminal point of the composite curve (point 'T').

From Fig. 6, it is estimated to achieve required CO_2 emission limit, 6.17 TWh/y CCS retrofit should be installed from year 2005 to 2020. After installation of CCS unit in a power plant, its power output decreases; therefore, it is necessary to install new renewable power plants to compensate power output loss caused by CCS retrofit. It is assumed that these new renewable power plants have zero CO_2 emissions. Tan and Foo [41] proposed the following formula to calculate compensatory renewable power:

Compensatory renewable power=R * EL,

where "EL" is parasitic energy loss ratio because of CCS retrofit in existing power plant.

For EL=0.15, compensatory renewable power required for case 1 is 0.93 TWh/y. It means total 92.55 TWh CCS plants and 13.95 TWh renewable power units need to be commissioned during the period of 15 years from 2005 to 2020 for case 1 to realize the set target of 30% reduction in CO_2 emissions in order to achieve CO_2 emissions level of year 2005.

2. CCS Retrofit and Compensatory Renewable Power for Case 2

The same steps of case 1 are also repeated for case 2 to estimate minimum CCS retrofit, while using CO_2 emissions limit, L, value of 158.53 Mt/y. Fig. 7 shows that for nuclear energy free scenario (case 2), minimum 9.19 TWh/y CCS retrofit (for RR=0.85) and 1.38 TWh/y (for EL=0.15) compensatory renewable power should be installed from year 2005 to 2020, which means total 137.85 TWh CCS retrofit and 20.70 TWh renewable power need to be put into operation during the period of 15 years from 2005 to 2020 for case 2 to realize the set target of 30% reduction in CO_2 emissions. But case 2 estimations were not able to achieve the CO_2 emissions level of year 2005; therefore, case 3 was suggested to fulfill this criterion.

3. CCS Retrofit and Compensatory Renewable Power for Case 3

As case 2 is not able to achieve the CO_2 emissions level of year 2005, therefore the 30% CO_2 emission reduction target increases to 54.5% in case 3. The same steps of case 1 are repeated for case 3, while using CO_2 emissions limit, L, value of 152.57 Mt CO_2/y. From Fig. 8, it is estimated that 16.43 TWh/y CCS retrofit (for RR=0.85) and 2.46 TWh/y (for EL=0.15) compensatory renewable electricity were required from year 2005 to 2020 to reduce CO_2 emissions in 2020, for case 2 scenario, at the level of year 2005 CO_2 emissions. So, total 246.45 TWh CCS retrofit and 36.90 TWh renew-

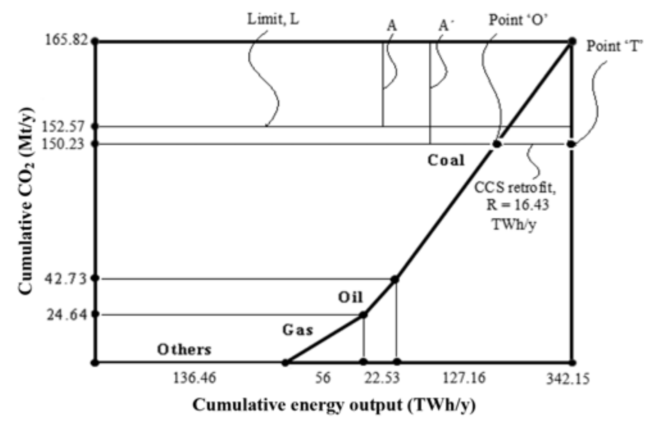

Fig. 8. Estimating minimum CCS retrofit, R, for case 3.

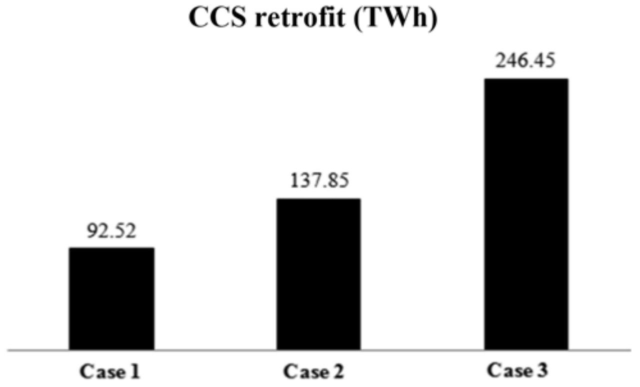

Fig. 9. Comparison of case 1, 2 and 3 with respect total CCS retrofit required for 15 years from year 2005 to 2020.

