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# A multi-objective optimization model for sustainable electricity generation and $CO_2$ mitigation (EGCM) infrastructure design considering economic profit and financial risk

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ABSTRACT

A large number of research works were undertaken for the planning of sustainable electricity generation and $CO_2$ mitigation (EGCM) infrastructure design under uncertainty. The typical methodologies assessed the performance of the problem under the variability of the uncertain parameters by optimizing the expected value of the objective function. This approach can have large probabilities of the value optimized in unfavorable scenarios. In this paper, we present a mathematical programming model in planning sustainable electricity generation and $CO_2$ mitigation (EGCM) infrastructure design, including financial risk management under uncertainty. The proposed model allows us to determine available technologies to produce electricity and treat $CO_2$ on the purpose of maximizing the expected total profit and minimizing the financial risk of handling uncertain environments (i.e. $CO_2$ mitigation operating costs, carbon credit prices and electricity prices, etc.), while fulfilling electricity demands and $CO_2$ mitigation standards. The multi-objective optimization problem was solved by using the weighted-sum method that imposes a penalty for risk to the objective function. The capability of the proposed modeling framework is illustrated and applied to a real case study based on Korea, for which valuable insights are obtained.


## 1. Introduction

Greenhouse gases (GHGs) emissions are expected to cause significant global climate change [1]. The most significant GHG is $CO_2$, which arises mainly from use of fossil fuels in power generation [2]. There has been concern about whether energy supplies can meet increasing electricity demands with the reduction of GHG emissions. The most common approach to reducing $CO_2$ emissions in electricity generation system is to replace the use of carbon-based fossil fuels with renewable energy sources or less GHG intensive fuels. However, we will need to rely on fossil fuels for several decades before alternative energy sources are fully developed. Thus, capture and storage (CCS) technologies will be a promising solution to reduce $CO_2$ emissions and keep the current energy system [1], which separate $CO_2$ from various emission sources (i.e., the power plant), transport them to a storage location and isolate them from the atmosphere for a long period [3]. It should consider geopolitical factors such as the location and capacity of the sequestration site. Also, it can pose significant cost burdens to small-scale power plant because large-scale CCS to capture and store large amounts of $CO_2$ brings considerable economic benefits. To supplement the technical and economic limit of CCS, carbon emission trading (CET) should be used for managing GHG emission in energy systems as a policy based incentive.

A large number of research works were undertaken for the planning of electricity generation and $CO_2$ mitigation (EGCM) strategies such as CCS and CET under meeting the GHG mitigation standards. The mathematical programming models have been proposed that address the design of the EGCM infrastructure; Carbon capture and storage (CCS) technologies were used to reduce GHG emitted from power plants during electricity generation process [3–6]. Carbon emission trading (CET) were also proposed to help attain reduction of GHG emission in a cost-effective way [7–9]. However, these studies address separately CET and CCS to mitigate $CO_2$ emission within EGCM infrastructure. It needs to identify both the cost and spatial arrangement of an integrated CCS and CET system due to the large economic benefits achieved by this process. We proposed an optimization model for EGCM infrastructure that generates a fully integrated, profit-maximizing CCS and CET system [4].

The previous study addresses deterministic approaches assuming that all problem parameters are invariant over a given planning horizon. However, uncertainties may exist in various impact factors of the EGCM system such as GHG emission inventory, GHG reduction costs, electricity prices and emission reduction credits. To obtain more realistic results, these uncertainties may affect modeling in the design of an EGCM system.

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**Nomenclature**

*Indices*

| | |
|---|---|
| $e$ | product form of electricity |
| $f$ | facility name for electricity generation |
| $g$ | geographical region |
| $g'$ | geographical region ($g' \neq g$) |
| $i$ | physical form of $CO_2$ |
| $p$ | type of power plant |
| $r$ | scenarios |
| $c$ | type of capture facility |
| $d$ | pipeline diameter |
| $l$ | type of transport mode |
| $s$ | type of sequestration facility |

*Sets*

| | |
|---|---|
| $x$ | feasibility set for first-stage decision variables |
| $y_r$ | feasibility set for second-stage decision variables in scenario $r$ |
| $k$ | set of profit targets |

