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Published in:
Journal of cleaner production

Link to article, DOI:
[10.1016/j.jclepro.2019.119746](https://doi.org/10.1016/j.jclepro.2019.119746)

Publication date:
2020

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Hwangbo, S., Sin, G., Rhee, G., & Yoo, C. K. (2020). Development of an integrated network for waste-to-energy and central utility systems considering air pollutant emissions pinch analysis. *Journal of cleaner production*, 252, [119746]. <https://doi.org/10.1016/j.jclepro.2019.119746>

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Development of integrated utility and waste-to-energy network considering hybrid global warming potential pinch analysis

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Abstract

This study aims to integrate utility supply networks in a petrochemical industrial complex and adjoining waste-to-energy networks to accomplish an eco-friendly energy management system. The waste-to-energy network studied in this contribution included the following main systems: (1) wastewater treatment plants for biogas production, (2) biogas upgrading process for biomethane generation, and (3) molten carbonate fuel cell systems together with a Rankine cycle to harness green electricity. Waste streams in the proposed model consist of wastewater in waste-to-energy network and wasted steam from utility supply networks. Derived green electricity is utilized to satisfy energy demands in the utility supply networks. To design and analyze as optimal waste-to-energy network system, a mixed integer nonlinear programming problem is formulated where each of the subsystem is simulated by developing an appropriate process model. The optimization problem is solved for optimization of the utility supply network and sustainability of the solutions with respect to global warming potential is studied. A case study of Yeosu petrochemical industrial complex in South Korea has been applied for the developed model. The total economic costs of the optimized utility supply network based on the integrated utility and waste-to-energy network are reduced by approximately 15% compared to the existing utility supply network. Furthermore, the results from the hybrid global warming potential pinch analysis indicate that the total quantities of global warming potential (emitted from the integrated utility and waste-to-energy network) decrease about 35%. Consequently, the feasibility of combining two networks has been demonstrated from environmental and economic points of view.

Keywords: Waste-to-energy network; Utility supply network; Hybrid global warming potential pinch analysis; Optimization; Petrochemical industry.

Abbreviations: WTE, waste-to-energy; USN, utility supply network, IUWTE, integrated utility and waste-to-energy, GWP, global warming potential; EIP, eco-industrial park; WWTP, wastewater treatment plant; CO₂, carbon dioxide; CO, carbon monoxide; MEA, monoethanolamine; MCFC, molten carbonate fuel cell; BSM2, benchmark simulation model no.2; SMR, steam methane reforming;

1. Introduction

Many countries and institutions have been insistently researching and investing on the energy management for the purpose of evolving an environmentally benign energy system. The modification and qualification of the existing process systems or the integration of a variety of energy/utility supply networks make it possible to reduce global warming potential (GWP) under the systematic energy management. Considerations of waste-to-energy (WTE) and eco-industrial park (EIP) can potentially generate sophisticated strategies for visualizing an opening of the clean energy economy

WTE, which is a form of energy recovery, is able to generate electricity and/or heat from the diverse treatment processes of wastes. Many studies based on WTE approach have been researched to identify environmentally benign processes and a promising waste management system with respect to energy and economics. Sustainable waste and environmental management based on WTE plants treating municipal solid waste has been suggested to reach the aims of protection of human beings and environment and resource conservation [1]. Energy, economic, and environmental analysis of WTE scenarios have been applied for Malaysia, which is greatly dependent on landfills for municipal solid waste management, to develop a better waste management strategy [2]. WTE supply chain for circular economy system has been researched to propose a number of key task-forces for executing feasible strategies and portfolio for WTE technologies have been addressed [3]. And, the biological process of biohydrogen production using wastewater and agricultural wastes has been evaluated by the political, economic, and environmental impacts [4]. Research on the application of WTE system to increase the yield of methane production from wastewater has been conducted [5].

Large quantities of waste biogas from wastewater treatment plants (WWTPs) allocated in a nearby huge petrochemical industrial complex can be exploited as fully as possible. Benchmark Simulation Model No.2 (BSM2) containing the conventional WWTP layout and default control strategy has been modeled and the amounts of waste biogas available can be explicitly calculated [6]. Biogas utilization at full-scale WWTPs in the United States has been identified considering economic, technical, social or regulatory issues [7]. The application of solid oxide fuel cells operated on anaerobic digester derived biogas in WWTPs have been reported using the process modeling software [8]. Biogas can be converted into biomethane by various biogas upgrading technologies as removing carbon dioxide (CO_2) and other contaminants. Current technologies of biogas upgrading available on the industrial scale encompass adsorption, absorption, membrane separation, and cryogenic separation [9]. A comparative study of chemical absorption processes, each of which employs aqueous solution of monoethanolamine (MEA), sodium hydroxide, and potassium hydroxide, has been carried out to evaluate the environmental impact [10]. Furthermore, the simultaneous upgrading of biogas from the anaerobic digestion and treatment of digestate subject to the microalgal-bacterial cultures have been investigated [11].

Biomethane produced from biogas upgrading processes can be transformed into biohydrogen which is an energy carrier and plays a defining role in the green industrial revolution [12]. The steam methane reforming (SMR) process is the most common method of producing hydrogen for large-scale industries, with great conversion efficiency. Hydrogen production methods are divided into conventional technologies depending on fossil fuels and renewable technologies. About a half of the total hydrogen production amounts up to date has relied on the SMR process consuming methane, natural gas, or other

methane-based gases [13]. However, the conventional SMR process dependent on fossil fuels is not the best route to account for clean industries because ascending order of magnitude increase in demand would accelerate the depletion of infinite reserves [14]. Therefore, researchers have been studying to substitute methane from fossil fuels with biomethane from biomass or waste materials to harness cleaner hydrogen. The distributed biohydrogen production from biomethane via the SMR process has been suggested and the results have detailed the availability of biomethane from WWTPs [15]. Furthermore, biomethane steam reforming process in membrane reactors has been represented to foster the production of high-grade hydrogen [16].

Produced biohydrogen can be converted into green electricity through fuel cells, which are underpinned by a flexible and modular technology and easily manipulated by from individual homes to industrial-scale complexes. Types of fuel cells consist of proton exchange membrane fuel cell commonly used in residential heating systems, solid oxide fuel cell appropriate for large combined heat and power, molten carbonate fuel cell (MCFC) suitable for grid-scale electricity production, and phosphoric acid fuel cell which was the first fuel cell system for commercial-scale combined with heat and power. MCFCs have become a promising fuel cell system as the market leader for large-scale industries [17]. High temperature fuel cells such as MCFCs are interconnected with steam reforming process to utilize a variety of fuels including carbon monoxide (CO), CO₂, any hydrocarbons as well as hydrogen [18]. MCFCs integrated with the subsidiary power generator such as Rankine cycle show the enhanced efficiency and a number of MCFC power plants are commercially operated in South Korea to generate green electricity in bulks [19]. Research on the removal of hydrogen sulphide, which is the most harmful component in biogas, has been conducted to satisfy MCFCs requirements in case biogas is supplied as the raw material [20]. The MCFC with gas turbine hybrid plant due to the high operating temperature and pressure has been optimized in terms of thermal, economic, and environmental viewpoints [21]. Moreover, energy and exergy analyses for integrated MCFCs with Rankine cycle and a proton exchange membrane electrolyzer have been investigated considering a parametric study for the configuration of the system performance [22].

An EIP aims to construct a collaborative network of a number of companies with local communities in an attempt to reduce waste and simultaneously satisfy energy or utility demands. The concept of EIPs has occurred to consider the growing environmental concern and primary objectives are mainly to deal with recycle/resue such as by-products or wastes and optimize energy network and waste/wastewater network [23]. Some integrated networks of companies involved in diverse industries can be designed with respect to heterogeneity of EIPs and diminish environmental impact under the implementation of enhancing sustainability [24].