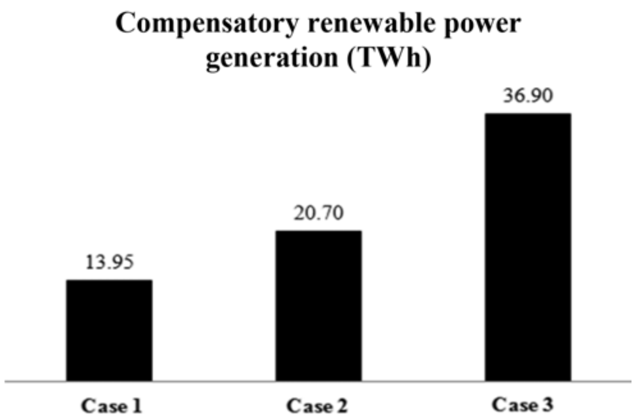

Fig. 10. Comparison of case 1, 2 and 3 with respect total compensatory renewable power required for 15 years from year 2005 to 2020.

able power installation is required during the period of 15 years from 2005 to 2020 for case 3 to achieve CO_2 emission level of year 2005.

COMPARISON OF RESULTS

Fig. 9 and Fig. 10 show comparisons of case 1, case 2 and case 3 with respect to total CCS retrofit and total compensatory renewable power estimations for 15 years from 2005 to 2020, respectively. From this comparison, it can be observed that case 3 requires more CCS retrofit and compensatory renewable power as compared to case 1 and case 2. The reason is that the share of the coal energy and carbon emission reduction target has been increased for case 3.

SENSITIVITY ANALYSIS

To see the tradeoff between CCS retrofit, R, and CO_2 emission limit, L, for three different CO_2 removal ratios (RR) ranging from 0.85 to 0.95, a sensitivity analysis was performed for six different CO_2 emission limits. The CO_2 emission limit range selected was from 145 to 163 TWh/y so that CO_2 emission limits above and below the CO_2 emission limits of three cases would be accounted for in the sensitivity analysis. Fig. 11 shows the results of the sensitivity analysis. Fig. 11 illustrates that as CO_2 emissions limit is reduced,

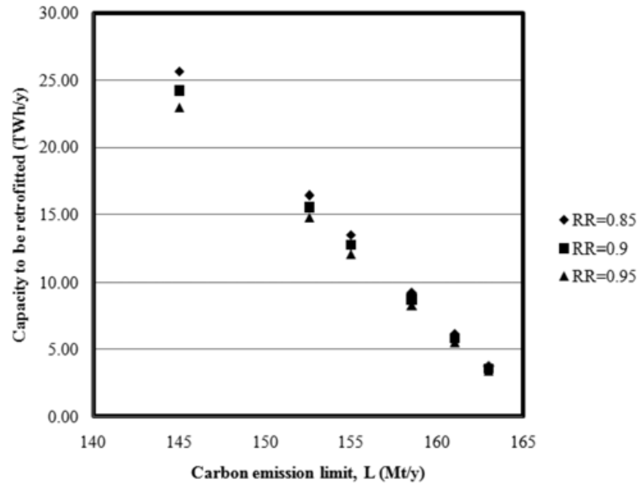

Fig. 11. Sensitivity analysis for CCS retrofits in Korean electricity sector with respect to removal ratio (RR) of CCS technology.

the CCS retrofit increases. Similarly, it is also inferred from this analysis that a CCS retrofit becomes more sensitive to removal ratio (RR) as the carbon emission limit is decreased. So we can deduce from this sensitivity analysis that CCS retrofit performance becomes more important when a large amount of CO_2 emission is required to be reduced. As in case 3, where a large reduction in CO_2 emissions is required, we can decrease CCS retrofit amount more rapidly by focusing on improving the CO_2 removal ratio, RR, of existing CO_2 capture technology. Therefore, research focus on increasing CO_2 removal ratio in CO_2 capture technology should be enhanced.

