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Optimization of site utility systems for renewable energy integration

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ABSTRACT

Considerable attention has been paid to the electrified energy supply based on renewable energy for achieving carbon-neutrality. A systematic and integrated approach is required to identify optimal operating strategies for the integration of electrified energy sources with conventional utility systems and to understand the techno-economic impact of using renewable energy on industrial energy management. Renewable-integrated industrial utility systems are modeled, which is optimized to investigate economic trade-off between capital investment, fuel consumption, power generation, and CO_2 emission tax. Sensitivity of key design parameters is examined with the optimization framework, which allows to gain conceptual understanding on the economic impact of CO_2 emission tax and prices of renewable electricity on site-wide heat and power management. Compared to the utility system based on the combustion of fossil fuels only, the operating cost of renewable-integrated system in the case study can be reduced about 14% in the operating cost and 9% in the capital cost through the strategic import of 20 MW_e renewable electricity. The presented case studies fully illustrate economic impacts related to the implementation of renewable electricity to industrial utility systems and demonstrate the benefit of process-integrated optimization for renewable energy integration in practice.

1. Introduction

The heat and power required for industrial manufacturing is typically generated on the industrial site from utility systems. The utility system has been regarded as an integral part for process industries for reducing the operating cost, as most of the energy consumed in industrial manufacturing is related to the supply of heat and power. The energy-efficient design and sustainable management of utility systems becomes more important these days to achieve carbon-neutral manufacturing, as the conventional way of generating heat and power heavily relies on the combustion of fossil fuels. Due to the industry-wide and rapid introduction of net-zero policies and the recognition of societal responsibility for environmental production, urgent actions are demanded for process industries not only to implement energy-saving technologies, but also to utilize carbon-free energy sources.

Process industries typically employ a centralized utility system, which plays a main role to generate, utilize and distribute heat and power, and allows the energy exchange with downstream processes. The number of units are introduced in utility systems to facilitate cost-effective generation and utilization of steam and to fully exploit cogeneration potential. As the steam generated or consumed at different levels from downstream processes are interacted within the utility system, a plant-wide approach in an integrated manner is required for site-wide energy management in industries. Achieving high energy efficiency or minimizing carbon emissions from industrial utility systems requires rigorous evaluation of economic trade-off related to energy generation and its distribution. Such difficulty in the determination of optimal design and operating conditions is also related with variable energy demands, although this non-constant characteristic in energy demands from downstream processes offers opportunities to strategically exchange the power with the grid.

The accurate estimation of system-wide cost for energy generation is not straightforward because of complex network configuration and design interactions [1]. Hence, the use of process modeling and optimization techniques has been widely practiced in process industries for improving energy efficiency of utility systems without compromising environmental performance. There are a wide range of methods available to examine plant-wide energy recovery and to suggest the most economic generation of heat and power for the industrial site. Graphic-based methods have been widely used to find the theoretical targets for optimal steam distribution and maximum steam recovery with the aid of Site Hot and Cold Profiles, leading to the cost-effective power generation [2]. The concept of total site analysis was extended beyond the industrial site and the heat and power management of commercial and residential buildings are locally integrated with

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Nomenclature

AF	1	Annualization factor
C_C	MM$/y	VHP steam price from coal
C_{FO}	MM$/y	VHP steam price from fuel oil
C_{NG}	MM$/y	VHP steam price from natural gas
C_P	MM$/y	Power price exported or imported
C_R	MM$/y	Renewable energy cost imported
C_W	MM$/y	Water price purchased
cm_C	lb/MMBtu	CO_2 emission from coal
cm_{FO}	lb/MMBtu	CO_2 emission from fuel oil
cm_{NG}	lb/MMBtu	CO_2 emission from natural gas
E_C	MM$/y	CO_2 emission cost for coal
E_{FO}	MM$/y	CO_2 emission cost for fuel oil
E_{NG}	MM$/y	CO_2 emission cost for natural gas
EXP	1	Exponent
H_{BFW}	kJ/kg	BFW mass enthalpy
H_{HP}	kJ/kg	HP mass enthalpy
H_{LP}	kJ/kg	LP mass enthalpy
H_{MP}	kJ/kg	MP mass enthalpy
H_{VHP}	kJ/kg	VHP mass enthalpy
IR	1	Fractional interest rate per year
i	1	Equipment used in the system
m_C	t/h	Steam mass flow from coal boiler
m_{FO}	t/h	Steam mass flow from fuel oil boiler
m_{NG}	t/h	Mass flow of natural gas
N	1	The number of equipment
NHV_C	kJ/kg	Heating value of coal
NHV_{FO}	kJ/kg	Heating value of fuel oil
n	1	The number of plant life time
P_C	$/t	Coal price
P_{FO}	$/t	Fuel oil price
P_{NG}	$/t	Natural gas price
P_P	$/kWh	Power price
P_W	$/kWh	Water price
P_R	$/MWh	Renewable energy price
Q_{cond}	kW	Condenser duty
Q_{T4}	kJ/h	T4 heat flow
Q_{T5}	kJ/h	T5 heat flow
Q_{T6}	kJ/h	T6 heat flow
Q_{T7}	kJ/h	T7 heat flow
RC	$	Reference cost
RP	1	Reference parameter
SC	$	Scaled cost
SP	1	Scaling parameter
T_{CO2}	$/t$CO_2$	CO_2 emission tax
W_P	kW_e	Power exported or imported
W_R	MW_e	Purchased renewable energy amount
η_C	1	Coal boiler efficiency
η_{FO}	1	Fuel oil boiler efficiency

industrial utility systems with the strategic use of thermal and electricity energy storages [3]. In the study of Wang et al. [4], the optimization of a steam turbine system was carried out for the combined use of geothermal energy, which is renewable energy, and a fossil-fuel based boiler, in which pinch analysis in a multi-period manner was applied for the time-dependent consideration of surplus and deficit of heat. The amount of power to be generated is then estimated, subject to the degree of steam superheating and the energy recovery from steam condensate as studied by Li et al. [5]. The main benefit of such graphic-based analysis is to provide conceptual insights for potentials of steam recovery and cogeneration through the visualization of site-wide steam use and generation.

