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# Design under uncertainty of carbon capture and storage infrastructure considering cost, environmental impact, and preference on risk

Suh-Young Lee [a], Jae-Uk Lee [a], In-Beum Lee [a], Jeehoon Han [b,*]

[a] Department of Chemical Engineering, POSTECH, Pohang, Republic of Korea
[b] School of Chemical Engineering, Chonbuk National University, Jeon-ju, Republic of Korea

## HIGHLIGHTS

- A stochastic decision-making algorithm for CCS networks incorporating tolerance on risk is provided.
- Optimization and modeling of CCS networks is performed.
- Economic and Life Cycle Assessment of CCS networks is conducted.
- A case study based on power-plant $CO_2$ emission in Korea is presented in this study.

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## ABSTRACT

We present a stochastic decision-making algorithm for the design and operation of a carbon capture and storage (CCS) network; the algorithm incorporates the decision-maker's tolerance of risk caused by uncertainties. Given a set of available resources to capture, store, and transport $CO_2$, the algorithm provides an optimal plan of the CCS infrastructure and a CCS assessment method, while minimizing annual cost, environmental impact, and risk under uncertainties. The model uses the concept of downside risk to explicitly incorporate the trade-off between risk and either economic or environmental objectives at the decision-making level. A two-phase-two-stage stochastic multi-objective optimization problem (2P2SSMOOP) solving approach is implemented to consider uncertainty, and the ε-constraint method is used to evaluate the interaction between total annual cost with financial risk and an Eco-indicator 99 score with environmental risk. The environmental impact is measured by Life Cycle Assessment (LCA) considering all contributions made by operation and installation of a CCS infrastructure. A case study of power-plant $CO_2$ emission in Korea is presented to illustrate the application of the proposed modeling and solution method.



## 1. Introduction

Carbon capture and storage (CCS) technologies capture the carbon dioxide ($CO_2$) emitted by burning fossil fuels and by industrial processes, and store it in underground geological formations and aquifers. These technologies have been considered as the most promising to mitigate $CO_2$ released from large-scale fossil fuel use [1–3]. On a global basis, if large-scale CCS is to considerably contribute to reducing $CO_2$ emission, it must operate at a massive scale, on the order of 3.5 billion tons of $CO_2$ per year [4]. Today, it operates on the scale of millions of metric tons (MT) of $CO_2$ per year [5]. The recent literature of CCS focuses on large-scale (>1 MT $CO_2$ per year) CCS systems, which are strongly favored by the economics of scale. The U.S Department of Energy planned to develop of large-scale CCS projects in 2018 [6,7], and many studies have been conducted to evaluate the potential of nation-wide [8–11] and Europe-wide CCS projects [12]. In this situation, establishing optimized CCS networks and developing effective algorithms to formulate networks is crucial to enable large-scale CCS systems that encompass a wide range of industrial clusters from capture facilities to sequestration sites [13,14].

Although the technology at each step of the process has been in use for many decades, large-scale commercialized CCS projects are very expensive and are composed of complex networks that may be susceptible to breakdown, so because of these uncertainties, no such projects have been developed [15,16]. The major complications in the planning of CCS networks are various sources of uncertainty, such as permeability and porosity of reservoir, fluctuation of $CO_2$ emission level of each source, variability of construction and

* Corresponding author.
*E-mail address:* jhhan@jbnu.ac.kr (J. Han).

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## Notation

*Indices*

$b_1$ environment burdens from operation
$b_2$ environment burdens from installation
$c$ type of capture facility
$d$ pipeline diameter
$g$ geographical region
$g'$ geographical region ($g' \neq g$)
$i$ physical form of $CO_2$
$k$ technology set
$l$ type of transport mode
$n$ damage category
$p$ type of utilization facility or production facility
$s$ type of sequestration facility
$si$ type of source industry
$sp$ source plant name
$x$ impact category
$sc$ scenarios

