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Carbon Capture, Utilization, and Storage: An Optimization Model

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Abstract— Carbon capture, and storage (CCS) is a key technology to mitigate climate change. Since this technology is almost costly, utilization of the carbon dioxide captured by the system is proposed as a way to compensate its costs. Thus, attention has increasingly focused on how the captured CO2 can be optimally utilized or stored. Hereby, an optimization model is proposed in this research to minimize the costs of carbon capture, utilization and storage (CCUS) technology. Various carbon utilization and storage options including injecting it to mature oil and coal wells for enhancing oil recovery or coal bed methane recovery, selling it to several industries, and storing it in empty oil and gas wells, in saline aquifers and under oceans are considered in this research. Taking into account revenues of CO2 sale, emission reduction, and CO2 certificate along with distances of sinks from power plants and capacities of sinks, the model also decides whether the use of CCUS technology in a power plant is economical. The applicability of the model is examined through two different scenarios.

Index Terms— Carbon Capture and Storage Technology, Utilization of CO2, Optimization Model.

1 Introduction

Human activities annually release about 25 billion tons of carbon dioxide (CO2) into the atmosphere, thereby increasing the levels of greenhouse gases, which can lead to a climatic crisis in the world. The world's forests and oceans can annually absorb only about 9-10 billion tons of CO2. Hence, developing CCS technology, in addition to developing renewable energies, improving productivity, and managing energy consumption, is a reasonable strategy to reduce the atmosphere's remaining CO2 as a greenhouse gas [1].

According to the International Energy Agency (IEA), costs of decreasing level of CO2 emission in 2050 to half of its level in 1990 is estimated to be 71% more if CCS technology is disregarded. Hence, CCS is an almost low-cost and reasonable technology that prevents the release of large quantities of CO2, produced by using fossil fuels for power generation in power plants and other industries, into the atmosphere by capturing CO2 and transporting it to where it can be useful.

Carbon Capture

There are three distinct methods to capture CO2 in CCS systems:

1) Post-combustion capture in which CO2 is scrubbed from flue gases at power stations or other large point sources.
2) Pre-combustion capture in which CO2 is removed from an artificial fuel gas (produced from coal, oil, or natural gas) prior to combustion.
3) Oxy-fuel combustion in which oxygen is used instead of air for combustion in order to produce pure CO2 gas and water vapor.

When carbon dioxide is separated and captured, it must be compressed in order for its volume to decrease so that it can be transported by pipelines or ships to an appropriate place for storage or utilization.

Carbon Storage and Utilization

There are some distinct carbon storage and utilization options:

1) Saline aquifer: CO2 is stored under the saline water. It has been identified as the most feasible and economical method for CO2 storage [1] [2].
2) Ocean storage: CO2 is stored under crusts in oceans. It has been known to be environmentally hazardous and only appropriate for large-scale CO2 storage [1].
3) EOR (enhanced oil recovery) and ECBM (enhanced coal bed methane recovery): CO2 is injected to declining oil wells or coal beds to increase oil recovery or methane recovery.
4) Industrial usages: captured CO2 is used in various industries for different usages such as soft drinks production and chemicals production.
5) Depleted gas, oil, or coal fields: CO2 is injected to depleted gas, oil, or coal fields to be stored.

Clean Development Mechanism (CDM)

According to Kyoto protocol, each members of the protocol's Annex I (developed) countries require to reduce greenhouse gas emissions to a certain level, so that the average greenhouse gas emissions in these countries during 2008 to

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2012 decreases to 2.5% less than that in 1990. CDM creates an opportunity for non-Annex I (developing) countries to develop their economy along with preserving the environment. CDM is the only mechanism that industrialized countries can cooperate with developing countries to reduce emissions. [1]

CDM allows Annex I countries to reduce emission through purchasing CERs (certified emission reduction) from non-Annex I countries. Instead, non-Annex I countries can access financial resources and technologies of Annex I countries for sustainable development of their economy [1].

2 Litrature Review

Some research studies in the literature have emphasized the necessity of CCS systems as a means to mitigate CO2 emission [3],[6],[7],[8]. Gibbins and Chalmers [3] expects key advances for CCS technology over the next 50 years. It states, however, that CCS technology is not likely to be commercially viable in projects, unless some regulations forces its use or makes its use valuable. Bode and Jung [4] investigates the liability of CCS to be accounted appropriately for as a climate mitigation option in Annex I and non-Annex I countries. It also examines the relation between CDM and CCS technology.