Contrary to intuitive design methods using graphs, a mathematical framework is constructed and used in a computer-aided environment for the design and optimization of industrial site utility systems [6]. One of the main benefits from the mathematical approach is to accommodate part-load performances of unit operations, with which operational optimization can be systematically and realistically carried out. Varbanov et al. studied the minimization of fuel cost for the utility system and considered the part-load performance of steam turbines and gas turbines to increase the model accuracy [7]. A mixed-integer nonlinear programming (MINLP) model has been widely-used because most of thermodynamic behavior of steam and power generation is highly nonlinear and it is necessary to evaluate various design options related to the selection of units to be used and the distribution of stream between steam users [8]. Superstructure approach is effective to evaluate a large number of design options available and to determine the most appropriate network configuration for energy generation and distribution [9]. Optimization-based design methods can be also useful to systematically consider uncertainty related to operational decisions for site utility systems. For example, data-driven modeling can be used for optimization, which allows effective characterization of operational information for equipment and uncertainty related to energy management [10]. Karthik et al. [11] developed a mathematical algorithm for predicting the price of power produced from intermittent energy sources, in which renewable energy was characterized in the form of reserve cost to optimize operating costs. Their approach was rather limited because the economic impact of utility systems' configurations on operating costs was not fully considered. Such convenience and effectiveness in combinatorial decision-making via mathematical optimization may not be attractive when computational difficulties in building mathematical models and simulating a complex network configuration during optimization become high. Methodological hybridization is also possible by combining a mathematical method with a graphical method, for example, a graphical method can be used for the initial screening of design options or finding starting points for the rigorous optimization. On the other hand, computational difficulties can be reduced with the strategic use of a commercial simulator as presented by Lee et al. [12].

Reducing CO_2 emissions by 95% in the industrial sector in 2020 is the key way to cut carbon emissions and reach net zero by 2050 [13]. Carbon tax, also being considered as a part of Emission Trading System (ET), is one of the policies being made to reduce CO_2 emissions globally by undertaking the role of a legal regulation for carbon emissions through charging it as duty to businesses and consumers [14]. Grounded on the carbon pricing map in 2021, more than 33 countries where industrial emission exists are implementing the regulatory policies on carbon emissions [15]. Hence, the consideration of carbon tax on process industries should be systematically analyzed. However, due to the current characteristics of the carbon tax, the price is measured by the market circumstance, depending on the degree of CO_2 emissions and the intensity of environmental policy. This change in price causes a great uncertainty on energy management in process industries that mainly use fossil fuels. Therefore, carbon tax should be considered rigorously not only to minimize the operating cost, but also to fully recognize techno-economic impact on industrial energy management, subject to industrial electrification and environmental regulations. In the study of Chen et al. [16], the impact of carbon tax on energy supply chain is modeled and the price fluctuation of carbon emissions is investigated with the mathematical algorithm.

In parallel with spreading of enabling technologies for the 4th industrial revolution, traditional energy infrastructure is thoroughly transformed through new directions, such as the stable and sustainable supply of large amounts of electricity, the efficient use and management of energy, and the reduction of greenhouse gas emissions in the entire energy life cycle [17]. In order to respond to rapidly-changing energy industries and fulfill new sustainable initiatives, the introduction of electrification through renewable sources in the industrial sectors should be considered [18]. Electrified energy systems can be inherently flexible to be centralized or distributed, which allows easiness in the adaptation of electrified energy supply to different types of industrial energy systems and provides robustness in energy management under variations in energy demand [19].

Electrification with renewable energy is one of main ways for reducing greenhouse gas emissions for process industries. According to an article from IRENA, the electricity currently accounts for 19% of overall energy used in final demand, called total final energy used, today, which is expected to increase about 49% by 2050 and to use 86% of the electricity sourced from renewable energy [20]. With the recent technical development made in renewable energy sectors, the production cost of renewable energy is clearly and rapidly declining. This aspect is one of the important advantages for the transition to electrified industrial manufacturing. In particular, it is expected to have substantial development for wind and solar technologies and to be technically mature in 10 years' time [21]. As reported by IRENA, the levelized cost of electricity from solar photovoltaic technology is expected to be $0.04/kWh in 2022, which is about 10 times lower than $0.381/kWh in 2010 [21]. Along with this price advantage, the use of renewable energy has gradually increased over the past decade, from 8.7% in 2009 to 11.2% in 2019 [22]. This technological development with the increased usage of renewable energy is considerably related to global actions for climate changes and achieving carbon reduction goals. Therefore, it is necessary to adopt the integration of renewable energy to industrial utility systems in a holistic manner and to systematically identify the cost-effective strategy for improving the industrial uptake of renewable energy in process industries.