*Parameters*

| | |
|---|---|
| $prob_r$ | probability of occurrence of scenario $r$ |
| $UNB_{p,g,r}$ | unit net benefit of selling electricity generated from type of power plant $p$ into region $g$ in scenario $r$ |
| $Cprice_r$ | price of carbon emission credits in scenario $r$ |
| $\Omega$ | target profit |
| $\rho_k$ | goal programming weight for financial risk formations |
| $CCR$ | capital charge rate – payback period of capital investment |
| $LR$ | learning rate-cost reduction as technology manufacturers accumulate experience |
| $CCC_{i,c,p,f,g}$ | capital cost of building capture facility type $c$ capturing $CO_2$ in physical form $i$ in electricity facility $f$ of plant type $p$ in region $g$ |
| $SCC_{i,s}$ | capital cost of establishing sequestration facility type $s$ sequestering $CO_2$ in physical form $i$ |
| $TCCPoff_{i,l,g,g',d}$ | capital cost of establishing pipeline with diameter $d$ offshore to transport $CO_2$ in physical form $i$ from harbor region $g$ onshore to sequestration region $g'$ offshore |
| $TCCPon_{i,l,g,g',d}$ | capital cost of establishing pipeline with diameter $d$ to transport $CO_2$ in physical form $i$ between regions $g$ and $g'$ onshore |
| $UCC_{i,c,p,r}$ | unit capture cost in scenario $r$ for $CO_2$ in physical form $i$ captured by capture facility type $c$ in power plant $p$ |
| $USC_{i,s,r}$ | unit sequestration cost in scenario $r$ for $CO_2$ in physical form $i$ sequestered by sequestration facility type $s$ |
| $UTCPoff_{i,l,d,r}$ | unit transport cost in scenario $r$ for $CO_2$ in physical form $i$ transported by pipeline with diameter $d$ offshore |
| $UTCPon_{i,l,d,r}$ | unit transport cost in scenario $r$ for $CO_2$ in physical form $i$ transported by pipeline with diameter $d$ onshore |
| $EP_{i,c}$ | energy penalty for type of $CO_2$ capture facility $c$ |

*Variables*

| | |
|---|---|
| $E[TNP]$ | expected total net profit |
| $TNP_r$ | total net profit in scenario $r$ |
| $TNB_r$ | total net benefit in scenario $r$ |
| $TNC_r$ | total net cost in scenario $r$ |
| $CCSCC_i$ | capital cost of CCS facilities for $CO_2$ |
| $CCSOC_{i,r}$ | operating cost of CCS facilities for $CO_2$ in scenario $r$ |
| $G_{e,p,f,g}$ | amount of electricity generated by electricity facility $f$ of plant type $p$ in region $g$ |
| $AEP_{i,p,f,g}$ | $CO_2$ emission permit reallocated to electricity facility $f$ of plant type $p$ in region $g$ |
| Risk $(x, \Omega)$ | financial risk of solution $x$ at a profit target $\Omega$ |
| $Z_{r,k}$ | binary variable equal 1 if the profit of scenario $r$ is smaller than the profit target $\Omega_k$ |
| $ETC_{i,r}$ | emission trading cost for $CO_2$ in scenario $r$ |
| $CFC_{i,r}$ | CCS facility cost for $CO_2$ in scenario $r$ |
| $BC_{i,c,p,f,g}$ | 1 if $CO_2$ in physical form $i$ is captured by capture facility type $c$ in electricity facility $f$ of plant type $p$ in region $g$, 0 otherwise |
| $NS_{i,s,g}$ | number of well or injection facilities of type $s$ sequestering $CO_2$ in physical form $i$ in region $g$ |
| $NTPoff_{i,l,g,g',d}$ | number of pipeline with diameter $d$ for transporting $CO_2$ in physical form $i$ between regions $g$ and $g'$offshore |
| $NTPon_{i,l,g,g',d}$ | number of pipeline with diameter $d$ for transporting $CO_2$ in physical form $i$ between regions $g$ and $g'$ onshore |
| $C_{i,c,p,f,g}$ | amount of $CO_2$ in physical form $i$ captured by capture facility type $c$ in electricity facility $f$ of plant type $p$ in region $g$ |
| $S_{i,s,g}$ | amount of $CO_2$ in physical form $i$ sequestered by sequestration facility type $s$ in region $g$ |
| $Q_{i,l,g,g,d}$ | flow rate of $CO_2$ in physical form $i$ transported by transport mode $l$ (pipeline) with diameter $d$ between regions $g$ and $g'$ |

Several research efforts were conducted for dealing with various uncertainties in the EGCM infrastructure. For example, interval mathematical programming (IMP) and stochastic mathematical programming (SMP) models were proposed to the design of the EGCM infrastructure under uncertainties [10–16]. These models allow assessing the performance of the problem under the variability of the uncertain parameters typically by optimizing the expected value of the objective function. These approaches can lead to solutions that perform well on average but have large probabilities of unfavorable scenarios. Hence, the introduction of a financial risk management enables to control the variability of the objective function in the space of uncertain parameters [17]. The financial risk management is to incorporate the trade-off between financial risk and expected profit into the decision-making procedure, which rises to a multi-objective optimization problem. This offers the opportunity of reducing the impact of unfavorable scenarios. Moreover, few research works have adopted financial risk management techniques in designing the EGCM infrastructure under uncertainties.

Therefore, this study aims to address the financial risk management associated with the planning of the EGCM infrastructure under uncertainty in prices (i.e. the electricity price and carbon credit price) and operating costs (i.e. the carbon capture and sequestration cost). A multi-objective optimization problem which consists of maximizing the expected total profit of the infrastructure and minimizing the financial risk is generated to consider this problem. Hence, the weighted-sum method is also presented to expedite the search for the Pareto solutions of the model. Finally, the capability of the proposed model is illustrated through its application to a real case study based on Korea.

## 2. Problem statement

The design problem addressed in this study has as objective to determine the optimal configuration of an EGCM infrastructure with the goal of maximizing the expected total profit and minimizing financial risk. This infrastructure model includes three main