Energy Conversion and Management 165 (2018) 316–333

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Network modeling of future hydrogen production by combining conventional steam methane reforming and a cascade of waste biogas treatment processes under uncertain demand conditions

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ARTICLE INFO

Keywords:
Future hydrogen supply network
Conventional steam methane reforming
Biological cascade system
Dual-objective two-stage stochastic model
Optimization

ABSTRACT

Our goal in this study was to design a hydrogen supply network to efficiently produce and manage hydrogen in case future hydrogen demand increases. Sludge from wastewater treatment plants can be converted into biogas using an anaerobic digestion process, and the generated biogas can be transformed into biomethane by amine technology as a biogas upgrading method. A cascade of four-associated technologies (COFAT) is developed in the proposed model as biomethane is converted into hydrogen by employing a biomethane-based steam reforming process. The suggested COFAT system which is not dependent on fossil fuels is integrated with a conventional steam methane reforming process and harnesses large amounts of hydrogen. Hydrogen management is performed using a hydrogen storage tank to meet regional hydrogen demand, and a hydrogen transport network is constructed using pipelines to transfer hydrogen between different regions. A dual-objective two-stage stochastic mixed integer linear program was used as a mathematical model to minimize the costs and downside risk simultaneously, and uncertain hydrogen demand conditions were included. A case study of the Gyeongsang-do province in the Republic of Korea was used in the proposed model, a 24% reduction in the total costs and a reduction of 94 tons of CO_2 eq of carbon emission per day were realized for the proposed hydrogen supply network assuming the present hydrogen purchase price of 3.5 US$ per kg. We believe that the results provide reasonable solutions for the construction of a future hydrogen supply network.

1. Introduction

The role of hydrogen in a new energy system is important due to global warming and the depletion of fossil fuels. It is expected that hydrogen will be used as an energy carrier, and hydrogen demand will consistently increase [1]. The significance of hydrogen has been demonstrated by comparing technical and environmental quality indexes between hydrogen and fossil fuels, and the idea of a hydrogen economy as a future energy system has been suggested [2,3]. It is anticipated that hydrogen demand, which is currently concentrated in huge petrochemical industries (such as the manufacture of ammonia, petroleum refining, and methanol production) would be regionally distributed, and various hydrogen production processes would be employed [4]. Therefore, hydrogen production must effectively manage hydrogen demands by region.

Even though hydrogen production technologies have been extensively researched, hydrogen is still largely produced by conventional steam methane reforming (CSMR) based on fossil fuels. The CSMR process is economical and able to produce large amounts of hydrogen. However, a large quantity of greenhouse gas is emitted through the CSMR process. Sorption-enhanced SMR and membrane technology have been studied to minimize carbon emissions [5,6]. But, these processes still use fossil fuels as a raw material. Therefore, recent research has focused on hydrogen production from renewable resources as raw materials. Hydrogen manufacture from biomass is divided into thermochemical processes such as pyrolysis and gasification and biological process such as biophotolysis and fermentation [7]. Producing hydrogen by a thermochemical process using palm oil solid waste has been studied in Malaysia [8], and hydrothermal gasification from marine biomass has been developed to produce hydrogen [9].

Hydrogen production using electricity from renewable energy resources has also been studied. Diverse solar-based hydrogen production methods, including photoelectrochemical water splitting, hydrogen synthesis by photosynthetic bacteria, and photovoltaic electricity generation, have been suggested [10]. Integration of photovoltaic-electrolysis (which is a mature technology) and solar water splitting has also been studied [11]. The economic viability of solar photovoltaic hybrid renewable energy systems has also been investigated [12]. However,

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https://doi.org/10.1016/j.enconman.2018.03.069
Received 5 December 2017; Received in revised form 23 February 2018; Accepted 24 March 2018

Nomenclature

Sets

r region/1–42/
s scenario/1–50/
m material/Wastewater, Sludge, Biogas, Biomethane, H_2, NG/
p process /WWTP, AD, AT, SMR/

Parameters

WC_r WWTP capacity (kg/day)
$WW2S$ conversion of wastewater to sludge (kg of sludge per kg of wastewater)
M large number
CF capital charge factor
$S2BG$ conversion of sludge to biogas (kg of biogas per kg of sludge)
$BG2BM$ conversion of biogas to biomethane (kg of biomethane per kg of biogas)
$BM2H_2$ conversion of biomethane to hydrogen (kg of hydrogen per kg of biomethane)
IR^{Max} maximum inventory ratio
IR^{Min} minimum inventory ratio
$H_2Demand_{r,s}$ hydrogen demand in the region (kg/day)
OD operating days (day/yr)
φ_r scaling factor for land by region
ζ_s probability
$Dist_{r,r'}$ distance between regions (km)
$\alpha_p^{Capital}$ fixed parameter for process capital cost
$\beta_p^{Capital}$ variable parameter for process capital cost
$\alpha_p^{Operating}$ fixed parameter for process operating cost
$\beta_p^{Operating}$ variable parameter for process operating cost
${}^{Storage}\alpha^{Capital}$ fixed parameter for storage capital cost
${}^{Storage}\beta^{Capital}$ variable parameter for storage capital cost
${}^{Storage}\alpha^{Operating}$ fixed parameter for storage operating cost
${}^{Storage}\beta^{Operating}$ variable parameter for storage operating cost
${}^{Transport}\alpha^{Capital}$ fixed parameter for transport capital cost
${}^{Transport}\beta^{Capital}$ variable parameter for transport capital cost
${}^{Transport}\alpha^{Operating}$ fixed parameter for transport operating cost
${}^{Transport}\beta^{Operating}$ variable parameter for transport operating cost
H_2price hydrogen price (US$/kg)