Utility supply networks (USNs) which play a critical role in industries are natural part of any petrochemical industrial complex in order to balance maintenance and operation needs among others. Utilities such as water, steam, and electricity are transferred between companies and various utility production processes from the inside and outside of USNs give challenges of the development of an optimal USN. The principal goal of USNs is to fulfill utility demands in all companies under the single or multiple objectives from an environmental and/or economic point of view [25]. Steam utility in general is produced by fossil-based boilers and electricity and water utilities are generated by in-company turbines or exported from the external utility sources. In USNs, manufactures correspond to the source companies, which explicitly produce distinct types of steam, and demand markets match the sink companies, which only consume steam without the steam generation [26]. Uncertainties of utility demands for each company and raw material prices have been considered to develop optimal USNs by a stochastic programming [27, 28]. And, the creation of EIPs based on utility sharing in reality has been achieved to evaluate an official national policy in the Netherlands [29]. Ulsan metropolitan city in South Korea has also applied for the

implementation of EIPs containing numerous industries according to the Korean National Cleaner Production Center [30]. The development of an optimal heat utility network in an EIP has been practiced targeting for Yeosu petrochemical industrial complex over the minimization of the total energy costs [31]. Research on bio-energy product supply chain based on WTE approach have been performed in a case study in Iran and the assessment of the optimal biomass supply network has been verified from economic, social, and environmental perspectives [32, 33]. However, the collaboration of USNs and WTE network regarding the real petrochemical industrial complex and the existing WWTPs and the design of model-based integrated USNs and WTE network have been hardly studied.

Therefore, the purposes of this study are 1) to develop an integrated utility and waste-to-energy (IUWTE) network by employing USNs in a huge petrochemical industrial complex and neighboring WWTPs available and 2) to apply the proposed hybrid GWP pinch analysis for the IUWTE network to account for environmental impact resulting in advanced graphical results. Therefore the resulting waste-to-energy (WTE) network included Three main subsystems in a row namely WWTP for biogas production with anaerobic digestion, biogas upgrading process, and MCFC system combined with Rankine cycle. The WTE network aims to finally generate green electricity for satisfying energy demands in the optimized USNs. The developed IUWTE model uses two waste streams, which are wastewater in the WWTPs for biogas production and waste steam from the USNs for green electricity generation via the MCFC system. The optimal integration/interaction between the WTE network and the optimal USN are studied using techno economic as well as sustainability (namely global warming potential) aspects. The results show the feasibility of establishing advanced EIPs by meeting the needed energy demands in the IUWTE network without being contingent on the fossil fuels.

2. Problem statement

The purpose of this study is to construct an environmentally benign energy network based on waste streams by integrating an USN and a WTE network. Figure 1 shows the general framework of an IUWTE network. The structure of the existing USNs aims to satisfy energy demands by using energies, each of which is directly generated by turbines in USNs and imported from external sources based on fossil fuels. The proposed model combines a WTE network with USNs and harness green electricity from wasted steam and wastewater from USNs and the WTE network respectively. Produced green electricity is able to fulfill energy demands in the optimized USN (Figure 1 (A)). The IUWTE network is entirely underpinned by four process systems, each of which is an USN, a WWTP, a biogas upgrading process, and MCFC (Figure 2 (B)). Wastewater is treated by WWTPs and the resulting sludge produced in the WWTPs are converted through anaerobic digesters into biogas. Biogas is transformed into biomethane via a biogas upgrading process. Generated biogas from the biogas upgrading process and wasted steam from USNs go into an internal SMR process in the MCFC in order to produce green electricity, which is considered to satisfy energy demands in USNs. Companies allocated in USNs are technically divided into source companies and sink companies. Source companies operate boilers and enable to produce utilities. Sink companies, which do not have any boilers, import steam utility that is generated by source companies to meet their energy demands. Source companies are sorted out into three types (type A, type B, and type C). Type A can simultaneously produce very-high pressure steam and high-pressure steam, type B is able to generate high-pressure steam, and type C only makes medium-pressure steam. A turbine is connected with a high-pressure steam header and produce lower pressure steam, water, and electricity. Indeed, lower pressure steam can be generated by not the turbine but a letdown valve. Boilers in USNs basically use fossil fuels to boiler

water and the bulk of greenhouse gases such as SO_x and CO_2 are emitted in the air. A WWTP in this study is described by a plantwide BSM2 model in which anaerobic digester are used to produce biogas [6, 34]. The WWTP model with real data including information related to wastewater approximately computes biogas flow rate and the ratio of methane to CO_2 . The biogas upgrading process efficiently removes CO_2 and produces biomethane in high yield. The MEA process is employed to upgrade biogas in this research. The MEA process is undoubtedly the most versatile system for capturing CO_2 in many industries and global implications of the MEA process have been shown [35]. Moreover, results from simulation of the MEA process have already demonstrated great efficiency of the CO_2 removal [36]. Finally, MCFC system harness green electricity using produced biomethane and wasted steam from USNs. As aforementioned in the introduction part, MCFC is the high temperature fuel cell and the most suitable system for large-scale electricity production. Hydrogen and hydrocarbons from internal SMR process and water gas shift reaction are converted into electricity via fuel cells [37]. Rankine cycle is combined with MCFC to utilize high temperature gas discharged by MCFC and generates additional green electricity. Produced green energy from the IUWTE network is distributed into energy demands in USNs.

Figure 1. A framework of the IUWTE network; (A): Comparison of the existing USNs and the integration of USNs with WTE network and (B): Specific diagram of the IUWTE network with unit operations. FF: fossil fuel; WS: wasted steam; WW: wastewater; BG: biogas; BM: biomethane; VSH: very high-pressure steam header; HSH: high-pressure steam header; MSH: medium-pressure steam header; LSH: low-pressure steam header; LV: letdown valve; ASR: activate sludge reactors; AD: anaerobic digester; SR: steam reforming; WGS: water gas shift reaction; FC: fuel cell; HX: heat exchanger.

2.1. Modeling and tools integration to simulate the IUWTE network

Figure 2 presents the suggested network model based on appropriate integration of several tools/modeling platforms of involved subsystems to describe the IUWTE network. WWTPs, the biogas upgrading process, and MCFC are simulated by MATLAB and Aspen Plus using process and kinetic

parameters and one of the main results is the quantity of green energy available. A mathematical model based on feasible green energy amounts is designed to optimize USNs and optimal USNs for minimizing total costs are constructed. Hybrid GWP pinch analysis is performed according to the optimal structure of USNs. Pinch analysis for carbon emission under energy sector planning has been researched [38]. Carbon pinch analysis under the electricity sector has been also suggested [39]. In this study, external GWP staying off of the USNs and internal GWP for each company in the USNs are logically investigated. As a result, the total depletion of GWP can be calculated and variations of the quantities of GWP for each company are graphically figured out.

Figure 2. The integrated model of the IUWTE network which is used to perform simulation for WTE network, optimization for USNs, configuration of optimal USNs, and environmental assessment based on hybrid GWP pinch analysis.

3. The IUWTE network design

The structure of the IUWTE network is divided into a process systems modeling part and an optimization part.

3.1. Process systems modeling of the MEA process and the MCFC system with Rankine cycle

This study has focused on modeling of MEA process and MCFC system, while the WWTPs and biogas production are modelled using the existing BSM2 model in matlab Simulink® commonly used for this purposes in literature(). Conventional MEA process consists of an absorber reactor and a stripper reactor. Main purpose of the MEA process is efficiently to remove CO₂ and reactions in each reactor are described in Table 1 (Eqs. (1) – (8)). Molar ratio of CO₂ in biogas from the BSM2 model is about 0.35 and two consecutive absorbers are cascaded to upgrade the purity of biomethane. All reactors in MEA process are rate-based equilibrium reactor and electrolyte non-random two-liquid model with Redlich-Kwong

(eNRTL-RK) equation for property method is used. Recovery processes for MEA and water are coupled with each reactor to reuse materials as much as possible with respect to economic optimization.

Table 1. Property method, reactions, and specifications of MEA process [40].