Under the electrified renewable energy systems, designing and optimizing the utility system is complex and sophisticated as different types of fuel are simultaneously used with non-constant consumption rate and there are a number of uncertain operating parameters. Therefore, as reviewed in the previous literature, various design methods were attempted to improve the optimization frameworks or to deal with design complexity more effectively.

However, the consideration of renewable energy in the optimization of utility systems based on fossil fuels has not been fully studied, together with the impact of carbon tax on utility management. Although the price of energy sources is constantly changing according to market conditions and environmental policies, how the price of energy sources affects the cost-effectiveness design of utility systems and the optimal selection of operational decisions for industrial energy production are not well understood under decarbonized and electrified energy mix. Until full and thorough transition to net-zero society, the combined use of renewable energy and fossil fuels are expected. It would be necessary to fill the knowledge gap for the most appropriate way of integrating renewable energy to the fossil-fuel based utility systems under different levels of renewable energy use and site-wide CO_2 tax.

On the other hand, various studies conducted for the optimization of industrial utility were carried out by fixing the cost of renewable energy or considering the time-dependent characteristic of renewable energy. However, it has not been fully investigated about how the change in renewable energy cost affects the fossil-fuel based utility system under variable carbon tax scenarios. In this study, it is analyzed through case studies to understand the techno-economic impact of the variation of renewable energy price and carbon tax on the site utility systems, with which the technical feasibility of the renewable-integrated utility systems is assessed and its economic implications are understood. The base case of the utility system studied in this work was taken from Varbanov et al. [7], which was modeled and simulated in a commercial simulator UNISIM® environment. The optimization framework is constructed to consider both the operating cost and capital investment of the site utility systems.

The main novelty of the current work from the viewpoint of methodology is to model and optimize industrial site utility systems with fully considering non-linear characteristics existing in steam and power generation and its system-wide interactions. The most of previous work reported in the optimization of site utility systems are typically based on a simplified energy balances of steam mains with fixed steam conditions or simplified linear models of steam or power generators in the utility systems, as a large number of units are interconnected and interacted. Hence, the optimization of industrial site utility systems is typically built with the application of deterministic optimization solvers, in which a considerable degree of simplification in the mathematical model is widely observed. This is mainly because of complexity in the computation related to the calculation of thermodynamic properties.

On the other hand, the use of process simulators was considered to accommodate nonlinear characteristics and design complexities for the modeling of utility systems because reliable and robust numerical calculation can be made. However, when the process simulator is employed, sensitivity analysis of key design variables is typically carried out and systematic determination of optimal values for variables are not often practiced. The external optimization solver, for example, MATLAB, is linked with process simulators, with which economic trade-off is evaluated and the most appropriate operating conditions are selected.

In this study, the optimization framework is constructed within the UNISIM® simulator environment, in which nonlinear energy balances are accurately modeled and simulated with rigorous application of thermodynamic properties. The optimization is carried out with an inbuilt solver available within the UNISIM® simulator, with which system-wide interactions between steam generation, distribution and utilization are rigorously considered during the optimization. The optimization is constructed such that rigorous economic trade-off between energy generation costs and the purchasing expenses for renewable energy, subject to CO_2 tax.

Process modeling and simulation of site utility systems is, first, given in the next section in which the process modeling and design basis are given and the integration of renewable energy to the utility system is explained. Then, the optimization framework with mathematical formulation is explained for how economic trade-off is examined, subject to the integration of renewable energy and the consideration of carbon tax. Finally, the case study is presented, which clearly demonstrates the benefit of the optimization framework developed in this study, and addresses techno-economic issues and impacts of renewable energy on the design and operation of site utility systems.

2. Modeling and simulation of utility systems subject to renewable energy integration

For the environmental improvement of the fossil fuel-based utility system, this study is intended to understand techno-economic impact of CO_2 emission tax and renewable energy integration to the conventional fossil-fuel based utility systems, with which practical guidance for the design and operation of site utility systems can be obtained under electrified environment in the future. The study conducted in this work follows procedures schematically illustrated in Fig. 1.

2.1. Design basis for process modeling

The site utility system considered in this work is based on Varbanov et al. in which coal, fuel oil and natural gas are burnt for steam and power generation [7]. This case was selected as three types of fossil fuels having different CO_2 emission factors are consumed, which allows the effective assessment of renewable energy integration for industrial utility systems.

The utility system consists of two boilers and a gas turbine integrated with a HRSG (Heat Recovery Steam Generator), which are employed for