According to most estimates, thermal efficiency of a power plant decreases from 7% to 8% after the application of CCS retrofit [2,5]. This decrease in thermal efficiency leads to 0.15 to 0.25 (EL) drop of total power output [5,8,10]. Therefore, a sensitivity analysis was carried out for compensatory renewable power generation and CO_2 emissions limit, L, varying from 145 to 163 TWh/y with respect to parasitic energy loss ratio (EL) ranging from 0.15 to 0.25. Table 5 shows these sensitivity analysis results. From Table 5, it can be concluded that for a given RR value, the compensatory renewable power

Table 5. Sensitivity analysis for compensatory renewable power generation (R*EL) in Korean electricity sector with respect to parasitic energy loss ratio (EL)

RR	EL	Limit, L (Mt Co_2/yr)					
		145	Case 3 (152.57)	155	Case 2 (158.53)	Case 1 (161.02)	163
0.85	0.15	3.84	2.46	2.02	1.38	0.93	0.56
	0.2	5.13	3.29	2.70	1.84	1.23	0.75
	0.25	6.41	4.11	3.37	2.30	1.54	0.94
0.9	0.15	3.63	2.33	1.91	1.31	0.88	0.54
	0.2	4.84	3.11	2.55	1.74	1.17	0.71
	0.25	6.05	3.88	3.19	2.18	1.46	0.89
0.95	0.15	3.44	2.21	1.81	1.24	0.83	0.51
	0.2	4.59	2.95	2.42	1.65	1.11	0.68
	0.25	5.74	3.68	3.02	2.07	1.39	0.85

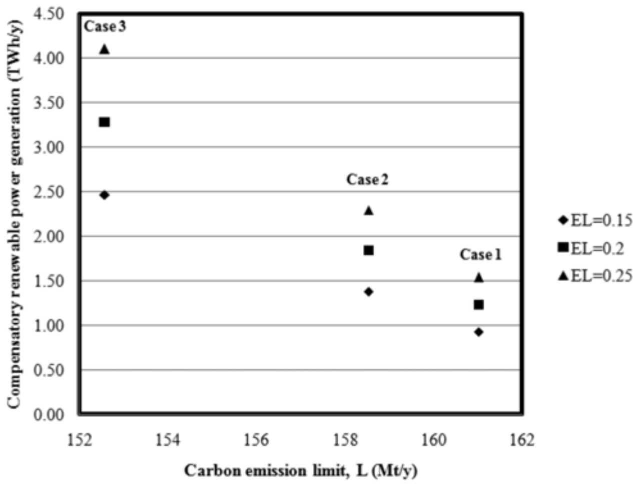

Fig. 12. Sensitivity analysis for compensatory renewable power generation with respect to parasitic energy loss ratio (EL) when RR=0.85.

requirement increases for lower CO_2 emissions limit and higher parasitic energy loss ratio (EL). Moreover, the compensatory renewable power requirement becomes more sensitive to parasitic energy loss ratio (EL) as the CO_2 emission limit is reduced. This can be visualized in Fig. 12 where compensatory renewable power is highly sensitive to parasitic energy loss ratio for case 3. Thus, for case 3, which has higher CO_2 emissions and lower CO_2 emission limit, a lower parasitic energy loss ratio will lead to low amount of compensatory renewable power installation, which is expensive as compared to fossil fuel based power generation sources. Therefore, to make case 3 feasible and cost effective, the research focus on process integration of CCS retrofit plant and power plant should be increased so that new alternative process integration schemes would be developed in which parasitic energy loss ratio of a power plant due to CCS retrofit could be decreased.