Property method			
eNRTL-RK (Electrolyte NRTL model with Redlich-Kwong equation)			
MEA process			
Absorber Reaction		Stripper Reaction	
(1)	$MEA H^+ + H_2O \leftrightarrow MEA + H_3O^+$		
(2)	$2H_2O \leftrightarrow H_3O^+ + OH^-$		
(3)	$HCO_3^- + H_2O \leftrightarrow CO_3^{2-} + H_3O^+$		
(4)	$OH^- + CO_2 \rightarrow HCO_3^-$	Same as (1) to (7)	
(5)	$HCO_3^- \rightarrow OH^- + CO_2$		
(6)	$MEA + CO_2 + H_2O \rightarrow MEACOO^- + H_3O^+$	(8)	$H_2O + H_2S \leftrightarrow HS^- + H_3O^+$
(7)	$MEACOO^- + H_3O^+ \rightarrow MEA + CO_2 + H_2O$	(9)	$H_2O + HS^- \leftrightarrow S^{2-} + H_3O^+$
First absorber			
Condenser temperature: 68 °C		Condenser temperature: 18 °C Reflux ratio: 0.16 Reboiler temperature: 130 °C Boilup ratio: 0.15	
Reflux ratio: 0.33			
Reboiler temperature: 44 °C			
Boilup ratio: 0.53			
Second absorber			
Condenser temperature: 62 °C			
Reflux ratio: 0.42			
Reboiler temperature: 57 °C			
Boilup ratio: 0.39			

MCFC system included in this study contains four sub processes, each of which is internal SMR process, water gas shift reaction model, fuel cell system, and Rankine cycle and specific reactions are summarized in the Table 2. Biomethane from MEA process and waste steam from USNs are consumed in the SMR process and the removal of CO and the additional production of hydrogen are occurred in waste gas shift reaction (Eqs. (10) and (11)). Fundemantal reactions on the anode and the cathode allocated in a fuel cell system are represented in Eqs. (12) – (14). Methanation, CO hydrogenation, and Bouodouard reaction are additionally considered in order to design a robust MCFC (Eqs. (15) – (18)) [41].

Table 2. Property method, reactions, and specifications of MCFC system [42].

Property method			
SRK (Soave-Redlich-Kwong)			
Steam biomethane reforming process			
Reforming Reaction		Water gas shift Reaction	
(10)	$CH_4 + H_2O \rightarrow CO + 3H_2$	(11)	$CO + H_2O \rightarrow CO_2 + H_2$

Reactor temperature: 730 °C		Reactor temperature: 430 °C	
Molten carbonate fuel cell system			
Anode Reaction		Cathode Reaction	
(12)	$H_2 + CO_3^{2-} \leftrightarrow CO_2 + H_2O + 2e^-$	(14)	$O_2 + 2CO_2 + 4e^- \leftrightarrow 2CO_3^{2-}$
(13)	$CO + CO_3^{2-} \leftrightarrow 2CO_2 + 2e^-$		
Additional reaction			
(15)	$CO + H_2O \leftrightarrow CO_2 + H_2$		
(16)	$CO + 3H_2 \leftrightarrow CH_4 + H_2O$		
(17)	$CO + H_2 \leftrightarrow C + H_2O$		
(18)	$2CO \leftrightarrow C + CO_2$		
Fuel cell operating temperature: 650 °C			

Power output W produced from MCFC system can be calculated by Eq. (19). Multiplication of current density CD , total activate area of a fuel cell AR_{cell} , cell voltage V_{cell} , number of cells N_{cell} , and inverter efficiency from direct current to alternating current IE determines the total power output [37, 43].

$$W = CD \times AR_{cell} \times V_{cell} \times N_{cell} \times IE \quad (19)$$

In addition, Rankine cycle has been combined with the conventional MCFC to generate supplementary electricity because high temperature gas is discharged from the MCFC system.

3.2. Mathematical model of the USN

Green electricity from the MCFC combined with Rankine cycle is used to satisfy energy demands in USNs and simulatenously optimal structure of USNs is constructed by the mathematical model.

3.2.1. Obejctive function

The objective function in the mathematical model is to minimize the total economic costs TC (Eq. (20)). The total economic costs consist of the total raw material costs TRC , the total capital costs for steam pipeline network TCC , and the total operating costs for steam pipeline network TOC . The total raw material costs are determined by the amounts of fuel consumption in a boiler $X_{f,ft,b,c}$, fuel price FP_f , amounts of SO_x emission from a boiler $X_{b,c}^{SO_x}$, SO_x treatment price EC^{SO_x} , amounts of CO_2 emission from a boiler $X_{b,c}^{CO_2}$, CO_2 treatment price EC^{CO_2} , water amounts from external facilities to a water unit $^{Ex}X_{wn,c}^{Water}$, water purchase price WP , electricity amounts from external facilities to an electricity unit $^{Ex}X_{en,c}^E$,

electricity purchase price EP , and operating days OD (Eq. (21)). The total capital costs for steam pipeline network are calculated by the binary variable whether a pipeline between two companies is installed or not $B_{s,h,c,c'}$, fixed capital parameter FC , steam amounts between two companies $X_{s,h,c,c'}$, variable capital parameter VC , operating days, distance between companies $D_{c,c'}$, and depreciation factor DF (Eq. (22)). The total operating costs for steam pipeline network are computed by the binary variable whether a pipeline between two companies is installed or not, fixed operating parameter FO , steam amounts between two companies, variable operating parameter VO , operating days, and distance between companies (Eq. (23)).

$$\text{Minimize } TC = TRC + TCC + TOC \quad (20)$$

$$TRC = \left\{ \sum_c \sum_b \sum_{ft} \sum_f (FP_f \times X_{f,ft,b,c}) + \sum_c \sum_b (EC^{SO_x} \times X_{b,c}^{SO_x} + EC^{CO_2} \times X_{b,c}^{CO_2}) \right. \\ \left. + \sum_c \sum_{wn} (WP \times^{Ex} X_{wn,c}^{Water}) + \sum_c \sum_{en} (EP \times^{Ex} X_{en,c}^E) \right\} \times OD \quad (21)$$

$$TCC = (FC \times B_{s,h,c,c'} + VC \times X_{s,h,c,c'} \times OD) \times D_{c,c'} / DF \quad c \neq c' \quad (22)$$

$$TOC = (FO \times B_{s,h,c,c'} + VO \times X_{s,h,c,c'} \times OD) \times D_{c,c'} \quad c \neq c' \quad (23)$$

3.2.2. Fuel tanks in source company

Fuel tanks are allocated only in source companies. The quantities of fuel consumption in a boiler is less than or equal to the sum of fuel amounts in a boiler $X_{f,ft,c}$ and fuel inventory in a fuel tank FI (Eq. (24)).

$$X_{f,ft,b,c} \leq X_{f,ft,c} + FI \quad c \in SOURCE \quad (24)$$

3.2.3. Boilers to produce steam in source company

Boilers are also included only in source companies. The amounts of steam generation from boiler $X_{s,b,h,c}$ are determined by boiler efficiency BF_b , calorific values of fuels CV_f , and the amounts of fuel consumption in a boiler (Eq. (25)).

$$\sum_h \sum_s (X_{s,b,h,c} \times BF_b) = \sum_{ft} \sum_f (CV_f \times X_{f,ft,b,c}) \quad c \in SOURCE \quad (25)$$

The sum of amounts of fuel consumption in a boiler and water consumption in a boiler $X_{wn,b,c}^{Water}$ is equal to the sum of amounts of steam generation from a boiler $X_{s,b,h,c}$, greenhouse gas emission from a boiler (Eq. (26)).

$$\sum_h \sum_s (X_{s,b,h,c} + X_{b,c}^{SO_x} + X_{b,c}^{CO_2}) = \sum_{ft} \sum_f \sum_{wn} (X_{f,ft,b,c} + X_{wn,b,c}^{Water}) \quad c \in SOURCE \quad (26)$$

