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Research Paper

Integrated hydrogen supply networks for waste biogas upgrading and hybrid carbon-hydrogen pinch analysis under hydrogen demand uncertainty

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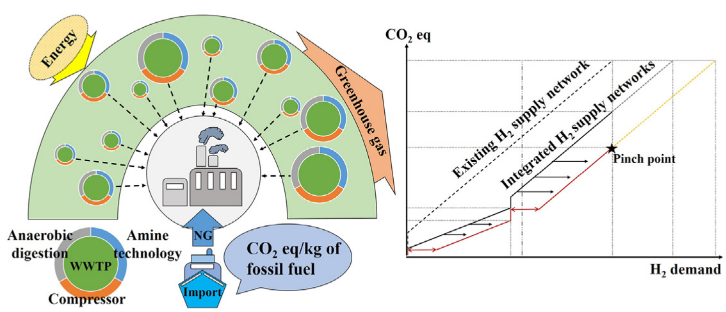
HIGHLIGHTS

- Integrated hydrogen supply networks (IHSNs) are developed.
- The environmental impact and demand uncertainty are considered.
- Multi-stage two-stage stochastic model is designed to solve the IHSNs model.
- Hybrid carbon-hydrogen pinch analysis is suggested to investigate the IHSNs model.
- A case study of Gyeongsang-do in Korea is applied for the IHSNs model.

GRAPHICAL ABSTRACT



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ABSTRACT

This study aims to develop integrated hydrogen supply networks (IHSNs) by combining a natural gas hydrogen supply network and a sludge-biogas-biomethane-hydrogen supply network which is an environmentally benign hydrogen production system. Sludge from wastewater treatment plants is converted into biogas by anaerobic digestion, biomethane is generated using amine technology, which is one of the biogas upgrading technologies, and finally, hydrogen is produced by steam reforming. Multi-objective two-stage stochastic mixed integer linear programming is used to simultaneously optimize the total annual cost and the total environmental cost under hydrogen demand uncertainty. An ε-constraint method is employed to solve the multi-objective function, and Pareto analysis is performed to compare the results from the economic cost and the environmental cost. Then, hybrid carbon-hydrogen pinch analysis is suggested to investigate two distinct hydrogen supply networks in IHSNs, and is verified by the results and a sensitivity analysis based on supplementary wind power. Gyeongsang-do where is one of the five provinces in the Republic of Korea is applied for a case study to validate the proposed model and the results illustrate the feasibility of IHSNs.

1. Introduction

Global warming due to the use of fossil fuels has been consistently driving research on efficient energy management and the development of renewable energy. Hydrogen (H_2), which is one of the most critical components in the energy field, not only has great advantages as a future energy carrier, but has also been utilized in a variety of industries (metallurgy, ammonia, petrochemistry, and methanol) [1,2]. Even though H_2 is an abundant chemical substance, it generally exists in molecular forms, such as water or organic compounds, and H_2 production processes are inherently necessary to manufacture pure H_2 [3].

H_2 production processes are mainly divided into steam reforming

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Nomenclature

Set

w	wastewater
s	sludge
$b1$	biogas
$b2$	biomethane
h	hydrogen
p	pipeline transportation mode
c	compressor
g	geographical region
sc	scenario