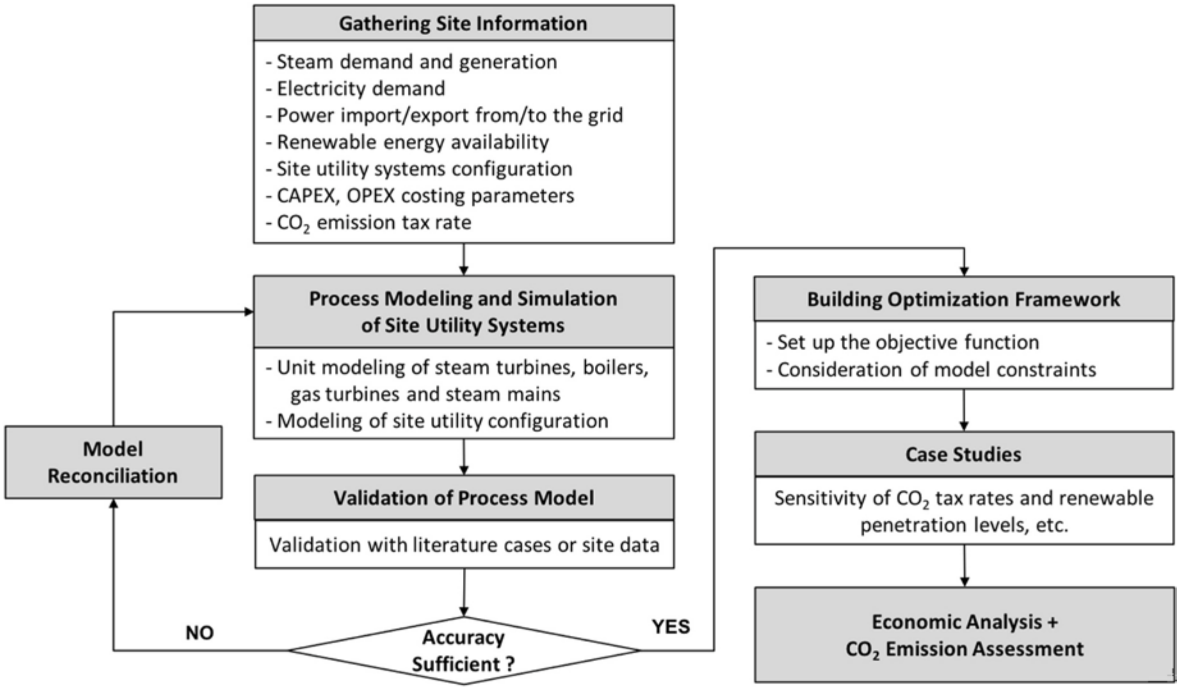


Fig. 1. A procedure for the case study of renewable-integrated site utility systems.

generating VHP (Very High Pressure) steam and meeting 68 MW_e of power demand for the site. Four steam headers are available and the VHP steam at 101 bar is produced from the BFW (boiler feed water) through a coal-fired boiler as well as a fuel-oil fired boiler, as shown in Fig. 2. LP steam after being expanded in the turbine is assumed to be condensed at 0.5 bar and the steam condensate is then recycled back to the BFW system. Process modeling of site utility systems is carried out in the UNISIM® environment.

Although steam turbines are utilized either to generate the power or to drive rotating machines, the base case presented in this paper is simplified without considering a driver option. As shown in Fig. 2, the utility system consists of four steam turbines which are utilized for the generation of power. T4 and T6 are the multiple pass-out turbines in which HP, MP, and LP steams are extracted in sequence. T5 and T7 are conventional back pressure turbines which have a single steam feed and exhaust. For the simulation of the multiple pass-out turbines, this complex turbine is decomposed with a series of back pressure turbines between VHP, HP and LP, which are used to estimate the power production [2]. The steam turbines are simulated with the ASME EOS (equation of state) available in UNISIM®. For the modeling of a boiler, a simplified model is used to calculate fuel duty required for the generation of VHP steam.

A gas turbine in this work uses natural gas as fuel, which has an advantage of eco-friendly power production over the steam turbine process. By following the Case B31A presented in the NETL report [23], a gas turbine system is modeled with a single shaft arrangement using a single compressor and a single turbine. Steam generation from a HRSG is modeled to produce VHP steam only, although multiple levels of steam can be produced. The gas turbine system is simulated using the Peng Robinson thermodynamic property packages of UNISIM® design, and

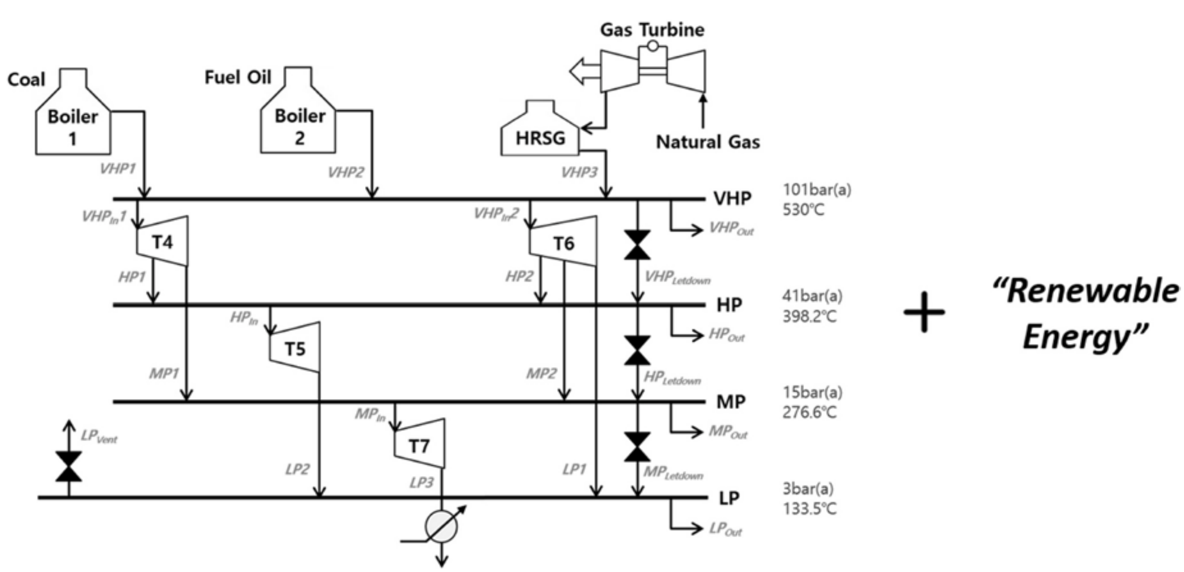


Fig. 2. The base case of a site utility system [7].

most of the operating conditions used for process modeling including the conditions of air and natural gas flowing into the gas turbine system refer to the NETL 2015 report [23].