The amounts of SO_x and CO_2 emissions from a boiler are calculated by the amounts of fuel consumption in a boiler, SO_x emission parameter $EP_f^{SO_x}$ and CO_2 emission parameter $EP_f^{CO_2}$ (Eqs. (27) and (28))

$$X_{b,c}^{SO_x} = \sum_{ft} \sum_f (EP_f^{SO_x} \times X_{f,ft,b,c}) \quad c \in SOURCE \quad (27)$$

$$X_{b,c}^{CO_2} = \sum_{ft} \sum_f (EP_f^{CO_2} \times X_{f,ft,b,c}) \quad c \in SOURCE \quad (28)$$

The amounts of necessary energy in a boiler $X_{en,b,c}^E$ are determined by the binary variable whether a boiler is operated or not $B_{s,b,h,c}$, fixed consumption parameter of electricity in a boiler FCP_b^E , the amounts of steam generation from a boiler, and variable consumption parameter of electricity in a boiler VCP_b^E (Eq. (29)).

$$X_{en,b,c}^E = FCP_b^E \times B_{s,b,h,c} + VCP_b^E \times X_{s,b,h,c} \quad c \in SOURCE \quad (29)$$

The amounts of steam generation from a boiler are limited by the binary variable whether a boiler is operated or not, minimum steam production capacity $MINSP_{b,c}$, and maximum steam production capacity $MAXSP_{b,c}$ according to the types of boilers and source companies (Eq. (30)).

$$MINSP_{b,c} \times B_{s,b,h,c} \leq X_{s,b,h,c} \leq MAXSP_{b,c} \quad c \in SOURCE \quad (30)$$

The relation between the binary variable whether a boiler is operated or not and the amounts of steam generation from a boiler is linearly relaxed as the following (Eq. (31)).

$$B_{s,b,h,c} / BN \leq X_{s,b,h,c} \leq B_{s,b,h,c} \times BN \quad c \in SOURCE \quad (31)$$

3.2.4. Steam headers for different types of steam

For all types of companies, the steam amounts in a steam header $X_{s,h,c}$ should be greater than or equal to steam demand $SD_{s,c}$ (Eq. (32)).

$$SD_{s,c} \leq X_{s,h,c} \quad (32)$$

Steam headers are separated into very high-pressure steam header, high-pressure steam header, medium-pressure steam header, and low-pressure steam header regarding the pressure levels and incorporate distinct mass balances according to the types of companies in USNs. Very-high pressure steam is directly produced by a boiler $X_{VHS,"BI","VHSH",c}$ and used to fulfill very-high pressure steam demands $X_{VHS,"VHSH",c}$ or transferred to a valve for the pressure down $X_{VHS,"VHSH","VI",c}$ (Eq. (33)). Source companies in type A have boilers to generate very-high pressure steam.

$$X_{VHS,"BI","VHSH",c} = X_{VHS,"VHSH",c} + X_{VHS,"VHSH","VI",c} \quad c \in TA \quad (33)$$

Source companies of type A contain the other boilers which are able to harness high-pressure steam. Therefore, the amounts of high-pressure steam released by a letdown valve connected with very high-pressure steam header $X_{HS,"VI","HSH",c}$, high-pressure steam generated from a boiler $X_{HS,"B2","HSH",c}$, and high-pressure steam transferred from other source companies $X_{HS,"HSH",c',c}$ are equal to the amounts of high-pressure steam to satisfy high-pressure steam demand $X_{HS,"HSH",c}$, high-pressure steam to a turbine $X_{HS,"HSH",t,c}$, high-pressure steam to a letdown valve $X_{HS,"HSH","V2",c}$, high-pressure steam to other companies $X_{HS,"HSH",c,c'}$, and wasted high-pressure steam $X_{HS,c}^{Waste}$ (Eq. (34)).

$$\begin{aligned} X_{HS,"VI","HSH",c} + X_{HS,"B2","HSH",c} + \sum_{c'} X_{HS,"HSH",c',c} = \\ X_{HS,"HSH",c} + X_{HS,"HSH",t,c} + X_{HS,"HSH","V2",c} + \sum_{c''} X_{HS,"HSH",c,c''} + X_{HS,c}^{Waste} \end{aligned}$$

$$c \in TA, c' \in TA \vee TB, c'' \in TA \vee TB \vee SINK \quad (34)$$

Source companies of type B do not include very high-pressure steam headers but encompass boilers to generate high-pressure steam. Therefore, the amounts of high-pressure steam produced from a boiler $X_{"HS","B3","HSH",c}$ and high-pressure steam from other companies are identical to the amounts of high-pressure steam to satisfy high-pressure steam demand, high-pressure steam to a turbine, high-pressure steam to a letdown valve, high-pressure steam to other companies, and wasted high-pressure steam (Eq. (35)).

$$\begin{aligned}
& X_{"HS","B3","HSH",c} + \sum_{c'} X_{"HS","HSH",c',c} = \\
& X_{"HS","HSH",c} + X_{"HS","HSH",t,c} + X_{"HS","HSH","V2",c} + \sum_{c''} X_{"HS","HSH",c,c''} + X_{"HS",c}^{Waste} \\
& c \in TB, c' \in TA \vee TB, c'' \in TA \vee TB \vee SINK
\end{aligned} \tag{35}$$

Mass balances for medium-pressure steam in source companies of types A and B have equal to each other but source companies type C present other mass balance for medium-pressure steam. In the case of types A and B, the amounts of medium-pressure steam from the turbine $X_{"MS",t,"MSH",c}$, medium-pressure steam from a letdown valve $X_{"MS","V2","MSH",c}$, and medium-pressure steam from other companies $X_{"MS","MSH",c',c}$ are equal to the amounts of medium-pressure steam to meet medium-pressure steam demands $X_{"MS","MSH",c}$, medium-pressure steam to a letdown valve $X_{"MS","MSH","V3",c}$, medium-pressure steam to other companies $X_{"MS","MSH",c,c''}$, and wasted medium-pressure steam $X_{"MS",c}^{Waste}$ (Eq. (36)).

$$\begin{aligned}
& X_{"MS",t,"MSH",c} + X_{"MS","V2","MSH",c} + \sum_{c'} X_{"MS","MSH",c',c} = \\
& X_{"MS","MSH",c} + X_{"MS","MSH","V3",c} + \sum_{c''} X_{"MS","MSH",c,c''} + X_{"MS",c}^{Waste} \\
& c \in TA \vee TB, c' \in SOURCE, c'' \in C
\end{aligned} \tag{36}$$

Medium-pressure steam mass balance in source companies of type C indicates that the amounts of medium-pressure steam from a boiler $X_{"MS","B4","MSH",c}$ and medium-pressure steam from other companies are equal to the amounts of medium-pressure steam to fulfill medium-pressure steam demands, medium-pressure steam to a letdown valve, medium-pressure steam to other companies, and wasted medium-pressure steam (Eq. (37)).

$$\begin{aligned}
& X_{"MS","B4","MSH",c} + \sum_{c'} X_{"MS","MSH",c',c} = X_{"MS","MSH",c} + X_{"MS","MSH","V3",c} + \sum_{c''} X_{"MS","MSH",c,c''} + X_{"MS",c}^{Waste} \\
& c \in TC, c' \in SOURCE, c'' \in C
\end{aligned} \tag{37}$$

Low-pressure steam generation is not straight influenced by boilers. The amounts of low-pressure steam from the turbine $X_{LS",t,"LSH",c}$, low-pressure steam from the letdown valve $X_{LS",V3",LSH",c}$, low-pressure steam from other companies $X_{LS",LSH",c',c}$ are equal to the amounts of low-pressure steam to satisfy low-pressure steam demand $X_{LS",LSH",c}$, low-pressure steam to other companies $X_{LS",LSH",c,c"}$, and wasted low-pressures steam $X_{LS",c}^{Waste}$ (Eq. (38)).