Parameters

$ADCap$	AD capacity (10^3 tons/yr)
$BGBMC$	biogas to biomethane conversion factor (kg of biomethane/kg of biogas)
BGD	biogas density (kg/m^3)
BGR	biogas reference flow rate (m^3/day)
BGR^{AD}	biogas reference flow rate from AD (m^3/day)
BMD	biomethane density (kg/m^3)
BMF	biomethane flow rate (kg/day)
$BMHV$	biomethane heating value (MJ/kg)
BMR	biomethane reference flow rate (m^3/day)
$BMprice$	biomethane price AD-MEA (US$/MMBtu)
$C^{pipeline}$	unit pipeline capital cost (US$/km)
C_0^{AD}	initial AD capital cost (10^6 €)
$C_0^{compressor}$	initial compressor cost (US$)
C_0^{MEA}	initial MEA capital cost (US$/yr)
CC	currency conversion (US$/€)
$CCRR$	carbon capture rate reference (kg/day)
$CDRBM$	carbon dioxide ratio in biomethane
CE	capture efficiency
CEC	capital equipment charge
CF	capital charge factor
$Dist_{b1,g}$	distance between AD in local region and MEA in petrochemical industry (km)
E^{BSM1}	energy consumption in BSM1 (kWh/day)
E^{BSM2}	energy consumption in BSM2 (kWh/day)
$EC^{kWh.MJ}$	energy conversion (kWh/MJ)
$EC^{MMBtu.kWh}$	energy conversion (kWh/MMBtu)
ECS	energy consumption in SMR (kWh/kg of H_2)
EER^{MEA}	electricity energy reference net consumption (kWh/kWh biomethane output)
$ER^{compressor}$	energy reference consumption in compressor (kW)
ER^{MEA}	energy reference net consumption (kWh/kg of biomethane)
$ER^{WWTP-AD}$	energy reference net consumption (kWh/day)
EU	energy use (kWh/kg)
$FC^{compressor}$	fraction of compressor capital cost
FC^{MEA}	fraction of MEA capital cost
$FC^{pipeline}$	fraction of pipeline capital cost
$FCOC^{ADMEA}$	facility capital and operating cost for producing biomethane (US$/day)
GES	greenhouse gas emission score (kg CO_2 eq/kg of NG)
$GECP$	greenhouse gas emitted from coal power plant (CO_2 eq kg/kWh)
$GEGP$	greenhouse gas emitted from gas combined power plant (CO_2 eq kg/kWh)
$GWPNG$	global warming potential for NG extraction (grams of CO_2 eq/MJ)
HBM	hydrogen production cost from biomethane (US$/kg)
$HBMC$	hydrogen to biomethane conversion factor (kg of biomethane/kg of H_2)
HDP_{sc}	hydrogen demand in petrochemical industry (kg/day)
HER^{MEA}	heat energy reference net consumption (kWh/kWh biomethane output)
HNG	hydrogen production cost from NG (US$/kg)
$HNGC$	hydrogen to NG conversion factor (kg of NG/kg of hydrogen)
MD	methane density (kg/m^3)
MEC	methane to electricity conversion (kWh/kg of methane)
$MRBG$	methane ratio in biogas (m^3 of methane/m^3 of biogas)
$NBGE$	needed biogas for energy consumption in reference (m^3/day)
$NGHV$	NG heating value (MJ/kg)
$NGprice$	NG price (US$/MMBtu)
O_0^{AD}	AD operating cost (€/ton)
OD	operating days (day/yr)
OMC	operating and maintenance charge
SD	sludge density (kg/m^3)
SR	sludge reference flow rate (m^3/day)
$SRBGC$	sludge to reused biogas conversion factor (kg of biogas/kg of sludge)
$STBGC$	sludge to generated total biogas conversion factor (kg of biogas/kg of sludge)
WWD	wastewater density (kg/m^3)
$WWFR_{w,g}$	wastewater flow rate (kg/day)
$WWSC$	wastewater to sludge conversion factor (kg of sludge/kg of wastewater)
WWR	wastewater reference flow rate (m^3/day)
ζ	probability

Variables

$ACC_{s,g}$	AD capital cost (US$/yr)
$AOC_{s,g}$	AD operating cost (US$/yr)
$CCC_{b1,g}$	compressor capital cost (US$/yr)
$CEC_{b1,g}$	compressor environmental cost (kg CO_2 eq/day)
$COC_{b1,g}$	compressor operating cost (US$/yr)
$E_{b1,g}^{compressor}$	energy consumption in compressor (kWh)
E_{sc}^{MEA}	energy consumption in MEA (kWh/day)
$ESEC_{h,sc}$	existing SMR environmental cost (kg CO_2 eq/day)
$HPC_{h,sc}$	hydrogen purchase cost (US$/yr)
$MCC_{b2,sc}$	MEA capital cost (US$/yr)
$MOC_{b2,sc}$	MEA operating cost (US$/yr)
$NEEC_h$	NG extraction environmental cost (kg CO_2 eq/day)
$PCC_{b1,g}$	pipeline capital cost (US$/yr)
$POC_{b1,g}$	pipeline operating cost (US$/yr)
$PSEC_{h,sc}$	predicted SMR environmental cost (kg CO_2 eq/day)
$SCC_{h,sc}$	SMR capital cost (US$/yr)
$SOC_{h,sc}$	SMR operating cost (US$/yr)
TAC	total annual cost (US$/yr)
TAC^{first}	total annual cost in first stage (US$/yr)
TAC^{second}	total annual cost in second stage (US$/yr)
TEC	total environmental cost (kg CO_2 eq/day)
TEC^{first}	total environmental cost in first stage (kg CO_2 eq/day)
TEC^{second}	total environmental cost in second stage (kg CO_2 eq/day)
$totalx_{b1,g}$	generated total biogas from AD (kg/day)
$totalx_{b2,sc}$	generated total biomethane flow rate (kg/day)
$x_{b1,g}$	biogas flow rate from AD to transportation mode (kg/day)
$x_{b1',g}$	biogas flow rate to meet AD and AD affiliates energy consumption (kg/day)
$x_{b2,sc}$	biomethane flow rate from MEA to SMR (kg/day)
$x_{b2',sc}$	biomethane flow rate to meet MEA and MEA affiliates energy consumption (kg/day)
$x_{s,g}$	sludge flow rate (kg/day)
$x1_{h,sc}$	hydrogen production flow rate from NG (kg/day)