Hetland et al. [5] proposed a conceptual design for integrating a CCS system to a NGCC power plant for storing the captured CO2 in oil and gas fields. De Coninck et al. [6] assesses the key determining scientific, technical and economic factors for the acceptability of CCS technology in Europe. It also claims that there are no significant legal barriers to CCS deployment in the EU. It highlights, nonetheless, the long-term storage of CO2 as a concern for legislators. The acceptability of CO2 capture and geological storage (CCS) within the Clean Development Mechanism (CDM) of the Kyoto Protocol is also examined in [6]. The results point out lack of evidence which currently shows that support for CCS technology impedes attention to renewable energies.

Johnson and Ogden [7] identifies the lowest-cost infrastructure for selecting CO2 production sources and storage options which are located in South America using a combination of optimization tool, techno-economic models for CCS components, and regional spatial data. For minimizing the costs, they also identify the optimal number and exact locations of the CO2 production and injection sites and the appropriate diameter of pipelines for transportation of CO2. Yeen Gavin et al. [8] examines the potential of the CCS technology as a climate change mitigation strategy for the electricity sector in Malaysia. Since 90% of electricity generation in Malaysia is still from fossil-fuel combustion methods, the use of CCS technology would be a reasonable option for reducing CO2 emissions. They also showed that the most important factors for reducing costs of CCS technology are: developing CCS technology in industrialized countries to reach a certain maturity, then using it in developing countries and incorporating existing revenue sources (such as CDM) into CCS systems in developing countries.

Anyhow, the industrial uses of the CO2 captured by CCS systems are not taken into account in [3],[4],[5],[7],[8]. Economic aspects of CCS systems are not also addressed in [4],[5],[6],[7]. The most promising study of the literature which seemed to make much effort for solving the problem and filling the relevant gap in the literature is [8]. No mathematical model, however, is presented in this study to make others able to use the model for the comparable problem.

3 Problem and Model Description

As mentioned before, most of the relevant studies in the literature have investigated CCS technology with either only a technological approach or an economic approach considering only geological storage options. To overcome these limitations in the literature and fill the gaps, a model is presented in this study to optimize the utilization of a CCUS system in a power plant considering also other storage options than geological ones.

The model examines the use or disuse of a CCS system in a power plant considering the consequential costs of the system (including setup costs and CO2 capture, transport and storage costs), emissions reduction revenues, revenues of the sale of CO2 to various industries and revenues of EOR/ECBM. The model also identifies the most efficient method for storing or utilizing CO2 of all practical options (including storage of CO2 in empty oil and gas wells or in saline aquifers, injection of CO2 to declining oil or coal wells for EOR or ECBM and the sale of CO2 to various industries).

It is assumed in the model that the method of CO2 capture is the post combustion method since other methods are not much economical yet. Moreover, CCS technology can presumably operate for 100 years and capture 95% of the CO2 which the power plant emits [10]. The inflation and discount rate for calculating the costs is assumed to be 15%.

4 Mathematial Formulation

The notations used to formulate the problem and the proposed optimization model are described below.

Notations

Indices:

i index for CO2 storage/utilization options, $i = 1,\ldots, n$

Parameters:

The parameters are all listed in "Table 1".

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TABLE 1 PARAMTERS' DEFINITIONS AND UNITS

Parameter	Definition	Unit
PC	Practical capacity of power plant	MW
C^{PP}	Power plant investment cost	\$/MW
C^{CCS}	CCS investment cost	\$
AC^{CCS}	Equivalent annual annuity of CCS investment cost	\$/yr
EL	Efficiency reduction (loss) rate	–
C^{EL}	Efficiency reduction costs of power plant	\$
AC^{EL}	Equivalent annual annuity of efficiency reduction costs of power plant	\$/yr
H	Working hours of power plant per year	hour
P^{P}	Power price	\$/MWh
CCT	Capture cost per ton	\$/ton
CC	Total CO2 capture cost	\$
ACC	Equivalent annual annuity of total CO2 capture cost	\$/yr
EF	Power plant emission factor	ton/MWh
TC	Total CO2 capture	ton/yr
C_i^{ti}	Transportation investment cost for i[th] sink	\$/km
AC_i^{ti}	Equivalent annual annuity of transport investment cost for i[th] sink	\$/(yr*km)
C_i^{to}	Transportation operation cost for i[th] sink	\$/ton
C_i^{si}	Storage investment cost of for i[th] sink (except industries)	\$
AC_i^{si}	Equivalent annual annuity of Storage investment cost of for i[th] sink (except industries)	\$/yr
C_i^{so}	Storage operation cost of for i[th] sink (except industries)	\$/ton
d_i	Distance of power plant from i[th] sink	km
r^{EOR}	Enhanced Oil Recovery rate	bbl/ton
WD	Number of working days	day
P^{CER}	CDM price	\$/ton
SC	Social cost	\$/ton
C^{P}	CO2 price	\$/ton
Max_i^r	Max CO2 requirement of the i[th] sink	ton
Min_i^r	Min CO2 requirement of the i[th] sink	ton
P^{co}	Crude oil price	\$/barrel
$R_i =$	$\begin{cases} r^{EOR} * P^{co} & i \in \{\text{EOR wells}\} \\ C^{P} & i \in \{\text{industial usage}\} \\ 0 & \text{Otherwise} \end{cases}$	\$/ton
r^{C}	Carbon capture rate	–
M	Sufficiency large number	