$$X_{LS",t,"LSH",c} + X_{LS",V3",LSH",c} + \sum_{c'} X_{LS",LSH",c',c} = X_{LS",LSH",c} + \sum_{c''} X_{LS",LSH",c,c''} + X_{LS",c}^{Waste} \quad c \wedge c' \in SOURCE, c'' \in C \quad (38)$$

3.2.5. Letdown valve to decrease steam pressure

Steam pressure is able to be decreased by steam converting parameter $SCP_{s,s'}$, using letdown valves (Eq. (39)). All steam headers except for the low-pressure steam header incorporate letdown valves.

$$X_{s,v,h,c} = SCP_{s,s'} \times X_{s',h',v,c} \quad s < s', h < h' \quad (39)$$

3.2.6. Turbine to generate lower pressure steam, water, and electricity

A turbine linked with high-pressure steam header can consume high-pressure steam vent $X_{HS",HSH",t,c}$ in order to make medium-pressure steam $X_{MS",t,"MSH",c}$, low-pressure steam, $X_{LS",t,"LSH",c}$, and water $X_{t,wn,c}^{Water}$ (Eq. (40)). The amounts of produced water from the turbine is determined by the amounts of high-pressure steam vent with condensate parameter CP (Eq. (41)). The amounts of electricity from the turbine $X_{t,en,c}^E$ is calculated by turbine parameters for steam types TP_s , turbine parameter for water TP^{Water} , and amounts of steam and water associated with the turbine (Eq. (42)).

$$X_{HS",HSH",t,c} = X_{MS",t,"MSH",c} + X_{LS",t,"LSH",c} + \sum_{wn} X_{t,wn,c}^{Water} \quad c \notin TC \quad (40)$$

$$\sum_{wn} X_{t,wn,c}^{Water} = CP \times X_{HS",HSH",t,c} \quad c \notin TC \quad (41)$$

$$X_{t,en,c}^E = TP_{HS"} \times X_{HS",HSH",t,c} - TP_{MS"} \times X_{MS",t,"MSH",c} - TP_{LS"} \times X_{LS",t,"LSH",c} - \sum_{wn} (TP^{Water} \times X_{t,wn,c}^{Water}) \quad c \notin TC \quad (42)$$

3.2.7. Water unit to control water

The amounts of water in a water unit $X_{wn,c}^{Water}$ should be greater than or equal to water demand WD_c (Eq. (43)).

$$WD_c \leq X_{wn,c}^{Water} \quad (43)$$

The amounts of water from external water facilities $^{Ex}X_{wn,c}^{Water}$ and produced water from turbine $X_{t,wn,c}^{Water}$ are indential to the amounts of water in the water unit and water consumption in boilers $X_{wn,b,c}^{Water}$ (Eq. (44)).

$$^{Ex}X_{wn,c}^{Water} + X_{t,wn,c}^{Water} = X_{wn,c}^{Water} + \sum_b X_{wn,b,c}^{Water} \quad (44)$$

3.2.8. Electricity unit to manipulate electricity

The amounts of electricity in an electricity unit $X_{en,c}^E$ should be greater than or equal to electricity demand ED_c (Eq. (45)).

$$ED_c \leq X_{en,c}^E \quad (45)$$

The amounts of electricity from external energy sources based on fossil fuels $^{Ex}X_{en,c}^E$, electricity generation from the turbine $X_{t,en,c}^E$, and green electricity generation from IUWTE network $^{MCFC}X_{en,c}^E$ are equal to the amounts of electricity to electricity demands $X_{en,c}^E$ and electricity consumption in boilers $X_{en,b,c}^E$ (Eq. (46)). The quantites of green electricity should be less than or equal to the energy potential $W2E$ which is expected by using IUWTE network in aforementioned process modeling section (Eq. (47)).

$$^{Ex}X_{en,c}^E + X_{t,en,c}^E + ^{MCFC}X_{en,c}^E = X_{en,c}^E + \sum_b X_{en,b,c}^E \quad (46)$$

$$\sum_c \sum_{en} ^{MCFC}X_{en,c}^E \leq W2E \quad (47)$$

3.2.9. Sink companies in the absence of boilers

Sink companies do not contain boilers and import needed steam types from source companies in USNs or operate letdown valves to make lower pressure steam. High-pressure steam is inevitably transferred from source companies $X_{HS", "HSH", c', c}$ and it is consumed to satisfy high-pressure steam demands $X_{HS", "HSH", c}$, transports to a letdown valve $X_{HS", "HSH", "V2", c}$, or emitted as wasted steam $X_{HS", c}^{Waste}$ (Eq. (48)). The amounts of medium-pressure steam from other companies $X_{MS", "MSH", c', c}$ and medium-pressure from the letdown valve $X_{MS", "V2", "MSH", c}$ are equal to the amounts of medium-pressure steam to meet medium-pressure demands $X_{MS", "MSH", c}$, medium-pressure steam to a letdown valve $X_{MS", "MSH", "V3", c}$, and wasted medium-pressure steam $X_{MS", c}^{Waste}$ (Eq. (49)). The amounts of low-pressure steam from other companies $X_{LS", "LSH", c', c}$ and low-pressure from the letdown valve $X_{LS", "V3", "LSH", c}$ are equal to the amounts of low-pressure steam to meet low-pressure demands $X_{LS", "LSH", c}$ and wasted low-pressure steam $X_{LS", c}^{Waste}$ (Eq. (50)).

$$\sum_{c'} X_{HS", "HSH", c', c} = X_{HS", "HSH", c} + X_{HS", "HSH", "V2", c} + X_{HS", c}^{Waste} \quad c' \in TA \vee TB \quad (48)$$

$$\sum_{c'} X_{MS", "MSH", c', c} + X_{MS", "V2", "MSH", c} = X_{MS", "MSH", c} + X_{MS", "MSH", "V3", c} + X_{MS", c}^{Waste} \quad c' \in SOURCE \quad (49)$$

$$\sum_{c'} X_{LS", "LSH", c', c} + X_{LS", "V3", "LSH", c} = X_{LS", "LSH", c} + X_{LS", c}^{Waste} \quad c' \in SOURCE \quad (50)$$

3.2.10. Steam transfer between companies

The installation of pipelines between companies in USNs is linearly constrained by Eq. (51). Simultaneous utility transfer in-between is not allowed (Eq. (52)).

$$B_{s, h, c', c} / BN \leq X_{s, h, c', c} \leq B_{s, h, c', c} \times BN \quad c \neq c' \quad (51)$$

$$B_{s, h, c', c} + B_{s, h, c, c'} \leq 1 \quad c \neq c' \quad (52)$$

3.2.11. Waste steam generation for the IUWTE network

Wasted steam from steam headers in USNs should be sufficiently generated to play a role of input component for the internal SMR of MCFC in the IUWTE network as well as react with biomethane from MEA process in the IUWTE network. The quantities of wasted steam from USNs are manipulated by steam-to-carbon ratio $S2CR$ and biomethane potential $BIOCH4$ determined in the IUWTE network (Eq. (53)).

$$BIOCH4 \times S2CR \leq \sum_c \left(X_{HS,c}^{Waste} + X_{MS,c}^{Waste} + X_{LS,c}^{Waste} \right) \quad (53)$$

4. Case study

A case study of Yeosu petrochemical industrial complex in South Korea has been applied for this study. A number of companies are allocated within Yeosu industry and various neighboring WWTPs are placed near Yeosu industry (Figure 3 (A)). 15 chemical companies in which utility demand data are disclosed have been selected as components of the USN in this case study. The USN comprises 10 source companies able to produce utilities and 5 sink companies unable to generate utilities (Figure 3 (B)). The total capacity available of WWTPs to treat wastewater is about 299,020 ton per day and average daily treatment flow rate is approximately 233,280 ton per day. WWTPs are divided into large-scale WWTPs and medium-size WWTPs according to the general standard of the total capacity of daily wastewater treatment amounts, 500 tons per day. The number of large-scale WWTPs is a total of 6 and the number of medium-scale WWTPs is a total of 10, respectively (Figure 3 (C)). Specific capacities and average daily treatment flow rates of wastewater from open data in Korea Environment Corporation are described in Table 3.