CONCLUSION

Graphical pinch methodology to estimate CCS retrofit and compensatory renewable power demand has been extended to the South Korean electricity generation sector. A detailed analysis of the CO_2 emission limit estimation was presented. To achieve this purpose, three case studies were proposed for the South Korean power generation sector. In case 1, the CO_2 emission limit for year 2020 was estimated while using KEPCO 2020 power generation forecast data to calculate total CO_2 emissions. For case 1, it was estimated that 92.55 TWh total CCS retrofit and 13.95 TWh total renewable power for 15 years (2005-2020) should be installed to achieve 30% CO_2 emissions reduction target. From KEPCO year 2020 power generation forecast data, it was observed that 41.16 TWh renewable and hydro combined, and 128.66 TWh nuclear power will be installed until 2020. As the share of nuclear energy was very high while on the international level, a policy shift against nuclear energy has been observed; therefore, in the second case, it was assumed that nuclear energy would be replaced by coal. For the second case, it was estimated that 137.85 TWh total CCS retrofit and 20.70 TWh total renewable power need to be put into operation for 15 years (2005-2020) to achieve the 30% CO_2 emission reduction target. But this 30% CO_2 emission reduction target was not sufficient to achieve CO_2 emission levels of year 2005; therefore, a third case was proposed for the case 2 scenario in which the CO_2 emission reduction target increased from 30% to 54.50% to achieve CO_2 emissions level of year 2005. For case 3, 246.45 TWh total CCS retrofit and 36.90 TWh total renewable power installation were estimated. These estimates from the pinch approach can be used for preliminary planning before developing detailed mathematical programming models. Moreover, sensitivity analysis results describe that CCS retrofit and compensatory renewable power for case 3 is more sensitive to CO_2 removal ratio, RR, and parasitic energy loss ratio, EL, respectively. Therefore, in order to make case 3 feasible and cost effective, the research focus on CCS capture technology (to reduce CO_2 removal ratio, RR) and process integration of power plants and CCS retrofit plants (to reduce parasitic energy loss ratio, EL) should be enhanced.

ACKNOWLEDGEMENT

This research was supported by the Higher Education Commission (HEC), Govt. of Pakistan under the scholarship program titled MS Level Training in Korean Universities/Industry, Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2011-0001114), Brain Korea 21 Project initiated by the Ministry of Education of Korea (ME), Energy Efficiency & Resources Development and Human Resources Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Ministry of Knowledge Economy (MKE), Republic of Korea (2010201020006D,20094010100040) and the LNG Plant R&D Center funded by the Ministry of Land, Transportation and Maritime Affairs (MLTM) of the Korean government.

NOMENCLATURE

L : CO_2 emissions limit (Mt CO_2 per year)
R : CCS retrofit (terawatt hours per year, TWh/y)
RR : CO_2 removal ratio
EL : parasitic energy loss ratio
i : energy source
C_i : carbon intensity of energy source i (kg CO_2 per kWh)
P_i : power output from energy source i
$\Sigma_i C_i{*}P_i$: total CO_2 emissions (Mt CO_2 per year)
R*EL : compensatory renewable power (terawatt hours per year, TWh/y)
$\Sigma_i P_i$: total power output (terawatt hours per year, TWh/y)

ABBREVIATIONS AND ACRONYMS

CCS : CO_2 capture and storage
KEPCO : Korea Electric Power Corporation

REFERENCES

1. R. Quadrelli and S. Peterson, *Energy Policy*, **35**(11), 5538 (2007).
2. D. Weisser, *Energy*, **32**(9), 1543 (2007).
3. M. Jefferson, *Energy Policy*, **36**(11), 4116 (2008).