*Parameters*

$CCC_{i,c,si,sp,g}$ capital cost of building $CO_2$-capture facility type $c$ capturing in source plant $sp$ of industry type $si$ in region $g$, $
$CCRpipe$ capital charge rate of pipelines – the rate or return required on invested capital cost, $0 \leqslant CCRpipe \leqslant 1$
$CCRfacility$ capital charge rate of facilities – the rate or return required on invested capital cost, $0 \leqslant CCRfacility \leqslant 1$
$Loff_{l,g,g'}$ average delivery distance between regions $g$ and $g'$ by transport mode $l$ offshore, km trip$^{-1}$
$Lon_{l,g,g'}$ average delivery distance between regions $g$ and $g'$ by transport mode $l$ onshore, km trip$^{-1}$
$LR$ learning rate—cost reduction as technology manufacturers accumulate experience, $0 \leqslant LR \leqslant 1$
$SCC_{i,s,g}$ capital cost of establishing $CO_2$ sequestration facility type $s$ sequestrating $CO_2$ in physical form i in region g, $
$TPICoff_d$ total capital cost of installing pipeline with pipe diameter $d$ offshore, $ km$^{-1}$
$TPICon_d$ total capital cost of installing pipeline with diameter $d$ onshore, $ km$^{-1}$
$TPOCoff_{sc,d}$ total operating cost of pipeline with pipe diameter $d$ offshore in each scenario $sc$, $ km$^{-1}$ t $CO_2^{-1}$
$TPOCon_{sc,d}$ total operating cost of pipeline with pipe diameter $d$ onshore in each scenario $sc$, $ km$^{-1}$ t $CO_2^{-1}$
$UCC_{sc,i,c,si}$ unit capture cost for $CO_2$ captured in physical form $i$ by capture facility type $c$ in source industry $si$ in each scenario $sc$, $ t $CO_2^{-1}$
$USC_{sc,i,s}$ unit sequestration cost for $CO_2$ sequestered in physical form $i$ by sequestration facility type sin each scenario $sc$, $·t $CO_2^{-1}$
$wo^{Ca}_{sc,b_1,c}$ entry of emission inventory from operation $b_1$ associated with the capture per one unit of $CO_2$ by capture facility type $c$ in each scenario $sc$, kg·t $CO_2^{-1}$
$wo^{Tr}_{sc,b_1,l}$ entry of emission inventory from operation $b_1$ per one unit of $CO_2$ mass transported one unit of distance by transportation means $l$ in each scenario $sc$, kg km$^{-1}$·t $CO_2^{-1}$
$wo^{Sq}_{sc,b_1,s}$ entry of emission inventory from operation $b_1$ associated with the sequestration of one unit of $CO_2$ by sequestration facility type sin each scenario $sc$, kg·t $CO_2^{-1}$
$\upsilon_{sc,n,x,b_1}$ damage factor of environment burden $b_1$ in terms of damage category $n$ and impact category $x$
$wi^{Ca}_{b_2,c}$ entry of emission inventory from installation $b_2$ from installing one capture facility of type $c$, kg
$wi^{Tr}_{b_2,l}$ entry of emission inventory from installation $b_2$ per unit of distance from installing transportation means $l$, kg km$^{-1}$
$wi^{Sq}_{b_2,s}$ entry of emission inventory from installation $b_2$ from installing one sequestration facility of type $s$, kg
$\upsilon_{sc,n,x,b_2}$ damage factor of environment burden $b_2$ in terms of damage category $n$ and impact category $x$, kg
$\eta_n$ normalization factor for damage categories belonging to set $n$
$\vartheta_{r,n}$ weighting factor for each normalized damage category $n$ according to perspective categories $r$
$\Omega^{Fin}$ cost target, $
$\Omega^{Env}$ Eco99 target
$prob_{sc}$ probability of each scenario $sc$
$\rho_{risk}$ goal programming weight for risk formulations

*Binary variables*

$BC_{i,c,si,sp,g}$ investment of capture facility type $c$ capturing $CO_2$ in physical form $i$ in source plant $sp$ of industry type $si$ in region $g$
$X_{i,l,g,g'}$ 1 if $CO_2$ in physical form $i$ is to be transported from region $g$ to $g'$ by transport mode l, 0 otherwise

*Integer variables*

$NS_{i,s,g}$ number of well or injection facilities of type $s$ sequestering $CO_2$ in region $g$
$NTPon_{i,l,g,g',d}$ number of pipelines with diameter $d$ for transporting $CO_2$ in physical form $i$ between regions $g$ and $g'$ onshore
$NTPoff_{i,l,g,g',d}$ Number of pipelines with diameter $d$ for transporting $CO_2$ in physical form $i$ between regions $g$ and $g'$ offshore

*Continuous variables*

$C_{sc,i,c,si,sp,g}$ amount of $CO_2$ in physical form $i$ captured by capture facility type $c$ in source plant $sp$ of industry type $si$ in region $g$in each scenario $sc$, t $CO_2$·y$^{-1}$
$FCC$ facility capital cost, $·y$^{-1}$
$FOC_{sc}$ facility operating cost in each scenario $sc$, $·y$^{-1}$
$Qpipeline_{sc,i,l,g,g',d}$ flow rate of $CO_2$ in physical form $i$ transported by pipelines with diameter $d$ between regions $g$ and $g'$ in each scenario $sc$, t $CO_2$·y$^{-1}$
$S_{sc,i,s,g}$ amount of $CO_2$ in physical form $i$ sequestered by sequestration facility type $s$ in region $g$in each scenario $sc$, t $CO_2$·y$^{-1}$
$TAC_{sc}$ total annual cost in each scenario $sc$, $·y$^{-1}$
$TCC$ transport capital cost, $·y$^{-1}$
$TCCoffshore$ transport capital cost for $CO_2$ offshore, $·y$^{-1}$
$TCConshore$ transport capital cost for $CO_2$ onshore, $·y$^{-1}$
$TOC_{sc}$ transport operating cost in each scenario $sc$, $·y$^{-1}$
$IO^k_{sc,n,x,g}$ environment impact of operation of technology set $k$ in terms of damage category $n$ and impact category $x$ in region $g$in each scenario $sc$, impact·y$^{-1}$
$II^k_{n,x,g}$ environment impact of installation of technology set $k$ in terms of damage category $n$ and impact category $x$ in region g, impact·y$^{-1}$
$D_{sc,g,n}$ environment damage score of the damage category $n$ in region $g$ in each scenario $sc$, damage·y$^{-1}$
$Eco99_{sc}$ total environment impact score in each scenario $sc$, score·y$^{-1}$
$\delta^{Fin}_{sc}$ positive deviation from the cost target $\Omega^{Fin}$ for design $x$ under scenario $sc$
$\delta^{Env}_{sc}$ positive deviation from the cost target $\Omega^{Env}$ for design $x$ under scenario $sc$

*Functions*

$FDRisk(x, \Omega^{Fin})$ financial downside risk of solution x at a cost target $\Omega^{Fin}$
$EDRisk(x, \Omega^{Env})$ environmental impact downside risk of solution x at an Eco99 score target $\Omega^{Env}$