Figure 3. Yeosu petrochemical industrial complex and WWTPs available in the vicinity for a case study; (A): Distribution of WWTPs and Yeosu industry on the real map, (B): Sink and source companies in the USN, and (C): Average daily flow rate of wastewater treatment for large-scale WWTPs and medium-size WWTPs.

Table 3. A comparison of capacity and average daily treatment flow rate of wastewater for individual WWTP employed in the case study.

Size of WWTP (over 500 tons/day)	Name of WWTP	Capacity (ton/day)	Average daily treatment flow rate of wastewater (ton/day)
A	Yeosu	110,000	80,301
B	Suncheon	130,000	107,926
C	Jungang	25,000	15,345
D	Gwangyang A	24,000	24,063
E	Gwangyang B	7,500	3,969
F	Jinwol	1,600	1,022
Size of WWTP (below 500 tons/day)			
G	Gwangam	70	55
H	Yongju	80	61
I	Najin	180	128
J	Seochon	60	45
K	Gajang	80	57
L	Gunghang	60	40
M	Hwadong	100	75
N	Jangsu	50	37
O	Bongdu	80	59
P	Sangok	160	97

As aforementioned in the problem statement section, source companies in the USN have three different types and main process units can be altered depending on the type. All companies require steam, water, and electricity demands and in the case of steam demand, 4 pressure levels separate steam demand table (Table 4). Types of boilers, which are only built in source companies, depends on the types of source companies. Boiler types B1 and B2 are used to produce very high-pressure steam and high-pressure steam respectively in source company type A. Boiler type B3 is utilized to generate high-pressure steam in source company type B. Source company type C operates boiler type B4 to make medium-pressure steam. The first company in source company type B has utility production ability but does not have any utility demand according to the reference data.

Table 4. Classification of main process units and utility demand data of source and sink companies in the existing USN. VHS: Very high-pressure steam, HS: High-pressure steam, MS: Medium-pressure steam, LS: Low-pressure steam, HSH: High-pressure steam header, MSH: Medium-pressure steam header, and LSH: Low-pressure steam header.

Main process unit	Utility demand	
	ton/day	kWh/day

Source		Boiler	Steam header	Turbine	VHS	HS	MS	LS	Water	Energy
Type A	1	B1, B2	All	O			2,033	3,089	1,322	2,211
	2				9,933	9,933			5,522	2,644
	3				9,933	12,011	3,800	2,544	4,856	2,644
	4				13,467	4,944	4,656	2,522	5,522	4,411
	5				9,300	1,633	1,456	1,567	4,411	3,756
Type B	1	B3	HSH, MSH, LSH	O						
	2				2,544	756	311	2,211	1,544	
Type C	1	B4	MSH, LSH	X				556	1,100	1,100
	2				3,711	2,122	1,100	1,544		
	3				689	4,044	1,322	1,100		
Sink										
Sink	1	X	HSH, MSH, LSH	O			778			1,100
	2				1,322	1,100	1,322	2,211		
	3				311	444		1,100		
	4					133		444		
	5				1,433	1,011	156	2,644	2,211	

The case study has assumed that WWTPs everywhere in the vicinity of Yeosu petrochemical industrial complex can be integrated with USNs and in case external energies are exported and consumed to satisfy energy demands in USNs, 0.68 kg of carbon per kWh is approximately emitted [44]. The professional optimization tool, GAMS version 24.6 with the CPLEX solver, has conducted the optimization of USNs [45].

5. Results and discussion

A WWTP model which has been designed depending on the BSM2 model is applied for neighboring WWTPs near Yeosu industry. The total quantites of biogas generation according to the simulation results are approximately 30 tons per day and mole fracionts of biomethane and CO₂ are 0.65 and 0.35, respectively.

5.1. Simulation results of the MEA process and the MCFC system combined with Rankine cycle

Figure 4 shows the results of the MEA process simulation conducted in this case study. Two absorbers in a row are connected to extract high yield of biomethane from biogas and the stripper captures almost all of CO₂ in biogas. Absorbers use make-up water and make-up MEA to efficiently balance the chemical reactions in the reactors and discharged water by flash drums is reused in the absorbers. Rich amine streams from absorbers are mixed and enter the stripper as an input stream, as a result, CO₂ is separated from the mixed input stream. Lean amine stream including MEA in bulks is also recycled to maintain optimal operations. Main streams in the MEA process are marked by from A to I and mole fractions of crucial components in each stream are presented in Figure 4. Stream A is the biogas stream from a WWTP based on BSM2 model and has 0.65 mole fraction of biomethane and 0.35 mole fraction of CO₂. Steam B is the output gas stream from the first absorber and indicates 0.60 mole fraction of biomethane, 0.14 mole fraction of CO₂, and 0.30 mole fraction of water. Huge amounts of water are separated by the

first flash drum and stream C passing through a compressor and a heat exchanger contains 0.77 mole fraction of biomethane, 0.20 mole fraction of CO₂, and 0.03 mole fraction of water. Stream D from the second absorber which will provide one of the input streams into the MCFC system includes 0.92 mole fraction of biomethane, 0.05 mole fraction of CO₂, and 0.03 mole fraction of water. Streams F and G are make-up water streams with one mole fraction of water and streams H and I are make-up MEA streams with 0.61 mole fraction of MEA and 0.51 mole fraction of MEA, resulting from design specification technique in Aspen Plus. A total of 5 recycle streams is considered to reuse MEA and water as much as possible. As a result, 1,200 kg of MEA per day and 1,100 kg of water per day are approximately recycled into the MEA process. With respect to the energy consumption, the total 25,733 kWh per day is used to operate heat exchangers, compressor, pump, condensers, reboilers, and flash drums.

Figure 4. Simulation results of the MEA process performed in the case study and mole fractions of principal components in main streams.

The simulation results of the MCFC system combined with Rankine cycle are illustrated in Figure 5. Biomethane from the MEA process and waste steam from the USNs are mixed and consumed in the internal SMR process. Water gas shift reaction is employed to reduce the ratio of CO and increase amounts of hydrogen since the gas from the internal SMR process encompasses great quantities of CO. The gas generated from water shift gas reaction system goes into the high temperature fuel cell. The fuel cell system is designed depending on Eqs. (12) to (18) and the equilibrium reactor has been considered to construct the fuel cell because all reactions are assumed to react on the phase equilibrium which is a common assumption

used in process systems modeling. The high temperature gas from the fuel cell can be suitable for Rankine cycle to obtain supplementary green electricity and recycled into the fuel cell system. Main streams and mole fraction of important materials in the MCFC system are as followings. Steam A coupled with the output stream in the MEA process has 0.92 mole fraction of biomethane. 0.05 mole fraction of CO₂, and 0.03 mole fraction of water. Steam B consists of wasted steam from the USNs and the amounts of needed steam are determined by the steam to carbon ratio, which is assumed as 3 in this study. Stream C from the internal SMR process contains 0.35 mole fraction of water, 0.49 mole fraction of hydrogen, and 0.16 mole fraction of CO. Stream D includes 0.05 mole fraction of CO₂, 0.29 mole fraction of water, 0.54 mole fraction of hydrogen, and 0.10 mole fraction of CO. Green electricity generation by the MCFC system can be calculated by Eq. (19). The total green electricity amounts encompassing additional green electricity generation by Rankine cycle are about 111,996 kWh per day. Indeed, the net green electricity output except for energy consumptions in the MEA process, the internal SMR process as well as other facilities are approximately 41,339 kWh per day.

Figure 5. Simulation results of the MCFC system with Rankine cycle suggested in the case study and mole fractions of principal components in main streams.