Other process design basis and assumptions made in this work are as follows.

- Isentropic efficiency of a steam turbine = 85% [5].
- Polytropic efficiency of a gas turbine = 82.813% [23].
- Adiabatic efficiency of a compressor = 85% [23].
- Compressor pressure ratio of the air stream = 18.4 [23].
- Feed ratio of natural gas and air = 1:43.06 [23].
- Split ratio of reaction air and cooling air = 90.8:9.2 [23].
- Air is available at 25 °C and 101.3 kPa [23].
- Natural gas fuel is available at 37.78 °C and 3103 kPa [23].
- No pressure drop for unit operations and streams is considered.

Other than that, the operating conditions are the same as the design reported in reference [7].

2.2. Integration of renewable energy

Renewable energy is assumed to be purchased and supplied from outside the boundary of utility systems. Power balance is considered between power generation within the site utility systems and the import of renewable electricity, which is reflected in the objective function as an overall energy cost for process optimization to be described later. There is still a great uncertainty in the direct use of renewable electricity for the large-scale industrial processes and its system integration, because of intermittent and fluctuating energy production based on the utilization of renewable sources and its relevant difficulties for grid connection and energy storage.

Therefore, the current study aims to gain our understanding on how the existing utility systems should be operated with possible import of renewable electricity from external sources, under retrofitting scenarios. It is not aimed to carry out the new design of a renewable-integrated utility system, in which the integration of utility systems with renewable energy-generation systems is considered within the plant boundary. Consequently, this work did not conduct the mathematical modeling and simulation of renewable energy systems in detail, but considered the external renewable electricity from the grid to be imported to the fossil fuel-based utility system.

Clean electricity can be generated from various renewable sources, including solar, wind, hydro, tidal and biomass energy. And indirect CO_2 emissions may be emitted from the various stages of the life cycle of renewable energy production, for example, material extraction and its processing, and manufacturing of equipment and its disposal, etc. However, the direct CO_2 emissions from the generation of renewable energy is only considered in this study, which is assumed to be none. This is because the focus of this study is to investigate techno-economic impact of renewable energy integration for industrial utility systems through economic analysis, rather than to examine life-cycle CO_2 emissions and its environmental impacts.

The production cost for renewable electricity is very technology-specific and its trend over time is heavily fluctuating to a great extent, compared to that of fossil fuels, because its economics are heavily dependent on the surrounding environment and policy factors. Technologies for utilizing renewable energy sources have not been fully regarded as being mature at present and the considerable potential for price reduction is expected. Therefore, in the subsequent process optimization framework, the fixed cost of renewable electricity is first employed as a base scenario and then the unit cost of renewable electricity is varied from −10% to +10% through sensitivity analysis. The baseline cost for renewable electricity is taken as $67/MWh. This is the average purchasing price among fuel cell, solar, wind, hydro, bio and marine energy, which was reported in December 2020 by South Korea's Electric Power Statistics Information System [24].

In order to achieve energy-efficient design and cost-effective operation of industrial utility systems design, the design and optimization framework should be constructed in a holistic manner to systematically carry out economic trade-off between fuel and power generation subject to the usage of renewable electricity, as well as to rigorously screen design interactions among different steam generators and power generation units. Also, the integrated model for the utility systems is required to evaluate a wide range of steam flow paths available between boilers, gas turbines and steam turbines through steam mains, and to determine the optimal steam distribution within the utility plant. In the next section, the optimization framework conducted in this study is explained, which describes how design complexities are dealt with and cost minimization is carried out.

3. Process optimization of site utility systems

3.1. Optimization

The framework for the operational optimization of utility systems is constructed for the utility systems shown in Fig. 1 with the following objective function.

$$\textit{Objective Function}, f_{fuel_1,min} = C_C + C_{FO} + C_{NG} + C_P + C_W \tag{1}$$

$$where, C_C = P_C \frac{m_C\,(H_{VHP} - H_{BFW})}{\eta_C NHV_C} \tag{2}$$

$$C_{FO} = P_{FO} \frac{m_{FO}\,(H_{VHP} - H_{BFW})}{\eta_{FO} NHV_{FO}} \tag{3}$$

$$C_{NG} = P_{NG} m_{NG} \tag{4}$$

$$C_P = P_P W_P \tag{5}$$

$$C_W = P_W Q_{cond} \tag{6}$$

The optimization is formulated to minimize overall operating cost based on fuel usage, as given in Eq. (1). The objective function includes terms for the cost of fuels and cooling water as well as a term for the evaluation of economic impact through power import or export related to power generation. The objective function given in Eq. (1) is extended to consider capital cost together in the case study in the next section, which allows to investigate site-wide economic trade-off between capital investment and operating expenditure. Net heating values required for the calculation of fuel cost were taken from reference [7], while the efficiency for a coal and fuel oil boiler was set to be 88% as presented in the NETL 2015 report [23]. Other parameters or values to be used are presented in Table 1.