4. B. J. P. Buhre, L. K. Elliot, C. D. Sheng, R. P. Gupta and T. F. Wall, *Progress in Energy and Combustion Science*, **31**(4), 283 (2005).
5. Wall TF, *Proceedings of the Combustion Institute*, **31**(1), 31 (2007).
6. H. Yang, Z. Xu, M. Fan, R. Gupta, R. B. Slimane and A. E. Bland, *J. Environ. Sci.*, **20**(1), 14 (2008).
7. K. Riahi, E. S. Rubin and L. Schattenholzer, *Energy*, **29**(9-10), 1309 (2004).
8. K. Andersson and F. Johnsson, *Energy Convers. Manage.*, **47**(18-19), 3487 (2006).
9. U. Lee, Y. Lim, S. Lee, J. Jung and C. Han, *Ind. Eng. Chem. Res.*, **51**(1), 389 (2012).
10. B. F. Moller, M. Assadi and I. Potts, *Energy*, **31**(10-11), 1520 (2006).
11. J. Jung, Y. Lim, Y. S. Jeong, U. Lee, S. Yang and C. Han, *Korean Chem. Eng. Res.*, **49**(6), 764 (2011).
12. http://www.reuters.com/article/2011/06/15/energy-summit-korea-idUSL3E7HF0VV20110615.
13. B. Linnhoff, D. W. Townsend, D. Boland, G. F. Hewitt, B. E. A. Thomas and A. R. Guy, *A user guide on process integration for the efficient use of energy*, Institution of Chemical Engineers, Rugby (1982).
14. M. M. El-Halwagi and V. Manousiothakis, *AIChE J.*, **36**(8), 1209 (1990).
15. M. M. El-Halwagi, *Pollution prevention through process integration: Systematic design tools*, Academic Press, San Diego (1997).
16. M. M. El-Halwagi, *Process integration*, Elsevier Inc., Amsterdam (2006).
17. Y. P. Wang and R. Smith, *Chem. Eng. Sci.*, **49**(7), 981 (1994).
18. N. Hallale, *Adv. Environ. Res.*, **6**(3), 377 (2002).
19. M. M. El-Halwagi, F. Gabriel and D. Harrel, *Ind. Eng. Chem. Res.*, **42**(19), 4319 (2003).
20. Z. A. Manan, Y. L. Tan and D. C. Y. Foo, *AIChE J.*, **50**(12), 3169 (2004).
21. R. Prakash and U. V. Shenoy, *Chem. Eng. Sci.*, **60**(1), 255 (2005).
22. D. K. S. Ng, D. C. Y. Foo and R. R. Tan, *Ind. Eng. Chem. Res.*, **46**(26), 9107 (2007).
23. D. K. S. Ng, D. C. Y. Foo and R. R. Tan, *Ind. Eng. Chem. Res.*, **46**(26), 9114 (2007).
24. G. P. Towler, R. Mann, A. J.-L. Serriere and C. M. D. Gabaude, *Ind. Eng. Chem. Res.*, **35**(7), 2378 (1996).
25. J. J. Alves and G. P. Towler, *Ind. Eng. Chem. Res.*, **41**(23), 5759 (2002).
26. V. Agrawal and U. V. Shenoy, *AIChE J.*, **52**(3), 1071 (2006).
27. D. C. Y. Foo and Z. A. Manan, *Ind. Eng. Chem. Res.*, **45**(17), 5986 (2006).
28. V. Kazantzi and M. M. El-Halwagi, *Chem. Eng. Progress*, **101**(8), 28 (2005).
29. D. C. Y. Foo, V. Kazantzi, M. M. El-Halwagi and Z. A. Manan, *Chem. Eng. Sci.*, **61**(8), 2626 (2006).
30. R. Smith and O. Delaby, *Chem. Eng. Res. Design*, **69**(6), 492 (1992).
31. V. R. Dhole and B. Linnhoff, *Computer Chem. Eng.*, **17**(S1), S101 (1993).
32. B. Linnhoff and V. R. Dhole, *Chem. Eng. Technol.*, **16**(4), 252 (1993).
33. J. Klemeš, V. R. Dhole, K. Raissi, S. J. Perry and L. Puigjaner, *Appl. Thermal Eng.*, **17**(8-10), 993 (1997).
34. A. Goršek, P. Glaviè and M. Bogataj, *Chemical Engineering and Processing: Process Intensification*, **45**(5), 372 (2006).
35. S. Perry, J. Klemeš and I. Bulatov, *Energy*, **33**(10), 1489 (2008).
36. R. R. Tan and D. C. Y. Foo, *Energy*, **32**(8), 1422 (2007).
37. S. C. Lee, D. K. S. Ng, D. C. Y. Foo and R. R. Tan, *Appl. Energy*, **86**(1), 60 (2009).
38. D. C. Y. Foo, R. R. Tan and D. K. S. Ng, *Energy*, **33**(10), 1480 (2008).
39. D. Crilly and T. Zhelev, *Energy*, **33**(10), 1498 (2008).
40. M. J. Atkins, A. S. Morrison and M. R. W. Walmsley, Paper presented in *Society of Chemical Engineers New Zealand Annual Conference (SCENZ08)*, New Zealand (2008).
41. Raymond R. Tan, Denny Kok Sum Ng and Dominic Chwan Yee Foo, *Journal of Cleaner Production*, **17**(10), 940 (2009).
42. http://www.greengrowth.go.kr/english/en_subpolicy/en_greenhouse/en_greenhouse.cms.
43. Table 2.16, The 5th Basic Plan for Long-term Electricity Supply and Demand (2010-2024) http://cyber.kepco.co.kr/kepco_new/eng/ir/resource/powerStatistics.jsp?gubun=J.
44. http://en.wikipedia.org/wiki/Fukushima_Daiichi_Nuclear_Power_Plant#Nuclear_disaster_of_2011.
45. http://en.wikipedia.org/wiki/Nuclear_power_phase-out.