5.2. Optimization results of the optimal USN based on the IUWTE network

As aforementioned in the mathematical model part, the developed mathematical model to optimize the USNs includes the constraints for the net electricity potential from the MCFC system combined with Rankine cycle based on the consumption of waste steam from the USNs. The optimal USN structure of Yeosu petrochemical industrial complex is depicted in Figure 6. Steam utility is transmitted between source companies in the close distance as well as from source companies to sink companies. Source companies A4 and A5 have great utility demands compared to other companies according to the Table 4. Therefore, they have decided on direct steam production and consumption instead of participating in USNs. Even though source company B1 does not need to satisfy any utility demand, it generates and distributes high-pressure steam to near sink companies in order to meet their steam utility demands. Sink companies S1, S2, and S4 do not have high-pressure steam demands; however, high-pressure steam transferred from B1, A1, and A2 is utilized to fulfill medium-pressure steam or low-pressure steam demands by operating turbines or letdown valves. Source companies A1 and A2 have great capacities of the maximum steam production otherwise they have relatively lower steam utility demands compared to other source companies of type A, and companies in the vicinity of A1 and A2 can import extra steam available from A1 and A2. The total economic costs of the optimal USN in this study is 147,071,200 US\$ per year and about 15% of the total costs are reduced compared to those of the existing USN, 169,198,582 US\$ per year [25].

Figure 6. The structure of optimal USN based on the IUWTE network in the case study.

The flow rates of input and output materials in the IUWTE network are described in the Table 5. The total wastewater amounts treated in WWTPs allocated near Yeosu petrochemical industrial complex are 233,280 tons per day and about 29,383 kg of biogas per day can be extracted by anaerobic digesters in WWTPs. The total quantities of main components used in the MEA process as a biogas upgrading process are 29,383 kg biogas from WWTPs per day, 28,996 kg of make-up MEA per day, and 666 kg of make-up water per day. Produced biomethane stream from the MEA process has 12,036 kg of biomethane per day and 4,929 kg CO₂ per day is captured by the stripper in the MEA process. The MCFC

system consumes 12,036 kg of biomethane from the previous MEA process per day, 40,662 kg of waste steam from the USNs per day, and 1,740 kg of hydrogen inventory per day to manage high temperature reactors. About 1,112 kg of CO₂ per day is emitted from the MCFC system and the total green electricity generation is approximately 41,339 kWh per day excluding energy consumptions in other processes. The optimized USN exploits the total 4,797 tons of fossil fuels per day and 117,504 tons of water per day, emits 44 tons of CO₂ per day and 51 tons of SO_x per day, and vent 40,662 kg of wasted steam per day under the constraints of fulfilling utility demands and transmitting necessary waste steam into the MCFC system.

Table 5. Simulation and optimization results of input and output flow rates in each process in the proposed IUWTE network.

WWTP	MEA	MCFC-Rankine cycle	Optimal USN
Input flow rate			
Wastewater: 233,280 ton/day	Biogas from WWTP: 29,383 kg/day Make-up MEA: 28,996 kg/day Make-up water: 666 kg/day	Waste steam from USN: 40,662 kg/day Biomethane from MEA process: 12,036 kg/day Additional fuel: 1,740 kg/day	Total fossil fuels: 4,797 ton/day Water consumption: 117,504 ton/day
Output flow rate			
Biogas: 29,383 kg/day	Biomethane: 12,036 kg/day Captured CO ₂ : 4,924 kg/day	Emitted CO ₂ : 1,112 kg/day Produced electricity potential: 41,339 kWh/day	Emitted CO ₂ : 44 ton/day Emitted SO _x : 51 ton/day Wasted steam: 40,662 kg/day

5.3. Environmental results from the hybrid GWP pinch analysis

Hybrid GWP pinch analysis performed in this study can separately clarify the GWPs for each company and cumulative variance of the total GWP in the IUWTE network. Moreover, the specific GWP in the USNs can be demonstrated according to the internal and external factors. The internal factor is subject to the boilers operated in source companies in the USN and a total of 4 boiler types is distributed regarding the types of source companies (Table 4). The external factor is related to the expected GWP amounts in case companies import outside energy sources based on fossil fuels in order to likely meet energy demands and energy requirement in boilers. As aforementioned, 0.68 kg of CO₂ is approximately emitted to generate 1 kWh. Table 6 indicates GWP quantities of each company from internal and external factors in the base case. GWP from the internal factor does not happen in sink companies because they do not operate boilers but gain needed steam from source companies. Source companies in type A whose utility demands are great and in which very high-pressure steam can be harnessed show enormous GWP emissions. GWP from the external factor depends on whether extra electricity is needed from the outside or not. Companies which do not make any GWP based on the external factor use turbines to fulfill energy demands. On the other hand, companies in type C without self-generation capacity of electricity undoubtedly rely on the external energy sources since they do not encompass any turbines. The total amounts of GWP because of the internal factor are 147,558 kg of GWP per day and the total quantities of GWP because of the external factor are 9,540 kg of GWP per day.

Table 6. The hybrid GWP pinch analysis results of companies in the USN of the base case.

GWP from internal factor									GWP from external factor
SO _x					CO ₂				Expected CO ₂
Company	B1	Boiler type		B4	B1	Boiler type		B4	
		B2	B3			B2	B3		
S1									748
A1	8,976	1,055			6,936	1,318			
S2									1,202
S3									748
S4									302
B1			2,595				2,595		
C1				202				202	750
S5									1,504
C2				360				360	1,054
A2	8,964	3,955							
A3	18,457	2,769							466
C3				360				360	752
B2			371				371		947
A4	12,920	4,395			9,984	5,493			1,065
A5	7,947	4,834			6,141	6,043			
Sum	57,264	17,008	2,966	922	44,251	21,259	2,966	922	9,540
Total		78,160				69,398			9,540

Table 7 describes GWP amounts of each company from the optimized USN based on the developed IUWTE network. Companies that discharge GWP from the internal factor in the optimal USN are the same as those in the existing USN of the base case. Furthermore, source companies of type A also generate much of GWP. The reasons are that both cases are dependent on the same utility demands and maximum steam production capacities for companies and identical types of boilers are employed in both cases. However, GWP emissions are considerably reduced in the optimized USN. The total SO_x and CO₂ emission amounts in the optimal USN based on the IUWTE network are 50,865 kg per day and 44,174 kg per day, resulting in a decrease of about 35.1% SO_x and 36.5% CO₂ compared to the base case. The operation of boilers for steam production to generate electricity via turbines has been optimized by satisfying to some extent energy demands through green electricity from the IUWTE network. GWP generation from the external factor is calculated by distributing expected CO₂ amounts in the middle of the construction of the IUWTE network into each company according to the ratios of energy demands. Therefore, companies including great energy demands such as companies A4 or A5 are implied to assign the highest GWP emissions to those companies since significant quantities of green electricity from the IUWTE network are used. Otherwise, in the case of source company B1, any GWP emissions are not assigned to the company B1 because even though boilers in the company B1 were run to generate steam on purpose of the transfer, any energy demands are not required in the company B1. The total sum of GWP emissions from the internal and external factors are 95,039 kg per day and 6,035 kg per day, respectively. The results indicate that the GWP emissions from the internal and external factors are decreased by 35.6% and 36.8% compared to the base case.

Table 7. The hybrid GWP pinch analysis results of companies in the optimized USN based on the IUWTE network.