The word "Sink" is used instead of the phrase "Storage and Utilization Options" for brevity

Variables:

The variables are all listed in "Table 2".

TABLE 2 VARIBALES' DEFINITIONS

Variable	Definition
x_i	Amount of carbon allocated to i[th] sink (ton)
$y_i =$	1, if $x_i > 0$; 0, otherwise
b_i	Binary variable

Optimization Model

The proposed mathematical formulation is shown below:

$$Min\ Z = AC^{ccs} + AC^{el} + ACC + \sum_{i=1}^{n}(AC_i^{ti} * d_i * y_i + C_i^{to} * x_i) + \sum_{i=1}^{n}(AC_i^{si} * y_i + C_i^{so} * x_i) - \sum_{i=1}^{n} R_i * x_i - (p^{CER} + SC) r^{CC} * TC \quad (1)$$

$$S.t \quad x_i \leq y_i * M \qquad i = 1, \dots, n \quad (2)$$

$$x_i + b_i * M \geq Min_i^r \qquad i = 1, \dots, n \quad (3)$$

$$x_i \leq (1 - b_i) Max_i^r \qquad i = 1, \dots, n \quad (4)$$

$$\sum_{i=1}^{n} x_i = r^{CC} * TC \quad (5)$$

$$x_i \geq 0 \qquad i = 1, \dots, n \quad (6)$$

$$y_i \in \text{Binary} \qquad i = 1, \dots, n \quad (7)$$

Equation (1), which is the objective function, equals to sum of the costs subtracting sum of the revenues (costs – revenues). The costs include:

- Investment (setup) cost: setup cost of a CCS system is about 50% of that of the power plant.

$$AC^{CCS} = \frac{r * C^{CCS}}{1 - (1 + r)^{-100}}$$

$$C^{CCS} = 0.5 * PC * C^{PP}$$

- Efficiency reduction cost: CCS technology reduces efficiency of the power plant. Typically this reduction is about 15% of the practical capacity of power plant.

$$AC^{EL} = \frac{r * C^{EL}}{1 - (1 + r)^{-100}}$$

$$C^{EL} = PC * WD * H * P^{P} * EL$$

- Capture cost: it depends on the power plant's emission factor.

$$ACC = \frac{r * CC}{1 - (1 + r)^{-100}}$$

$$CC = TC * CCT$$

$$TC = PC * WD * H * EF$$

- Transportation costs: it includes equivalent annual annuity of investment or setup costs of pipeline or tanker for transferring CO2 from power plant to the i[th] storage or utilization option (sink) and operating costs of CO2 transportation.

$$AC_i^{ti} = \frac{r * C_i^{ti}}{1 - (1 + r)^{-100}}$$

- Storage costs: it includes equivalent annual annuity of investment or setup costs of CO2 storage or utilization in the i[th] storage or utilization option (sink) and operating costs of storing or utilizing CO2.

$$AC_i^{si} = \frac{r * C_i^{si}}{1-(1+r)^{-100}}$$

The revenues include:

- Revenues from EOR, ECBM and industries: It includes revenues of using CO2 for EOR or ECBM and the sale of CO_2 to various industries.
- Revenues from CDM: It includes revenues that non-Annex I (developing) countries obtain from the sale of CERs to Annex I (developed) counties.
- Revenue of emission reduction: Reducing CO2 of the environment by capturing the CO2 which a power plant emits has significant and positive socio-economic impact on people and governments.