Because of multiple fuels and energy sources to be simultaneously considered, and complex steam and power balances exist for the modeling of utility systems, the optimization problem is inevitably highly non-linear. The optimization is carried out with a nonlinear solver of a mixed method available in the UNISIM design. The mixed method used in our study is based on the sequential approach for the

Table 1
Site configuration values for the base case.

Parameters	Symbol	Values
Boiler efficiency	1	0.88
Coal price	$/t	65
Fuel oil price	$/t	120
Natural gas price	$/t	220
Power price (Export)	$/kWh	0.05
Power price (Import)	$/kWh	0.06
Water price	$/kWh	0.005
Net heating value of coal	kJ/kg	28,000
Net heating value of fuel oil	kJ/kg	40,000
Net heating value of natural gas	kJ/kg	47,206

optimization, in which the BOX method is applied, first, to find a near-optimal solution under a very loose tolerance for the convergence and then the optimization with SQP (Sequential Quadratic Programming) method is rigorously made to determine the final solution [25]. This sequential solver is very effective for dealing with non-linear problems because computational difficulties in convergence can be effectively dealt with the BOX method and the reduction in computational times can be achieved with the SQP method [25]. The shift size, a weighting factor between the results of the previous iteration and the present one, is initially set to be a large value of 3 or more so that it can be approached to a certain extent to the final solution. After that, it is sequentially reduced to a value less than 1 until the converged solution is obtained, conforming to the tolerance criteria and mass balances of the system.

Starting values of flowrates for the optimization were set with values reported in the Varbanov et al. [7]. Variables to be optimized are given in Table 2, which also shows the upper and lower bounds employed during the optimization. Letdowns from each header and the vent stream from a LP main is assumed to be zero, which prevents any wastage of steam and maximizes the production of electricity from steam turbines, although these values can be relaxed for operability issues.

Equations from Eq. (7) to Eq. (17) represent the mass balance of the utility system, while Eq. (18) to Eq. (21) for the energy balances related to each steam turbine. Table 3 shows constraints to be considered for the optimization. The optimization model with the objective function given in Eq. (1) is constructed with equality constraints of Eq. (7) to Eq. (21) and inequality constraints expressed in Table 3.

$$VHP - VHP_{Out} - HP_{Out} - MP_{Out} - LP_{Out} - LP3 = 0 \tag{7}$$

$$VHP1 + VHP2 + VHP3 - VHP = 0 \tag{8}$$

$$VHP - VHP_{In}1 - VHP_{In}2 - VHP_{Out} - VHP_{Letdown} = 0 \tag{9}$$

$$VHP_{In}1 - HP1 - MP1 = 0 \tag*{(Eq.10)}$$

$$VHP_{In}2 - HP2 - MP2 - LP1 = 0 \tag{11}$$

$$HP1 + HP2 + VHP_{Letdown} - HP = 0 \tag{12}$$

$$HP - HP_{In} - HP_{Out} - HP_{Letdown} = 0 \tag{13}$$

$$MP1 + MP2 + HP_{Letdown} - MP = 0 \tag{14}$$

Table 2
Optimization variables and their upper and lower bounds.

Variables [t/h]	Low bound	Upper bound
VHP1	50.0	250.0
VHP2	40.0	180.0
VHP3	0.0	70.0
$VHP_{In}1$	60.0	165.0
$VHP_{In}2$	115.0	335.0
VHP_{Out}	20.0	20.0
$VHP_{Letdown}$	0.0	0.0
Natural gas feeds stream for the gas turbine	0.0	15.0
HP1	15.0	75.0
HP2	15.0	65.0
HP_{Out}	54.5	54.5
$HP_{Letdown}$	0.0	0.0
MP1	30.0	90.0
MP2	30.0	70.0
MP_{Out}	55.9	55.9
$MP_{Letdown}$	0.0	0.0
LP1	60.0	150.0
LP2	0.0	90.0
LP3	40.0	75.0
LP_{Out}	128.0	128.0
$LP_{Letdown}$	0.0	0.0

Table 3
Inequality constraints for the optimization.

Variables	Constraints
Site power demand	Min. Power demand for the site is 68 MW_e.
HP1	Min. Steam flowrate is 15 t/h.
MP2	Min. Steam flowrate is 30 t/h.
LP2, $VHP_{Letdown}$, $HP_{Letdown}$ $MP_{Letdown}$, LP_{Vent}	The steam flowrate cannot be negative.

$$MP - MP_{In} - MP_{Out} - MP_{Letdown} = 0 \tag{15}$$

$$LP1 + LP2 + LP3 + MP_{Letdown} - LP = 0 \tag{16}$$

$$LP - LP3 - LP_{Out} - LP_{Vent} = 0 \tag{17}$$

$$VHP_{In}1(H_{VHP_{In}1}) - HP1(H_{HP1}) - MP1(H_{MP1}) - Q_{T4} = 0 \tag{18}$$

$$HP_{In}(H_{HP_{In}}) - LP2(H_{LP2}) - Q_{T5} = 0 \tag{19}$$

$$VHP_{In}2(H_{VHP_{In}2}) - HP2(H_{HP2}) - MP2(H_{MP2}) - LP1(H_{LP1}) - Q_{T6} = 0 \tag{20}$$

$$MP_{In}(H_{MP_{In}}) - LP3(H_{LP3}) - Q_{T7} = 0 \tag{21}$$

3.2. Validation of process modeling

The base case presented in this work is a non-optimized one, which was built with the application of modeling parameters extracted or estimated from the original case presented in the reference. For the validation of the proposed process modeling and simulation of utility systems, the optimized case is carried out with the minimization of overall operating costs, subject to the same site-wide power demand of 68 MW_e and the fixed working load of 18 MW_e production from the gas turbine. The optimized results from the current study are compared with the optimized one presented in the original reference [7], as shown in Fig. 3, in which the steam balances, the amount of power generated from steam turbines and the objective function values are compared. According to the results from Table 4, the power generation of the system in this study agrees well with the power demand from reference. And the total operating cost of the system that fulfills the power demand, 68 MW_e, is calculated as 31.45 MM$/y, which is less than 1% different from the reference value of 31.47 MM$/y. This validation demonstrates the applicability and suitability of the modeling and optimization framework developed in this study, with which system-wide characteristics and design interactions for the utility system can be adequately investigated further.