Variables

$X_{r,m}$ the amount of material in the first stage (kg/day)
$X_{r,\text{"Biogas"},\text{"AT"}}$ the amount of biogas at AT in the first stage (kg /day)
${}^{Demand}X_{r,\text{"Biogas"}}$ the biogas demand (kg/day)
${}^{Inventory}X_{r,H_2}$ the hydrogen inventory in the first stage (kg/day)
Y_{r,r',s,H_2} the amount of hydrogen between regions in the second stage (kg/day)
${}^{Import}X_{r,H_2}$ the amount of hydrogen imported in the first stage (kg/day)
$COFATc(b_{r,p},X_{r,m})$ process capital cost function in COFAT systems (US$/yr)
$COFATo(b_{r,p},X_{r,m})$ process operating cost function in COFAT systems (US$/yr)
$pc({}^{SMR}b_r^{NG},{}^{Import}X_{r,\text{"}H_2\text{"}})$ SMR2 capital cost function (US$/yr)
$po({}^{SMR}b_r^{NG},{}^{Import}X_{r,\text{"}H_2\text{"}})$ SMR2 operating cost function (US$/yr)
$hc({}^{Storage}b_r,X_{r,\text{"}H_2\text{"}},{}^{Inventory}X_{r,\text{"}H_2\text{"}},{}^{Import}X_{r,\text{"}H_2\text{"}},Y_{r',r,s,\text{"}H_2\text{"}})$ storage capital cost function (US$/yr)
$ho({}^{Storage}b_r,X_{r,\text{"}H_2\text{"}},{}^{Inventory}X_{r,\text{"}H_2\text{"}},{}^{Import}X_{r,\text{"}H_2\text{"}},Y_{r',r,s,\text{"}H_2\text{"}})$ storage operating cost function (US$/yr)
$lc({}^{Transport}b_{r,r'})$ transport capital cost function (US$/yr)
$lo({}^{Transport}b_{r,r'},Y_{r',r,s,\text{"}H_2\text{"}})$ transport operating cost function (US$/yr)
$H_2purchase$ the total hydrogen purchase cost (US$/yr)
$Cost^{First}$ the cost in the first stage (US$/yr)
$Cost_s^{Second}$ the cost in the second stage (US$/yr)
$Cost^{Total}$ the total cost (US$/yr)
$index_s$ risk index (US$/yr)
TC target cost (US$/yr)
$Risk^{Downside}$ downside risk (US$/yr)

Binary variables

$b_{r,p}$ binary variable indicating whether a process is used or not
$b_{r,\text{"NG"},\text{"SMR"}}$ binary variable indicating whether CSMR is used or not
${}^{Storage}b_r$ binary variable indicating whether storage is used or not
${}^{Transport}b_{r,r'}$ binary variable indicating whether transport between regions is operating or not

hydrogen production from renewable energy technologies has rarely been commercialized. Research on biological hydrogen production from municipal waste or industrial wastewater has been conducted for a long time [13,14]. Moreover, the advantages of different biological methods for bio-hydrogen production have been analyzed [15]. A framework for converting food wastes and wastewater into hydrogen using an anaerobic co-digestion process has also been developed [16]. Hydrogen and methane co-production using municipal solid waste has also been proposed [17]. Diverse fermentative hydrogen production technologies consuming wastewater and solid wastes have been analyzed [18]. The bio-conversion of wastewater sludge which comes from an activated sludge process to hydrogen has been examined by the anaerobic digestion based on a clostridium strain [19]. Two-phase anaerobic digestion has been recently developed to enhance the performance of hydrogen-rich biogas [20]. In addition, research on hydrogen production from domestic wastewater using microbial electrolysis cells has been performed on a pilot scale [21].

Hydrogen supply networks and hydrogen production technologies have been broadly studied. Cost optimizations with integrated hydrogen supply networks and utility supply networks in petrochemical industries have also been conducted [22]. Mathematical models for combining hydrogen supply networks and utility supply networks to prepare for an increase in hydrogen demand have been designed for uncertain demand conditions [23,24]. However, the developed network models have mainly exploited CSMR processes based on fossil fuels. To overcome this restriction, construction of hydrogen supply network systems that include biomass has been suggested [25]. Furthermore, research on a transfer of hydrogen to petrochemical industries by integrating biogas supply networks and utility supply networks has also been conducted [26]. In spite of a decrease in the dependence on fossil fuels, limitations in hydrogen demand have not been separated in detail or have only focused on petrochemical industries.

Therefore, a novel approach for hydrogen production and management is necessary to meet the requirements of various hydrogen demands in distinct areas in the future. The following facts should be recognized to propose feasible strategies: (1) hydrogen transfer should be considered because hydrogen demand exists in a number of regions, (2) plans for hydrogen storage and inventory should be included, and (3) it is not possible to harness an immense amount of hydrogen in processes other than CSMR, but (4) reasonable processes that can produce a great quantity of hydrogen without depending on fossil fuels should also be employed. In this study, we have explicitly utilized