Constraints (2) and (7) determine the values that y_i can take. Constraints (3) and (4) limit the amount of CO2 which should be allocated to each sink using the maximum amount of CO2 which can be transported to the sink and the minimum amount of the CO2 that is applicable for the sink. Constraint (5) and (6) determine the values that x_i can take. Constraint (5) defines that the total amount of carbon dioxide which should be transported to sinks must be equal to the total CO2 produced by the power plant.

TABLE 3 PARAMTERS ASSUMPTIONS

Parameter	Amount	Unit
PC	1159.3	MW
C^{PP}	550000	$/MW
EL	10%	–
H	24	hour
P^{P}	7	$/MWh
CCT	45	$/ton
EF	0.471	ton/MWh
C_i^{ti}	(93000,0, 934000)	$/km
C_i^{to}	(0.018, 0.018, 0.018)	$/ton
C_i^{si}	(12000,0, 12000)	$
C_i^{so}	(3.5, 0,3.5)	$/ton
d_i	(200, 150, 100)	km
r^{EOR}	2.75	bbl/ton
WD	290	day
P^{CER}	20	$/ton
SC	25	$/ton
C^{P}	16	$/ton
P^{co}	106	$/barrel
$R_i =$	95%	$/ton
r^{C}	(95, 122, 0)	-

It is worth mentioning that sources of the data in this research and listed in "Table 3" are [1],[9],[10],[11],[12],[13].

5 RESULTS AND DISCUSSION

We considered the model for a potential CCUS system in a 1159.3-MW power plant and three CO2 storage and utilization options including enhancing oil recovery in oil wells, selling of CO2 to industries and burying CO2 under saline aquifers. We used the data in "Table 3" and defined two scenarios to evaluate applicability of the mathematical formulation. The first scenario which is the main scenario determines the optimal amount of CO2 which should be allocated to the sinks or options and the second scenario identifies the most profitable option. The model is coded in GAMS (General Algebraic Modeling System) and solved by CPLEX solver for each scenario in a computer with 2.66 GHz CPU and 4 GB RAM. Different features of each scenario and the results of running the solver is shown in "Table 4" and described below:

TABLE 4 SCENARIOS

Scenario	Sink	Parameter of Sink		Allocated CO2 and Total Profit	
		Min_i^r	Max_i^r	x_i	Total Profit
1	1st	500000	2000000	2000000	303898000
	2nd	200000	1000000	1000000	
	3rd	600000	3000000	610352	
2	1st	0	Infinity	0	446244000
	2nd	0	Infinity	3610352	
	3rd	0	Infinity	0	

Scenario 1

As it is shown in "Table 4", in this scenario the capacities of the storage sinks are assumed to be limited by the minimum and the maximum amount of CO2 that the sinks require. Amounts more than the maximum and less than the minimum are not either utilizable or economical. Since using CO2 for EOR or in industries leads to gaining some revenue, the optimal solution of the model for the first scenario shows that the first and the second options (i.e. EOR and the use of CO2 in industries) should be filled with CO2 up to their maximum capacity. The remaining amount of CO2 should also be allocated to the third option which is not that profitable (i.e. burying CO2 under saline aquifers). Moreover, deploying a CCS system in the power plant is economical because the total profit is positive.

Scenario 2

In this scenario, the capacities of the storage sinks are assumed to be unlimited so that the model identifies the most profitable CO_2 storage sink or utilization option. The results show that the second option (i.e. selling of CO_2 to industries) is the most profitable option. Nonetheless, the capacity of utilizing CO_2 in industries is usually limited in real case studies.

6 Conclusion

A mathematical model is presented in this research not only to decide whether the use of a CCS system is economical, but also to optimally find the best combination of CO_2 storage or utilization sinks (options) to which the CO_2 captured by the CCS system should be transported. Various factors such as the revenue of selling CO_2, carbon certificates (CERs), the revenue of emission reduction as a negative cost, distances of sinks from power plants, and capacities of sinks are considered in this model to make it sufficiently comprehensive. Then, two different scenarios are defined by modifying the capacities of sinks (options) and solved by a commercial package in order to evaluate the applicability of the mathematical formulation, to determine whether the considered CCS technology is economical, to find the optimal allocation of CO_2 to sinks or options, and to identify the most profitable CO_2 storage sink or utilization option.

The results show that the model is absolutely satisfactory. Given the in-hand data and assumptions, the results also point out that establishment and use of a CCUS system in the alleged power plant is absolutely economical. They also highlight that the most profitable option for using the CO_2 captured by a CCS system would be selling it to industries if industries had the capacity to use whole the captured CO_2. As a perspective for a future work, a more general and unified model which considers all the potential CCS systems in a region can be very desirable.

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