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

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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

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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}
υ_{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
υ_{sc,n,x,b_2}	damage factor of environment burden b_2 in terms of damage category n and impact category x, kg
η_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
Ω^{Fin}	cost target, \$
Ω^{Env}	Eco99 target
$prob_{sc}$	probability of each scenario sc
ρ_{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}
δ^{Fin}_{sc}	positive deviation from the cost target Ω^{Fin} for design x under scenario sc
δ^{Env}_{sc}	positive deviation from the cost target Ω^{Env} for design x under scenario sc

Functions

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