Company	GWP from internal factor								GWP from external factor
	SO _x				CO ₂				Expected CO ₂
	B1	Boiler type B2	B3	B4	B1	Boiler type B2	B3	B4	
S1									237
A1	2,640	480			2,040	600			476
S2									476
S3									237
S4									96
B1			360				360		
C1				202				202	237
S5									476
C2				860				860	333
A2	8,488	2,598			6,559	3,248			570
A3	8,488	2,769			6,559	3,461			570
C3				1,248				1,248	237
B2			360				360		333
A4	11,508	2,113			8,892	2,641			950
A5	7,947	804			6,141	1,004			809
Sum	39,071	8,764	720	2,310	30,191	10,953	720	2310	6,035
Total		50,865				44,174			6,035

Figure 7 presents the graphical results of the GWP emissions from the internal and external factors based on the hybrid GWP pinch analysis. The GWP emission amounts of each company because of the internal factor that is the use of boilers are described in the Figure 7 (B) and the graph indicates that both of the base case and the optimized case have similar patterns in which source companies of type A discharge most GWP emissions. Figure 7 (C) associated with the GWP emissions from the external factor illustrates that source companies of type C which do not have any turbines and sink companies enable to directly produce steam have to be supported by the outside energy sources, and the great amounts of GWP emissions are generated. On the other hand, the optimal USN is able to use green electricity from the IUWTE network, and different configuration of the GWP emission pattern has been performed because expected GWP emissions during the implementation of the IUWTE network are distributed alongside the energy demands of each company. Cumulative GWP based on the hybrid GWP pinch analysis incorporating results in Figures 7 (B) and 7 (C) is suggested in Figure 7 (A). Vertical solid lines and inclined dashed lines mean cumulative GWP emissions from the internal and external factor, respectively. The more companies are involved in the USN, the greater difference between the total GWP emissions occurs.

Figure 7. The graphical results from the hybrid GWP pinch analysis in this case study; (A): Cumulative GWP amounts in the base case and the optimized USN from the IUWTE network, (B): GWP quantities of each company from the internal factor, and (C) GWP quantities of each company from the external factor.

The total of 15 companies in the existing USN is considered to optimize the USN based on the IUWTE network. In case more companies in Yeosu petrochemical industrial complex are underpinned by the IUWTE network, the total GWP amounts would be reduced greater than the current optimal results.

As a future perspective, we intended to expand this steady-state analysis of the network with a dynamic systems analysis in which considerations will take into account dynamic changes both in the supply side of waste streams as well as demand side fluctuations. Moreover stochastic based optimization scenarios will also be formulated to assess and propose robust designs and solutions for the waste-to-energy management solutions.

6. Conclusions

This study has developed an integrated waste-to-energy system model by integrating the USNs in a huge petrochemical industrial complex with the WTE network starting from the neighboring WWTPs. Biogas produced in WWTPs are used to generate biomethane by using the MEA process as a biogas upgrading process. The upgraded biomethane and the waste steam from the USNs are utilized in the MCFC system that is combined with Rankine cycle to generate green electricity. The optimization of the existing

USN is implemented as a mixed integer nonlinear optimization problem where green electricity from the suggested MCFC system is solved to satisfy energy demands in the optimized USN. This research shows significant findings compared to the existing works as following: First, a huge petrochemical industry and a number of biological processes are integrated to construct advanced WTE network. Second, the developed IUWTE network is described using an integrated model that consist of first-principles/predictive process models describing each subsystems in the network. This allows predictive simulation for the WTE network and the calculation of energy and mass balance as well as utility consumption and production.. As a result, the optimal design of the USN structure has been assessed by considering techno economic objective function. Third, the application of the hybrid GWP pinch analysis using GWP amounts from the IUWTE network indicates detailed GWP emissions and demonstrates the feasibility of the IUWTE from an environmental point of view.

The developed model has been applied for a case study of Yeosu petrochemical industrial complex, which has 15 companies in the USN and 16 WWTPs available in the vicinity. Two waste streams, which are wastewater as influent in WWTPs and wasted steam from the USN, have been taken into account. The net green electricity potential from the IUWTE network can properly fulfill energy demands in the optimal USN. The total economic costs of the optimized USN are approximately reduced by 15% compared to the existing USN and according to the developed hybrid GWP pinch analysis, the total GWP emission quantities decrease about 36% compared to the current USN. The model-based integrated network of this study can be applied for different petrochemical industries and if the efficiency of the fuel cell grows according to the technological roadmap, diverse WTE network would be continuously integrated with the results in this study.

Acknowledgement

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Nomenclature

Sets

s : steam (four types of steam)

h : steam header (four types of steam headers)

b : boiler (four types of boilers)

c : company (source and sink companies)

f : fuel (four types of fossil fuels)

ft : fuel tank (four types of fuel tanks)

v : valve (three types of valve)

t : turbine

wn : water unit

en : electricity unit

Subsets

$SOURCE$: all source companies

TA : source companies of type A

TB : source companies of type B

TC : source companies of type C

Parameters

FI : fuel inventory

BF_b : boiler efficiency

CV_f : calorific value of fuels

$EP_f^{SO_x}$: emission parameter of SO_x

$EP_f^{CO_2}$: emission parameter of CO₂

FCP_b^E : fixed consumption parameter of electricity in a boiler

VCP_b^E : variable consumption parameter of electricity in a boiler

$MAXSP_{b,c}$: maximum steam production

$MINSP_{b,c}$: minimum steam production

BN : big number

$SD_{s,c}$: steam demand

$SCP_{s,s'}$: steam converting parameter

CP : condensate parameter

TP_s : turbine parameter for steam

TP^{Water} : turbine parameter for water

WD_c : water demand

ED_c : electricity demand

$W2E$: electricity potential from waste-to-energy network

FP_f : fuel price

EC^{SO_x} : emission charge of SO_x

EC^{CO_2} : emission charge of CO₂

WP : water price

EP : electricity price

FC : fixed capital parameter

VC : variable capital parameter

$D_{c,c'}$: distance between companies

OD : operating days

DF : depreciation factor

FO : fixed operating parameter

VO : variable operating parameter

BIOCH4 : biomethane potential in waste-to-energy network

S2CR : steam to carbon ratio

Variables

$X_{f,ft,c}$: fuel amounts in a fuel tank (ton/day)

$X_{s,b,h,c}$: steam amounts from a boiler to a steam header in a company (ton/day)

$X_{b,c}^{SO_x}$: SO_x amounts generated from a boiler (ton/day)

$X_{b,c}^{CO_2}$: CO₂ amounts generated from a boiler (ton/day)

$X_{f,ft,b,c}$: fuel amounts from a fuel tank to a boiler (ton/day)

$X_{wn,b,c}^{Water}$: water amounts from a water unit to a boiler (ton/day)

$X_{en,b,c}^E$: electricity amounts from a electricity unit to a boiler (kWh/day)

$X_{s,h,c}$: steam amounts from a steam header to steam demand (ton/day)

$X_{s,h,v,c}$: steam amounts from a steam header to a valve (ton/day)

$X_{s,v,h,c}$: steam amounts from a valve to a steam header (ton/day)

$X_{s,h,c,c'}$: steam transfer amounts from a company to another company (ton/day)

$X_{s,h,t,c}$: steam amounts from a steam header to a turbine (ton/day)

$X_{s,c}^{Waste}$: wasted steam amounts (ton/day)

$X_{s,t,h,c}$: steam amounts from a turbine to a steam header (ton/day)

$X_{t,wn,c}^{Water}$: water amounts from a turbine to a water unit (ton/day)

$X_{t,en,c}^E$: electricity amounts from a turbine to an electricity unit (kWh/day)

$X_{wn,c}^{Water}$: water amounts from a water unit to water demand (ton/day)

$^{Ex} X_{wn,c}^{Water}$: water amounts from an external water source to a water unit (ton/day)

$^{Ex} X_{en,c}^E$: electricity amounts from an external energy source to an electricity unit (kWh/day)

$X_{en,c}^E$: electricity amounts from an electricity unit to electricity demand (kWh/day)

$^{MCFC}X_{en,c}^E$: electricity amounts from MCFC system in waste-to-energy network (kWh/day)

TRC : total raw material costs in a utility supply network (US\$/year)

TCC : total capital costs of a utility supply network (US\$/year)

TOC : total operating costs of a utility supply network (US\$/year)

TC : total costs of a utility supply network (US\$/year)

Binary variable

$B_{s,b,h,c}$: whether a boiler is operated or not

$B_{s,h,c,c'}$: whether a company is connected with another company or not