It should be noted that there is a certain degree of differences in steam distribution between steam turbines and steam headers. Such difference is related to the combinatorial nature in the selection of decision variables during the optimization, in which changes in steam flowrate and its split ratio among turbines and headers are screened and the most appropriate one should be selected. Also, the optimization solver used in this study is based on a deterministic approach, which may not guarantee the global optimality of the solution identified. This leads to different steam distribution of the utility systems, although the minimum cost identified from the optimization is more or less the same.

4. Case study

The optimization model validated in the previous section is applied to the case study in which four cases having different objectives are considered. Case 1 is to minimize overall fuel cost with the objective function given in Eq. (1). Case 2 is the optimization additionally considering impact of CO_2 emissions, while the introduction of renewable energy to the utility systems is considered in Case 3. The capital investment is simultaneously considered with fuel cost in Case 4. The

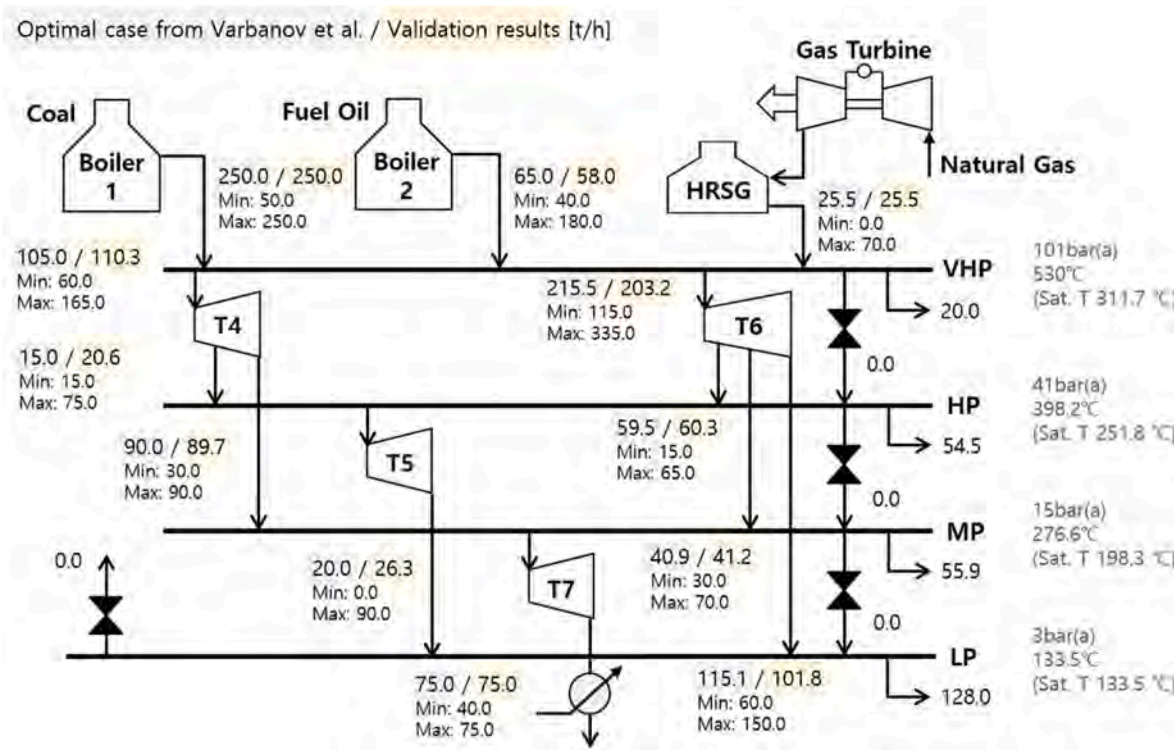


Fig. 3. Model validation for the utility system.

Table 4
Results of model validation and the case study.

	Reference Case	Validation Case	Case Study			
			Case 1	Case 2	Case 3[a]	Case 4*
Power [MW_e]						
T4	11.95	12.30	8.97	10.28	10.33	10.33
T5	2.61	2.61	0.0	4.14	4.37	4.37
T6	31.31	29.57	31.27	25.75	25.46	25.35
T7	5.52	5.52	2.95	2.96	2.95	2.95
Gas turbine	18.00	18.00	24.82	24.89	4.89	4.89
Power imported (+) or exported (−)	+1.39	0.00	0.00	0.00	+20.00	+20.11
Total	68.00	68.00	68.00	68.00	68.00	68.00
VHP steam production [t/h]						
Coal boiler	250.0	250.0	223.2	223.1	250.0	248.6
Fuel oil boiler	65.0	57.9	40.0	40.0	41.5	41.9
HRSG	25.5	25.5	35.2	35.3	6.9	6.9
Total	340.5	333.4	298.4	298.4	298.4	297.4
Cost [MM$/y]						
Fuel	30.87	31.45	29.68	29.70	23.95	23.89
CO_2 emission tax[b]	(17.50)	(17.05)	(15.70)	15.47	15.27	15.22
Power imported	−0.61	0.00	0.00	0.00	11.74	11.80
Total OPEX	31.47	31.45	29.68	45.17	50.96	50.92
Total CAPEX[b]	(16.2)	(15.99)	(15.08)	(14.89)	(13.79)	13.75

