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Integration of carbon capture and sequestration and renewable resource technologies for sustainable energy supply in the transportation sector

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ABSTRACT

In this study, a new design for a sustainable energy system was developed by integrating two technology frameworks: the renewable resource-based energy supply and the conventional (fossil fuel) resource-based energy production coupled with carbon capture and sequestration. To achieve this goal, a new superstructure-based optimization model was proposed using mixed-integer linear programming to identify the optimal combination of these technologies that minimizes the total daily cost, subject to various practical and logical constraints. The performance of the proposed model was validated via an application study of the future transportation sector in Korea. By considering six different scenarios that combined varying crude oil/natural gas prices and environmental regulation options, the optimal configuration of the energy supply system was identified, and the major cost drivers and their sensitivities were analyzed. It was shown that conventional resource-based energy production was preferred if crude oil and natural gas prices were low, even though environmental regulation was considered. Environmental regulation caused an increase in the total daily cost by an average of 26.4%, mainly due to CO_2 capture cost.

1. Introduction

Because CO_2 accumulation in the atmosphere has been identified as the most detrimental cause of climate change, reduction of CO_2 emissions has become a critical issue [1]. In particular, it is important to reduce CO_2 emissions, 95% of which are supplied from fossil fuels [2], in the transportation sector, a consumer of 25% of overall energy [3].

For the mitigation of CO_2 emissions, either carbon capture and sequestration (CCS) or renewable resource-based energy production can be employed. CCS is considered a practical means that can immediately address the CO_2 problem associated with conventional (fossil fuel) resource-based energy production [4], as it can be applied to any process and its relevant technologies are mature [5]. However, CCS cannot be a radical resolution to the CO_2 problem because it is an end-of-pipe technology [6]. Renewable resource-based energy production is a promising alternative for overcoming this issue [7] because it uses eco-friendly resources [8], thereby significantly reducing [9] or completely avoiding CO_2 generation [10]. However, the unit cost for this type of energy production is costly due to its immature technologies [11], and the technologies are only applicable to areas, where the renewable resources are abundant [12].

As a technological bridge for smooth transition of energy infrastructure from conventional resources to renewable resources, a combination of CCS and renewable resource technologies should be considered. However, the number of published works on this subject is limited. The majority of studies to date have focused on individual systems, including material [13] and process development [14] for CCS and unit operations [15] and supply chain management [16] for renewable technologies. Only a few researchers have developed integrated energy supply systems for specific types of energy demands [17] or resources [18].

Accordingly, the purpose of this study is to develop a new framework for the design and analysis of an integrated energy supply system that involves renewable resource-based energy production and conventional (fossil fuel) resource-based energy production coupled with CCS technologies. To achieve this goal, a technology superstructure that includes all possible technologies and energy/mass flows (from energy resources to the final energy demands) is generated (Section 2). Then, a superstructure-based optimization model is proposed using a mixed-integer linear programming (MILP) technique to identify the optimal configuration of technologies, which minimizes the total daily cost to meet the

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Nomenclature

Index

$f \in \boldsymbol{F}$	facilities
$g \in \boldsymbol{G}$	regions
$m \in \boldsymbol{M}$	transportation modes
$p \in \boldsymbol{P}$	products
$r \in \boldsymbol{R}$	resources

Set

$\boldsymbol{F}_p^P$	energy production facility
$\boldsymbol{F}_p^S$	intermediate product storage facility
$\boldsymbol{F}_p^C$	CO_2 capture facility
$\boldsymbol{M}_p$	transportation mode for product p
$\boldsymbol{M}_r$	transportation mode for resource r
$\boldsymbol{P}^E$	electricity
$\boldsymbol{P}^H$	H_2
$\boldsymbol{P}^F$	fuel
$\boldsymbol{P}^C$	CO_2
$\boldsymbol{R}^B$	biomass
$\boldsymbol{R}^C$	coal
$\boldsymbol{R}^N$	natural gas

Parameter

BN	upper bound of the transportation capacity
$CCapa_{fp}$	capacity of CO_2 capture facility f
CCF	capital charge factor
$DD_{gg'}$	transportation distance between regions, g and g'
DE_{pg}	energy demand in region g
DW_{pm}	driver wage
FE_{pm}	fuel economy for transportation mode m
FIC_f	capital cost of facility f
FP_{pm}	fuel price for transportation mode m
GE_{pm}	general expenses for transportation mode m
HHV_r	high heating value of resource r
LT_{pm}	loading/unloading time
ME_{pm}	maintenance expenses for transportation mode m
$PCapa_{fp}$	capacity of production facility f
$SCapa_{fp}$	capacity of intermediate storage facility f
SH_{pm}	solar heat in region g
SL_g	solar light in region g
SN	lower bound of the transportation capacity
SP_{pm}	average transportation speed
TA_{pm}	availability of transportation mode m for product p
$TCapa_{pm}$	capacity of transportation mode m for product p
TMC_{pm}	capital cost of transportation mode m for product p
UOC_f	unit operating cost of facility f
UPC_r	unit purchase cost of resource r
UTC_{pm}	unit transportation cost for transportation modes m for product p
UTC_{rm}	unit transportation cost for transportation modes m for resource r
β	storage holding period
δ_f	capacity of photovoltaic and CO_2 splitting facilities
η_f	efficiency of facility f
κ_{fg}	power output of a wind turbine in region g
σ	maximum number of parallel pipelines
γ	unit conversion factor
μ_f	CO_2 emission factor

Continuous variable

C_{fpg}	amount of CO_2 captured by facility f in region g
D_{pg}	amount of product p in region g
$FC_{\text{railcar/truck}}$	fuel cost for railcar and truck
FCC	total capital cost of facility
FOC	total operating cost of facility
$GC_{\text{railcar/truck}}$	general cost for railcar and truck
I_{fpg}	amount of product p stored in facility f in region g
$LC_{\text{railcar/truck}}$	labor cost for railcar and truck
$MC_{\text{railcar/truck}}$	maintenance cost for railcar and truck
P_{fpg}	amount of product p produced by facility f in region g
$Q_{pgg'm}$	amount of product p transported from region g to region g' by transportation mode m
$Q_{pg'gm}$	amount of product p transported from region g' to region g by transportation mode m
$Q_{rgg'm}$	amount of resource r transported from region g to region g' by transportation mode m
S_{pg}	amount of CO_2 sequestrated in region g
TCC	total capital cost of transportation mode
TDC	total daily cost
TOC	total operating cost of transportation mode
$TOC_{\text{electricity/fuel}}$	operating cost of transportation mode for electricity and fuel
$TOC_{\text{resources}}$	operating cost of transportation mode for resources
TPC	total primary resource cost
TSC	total CO_2 sequestration cost
U_{fpg}	amount of product p used in region g
U_{fprg}	amount of resource r used by facility f in region g

Integer variable

NF_{fpg}	number of facilities f in region g
$NP_{pgg'm}$	number of parallel pipelines that connect the regions, g and g'
NR_{pm}	number of railcars and trucks

Binary variable

$X_{pgg'm}$	1 if product p is transported from region g to region g' by transportation mode m, 0 otherwise
Y_{pg}	1 if product p is exported from region g, 0 otherwise
Z_{pg}	1 if product p is imported to region g, 0 otherwise

Abbreviation

CCS	carbon capture and sequestration
CO_2	carbon dioxide
H_2	hydrogen
MILP	mixed integer linear programming

final demands using limited energy resources and technology capacities (Section 3). The capability of the proposed model is illustrated through an application study on the transportation sector of future Korea with six different cases to examine the effect of fossil fuel (crude oil and natural gas) price volatility and environmental regulation options on the optimal configuration of the integrated energy supply system (Section 4). Resultantly, the features of the system configuration and the major costs breakdown are analyzed, and the major cost drivers and their sensitivity regarding the total required cost are determined (Section 5).

2. Integrated energy supply system

Fig. 1 shows a schematic diagram of the integrated energy supply system. Two types of primary resources (conventional and renewable) and three types of energy demands (electricity for