[a] Cases are based on 20 MW_e import of renewable electricity.
[b] The values given in the parenthesis are not included in the objective function.

objective functions applied to each case are provided subsequently along with a detailed description of different cases considered. The CO_2 tax is calculated with the application of CO_2 emission factors for fuels, while the renewable electricity is assumed to be purchased, rather than generated on the site. The results of the entire case studies are summarized in Table 4. For the information of Cases 3 and 4 from Table 4, electricity supplied from the renewable energy system to the site is assumed to be 20 MW_e.

4.1. Case 1: OPEX optimization based on fuel cost

The first case study of optimization for a utility system is to minimize operating cost based on fuel cost. Unlike the validation case, Case 1 is optimized without specifying the power production from the gas turbine. Optimization results based on the objective function of Eq. (1) are presented in Fig. 4. Under the same site power demand, overall VHP steam supplied from the boilers and HRSG in Case 1 is 298.4 t/h, which is decreased by 10.5% compared to the validation case. 43.19 MW_e of power overall was produced from steam turbines, while 24.82 MW_e was produced from the gas turbine. Accordingly, the fuel cost also decreased

Table 5
Scaling parameters for the capital costing of equipment [23,26].

Equipment	Coal boiler	Gas turbine	HRSG	Steam turbine
SP	Feed rate [lb/h]	Fuel gas flow [acfm]	Duty [MMBtu/h]	Turbine capacity [kW]
RP [1]	412,005	2234	1910	219,000
RC [$]	251,841	112,370	44,190	66,644
EXP [1]	0.69	0.6	0.7	0.8

Scaling parameters for the capital costing of equipment is given in Table 5, which are based on NETL 2015 report [23], while scaling parameters of fuel oil boilers are based on EPA 1978 report [26]. For the annualization, 30 years of plant life time and 12% of an interest rate are taken [27].

by 5% compared to the validation case. This result is related to higher efficiency in power generation from the gas turbine, compared to that of steam turbines although the fuel cost of natural gas is higher than that of fuel oil and coal. As a result, the power output of the gas turbine system increased by 38% and that of the steam turbine system decreased by 14% from the optimization.

4.2. Case 2: OPEX optimization considering CO_2 emissions

Combustion of fossil fuels in boilers and a gas turbine results in CO_2 emissions, and these greenhouse gas emissions cause global warming. Contrary to Case 1 in which only fuel cost is considered in the objective function, CO_2 emission tax is added to the objective function for Case 2 as given in Eq. (22). CO_2 emission factors used for the case study are 205.8 lb CO_2/MMBtu for coal, 161.3 lb CO_2/MMBtu for fuel oil and 117.0 lb CO_2/MMBtu for natural gas [28] and the relative difference in CO_2 emissions for fuels and its cost is exploited in the optimization. \$20/tCO_2 for CO_2 emission tax is considered in this case [29].

$$Objective\ Function, f_{min} = f_{fuel_1,min} + f_{CO_2\ emission,min} \tag{22}$$

$$where, f_{CO_2\ emission,min} = T_{CO_2}(E_C + E_{FO} + E_{NG}) \tag{23}$$

$$E_C = cm_C NHV_C \frac{m_C(H_{VHP} - H_{BFW})}{\eta_C NHV_C} \tag{24}$$

$$E_{FO} = cm_{FO} NHV_{FO} \frac{m_{FO}(H_{VHP} - H_{BFW})}{\eta_{FO} NHV_{FO}} \tag{25}$$

$$E_{NG} = cm_{NG} NHV_{NG} m_{NG} \tag{26}$$

For the net heating value of natural gas needed to calculate CO_2 emission cost from natural gas, a lower heating value provided in the UNISIM was used, as given in Table 1. The optimization results for Case 2 are presented in Fig. 5. The VHP steam production and overall power production between Cases 1 and 2 are almost the same, although the distribution of steam between steam turbines and headers are different.

Compared to the validation case, the optimization results of Case 2 have 1.75 MM\$/y saving on fuel cost and 1.58 MM\$/y saving on CO_2 emission cost. Although natural gas is more expensive than other fossil fuels, economic benefits through CO_2 tax can be gained from the lower amount of CO_2 emissions. Economic trade-off between the fuel cost and CO_2 emission cost results in the increase of natural gas consumption, although there is no significant difference in fuel cost between Case 1 and Case 2. This further implies that the contribution from CO_2 emission tax is the most important factor for the optimization in Case 2.

4.3. Case 3: OPEX optimization subject to renewable electricity integration

Case 3. investigates the economic impact on operating cost and the design of utility systems when some of the power demand for the site is met with renewable electricity. The objective function considered for Case 3 is presented in Eq. (27).

$$Objective\ Function, f_{min} = f_{fuel_2,min} + f_{CO_2\ emission,min} \tag{27}$$

$$where, f_{fuel_2,min} = C_C + C_{FO} + C_{NG} + C_R + C_W \tag{28}$$

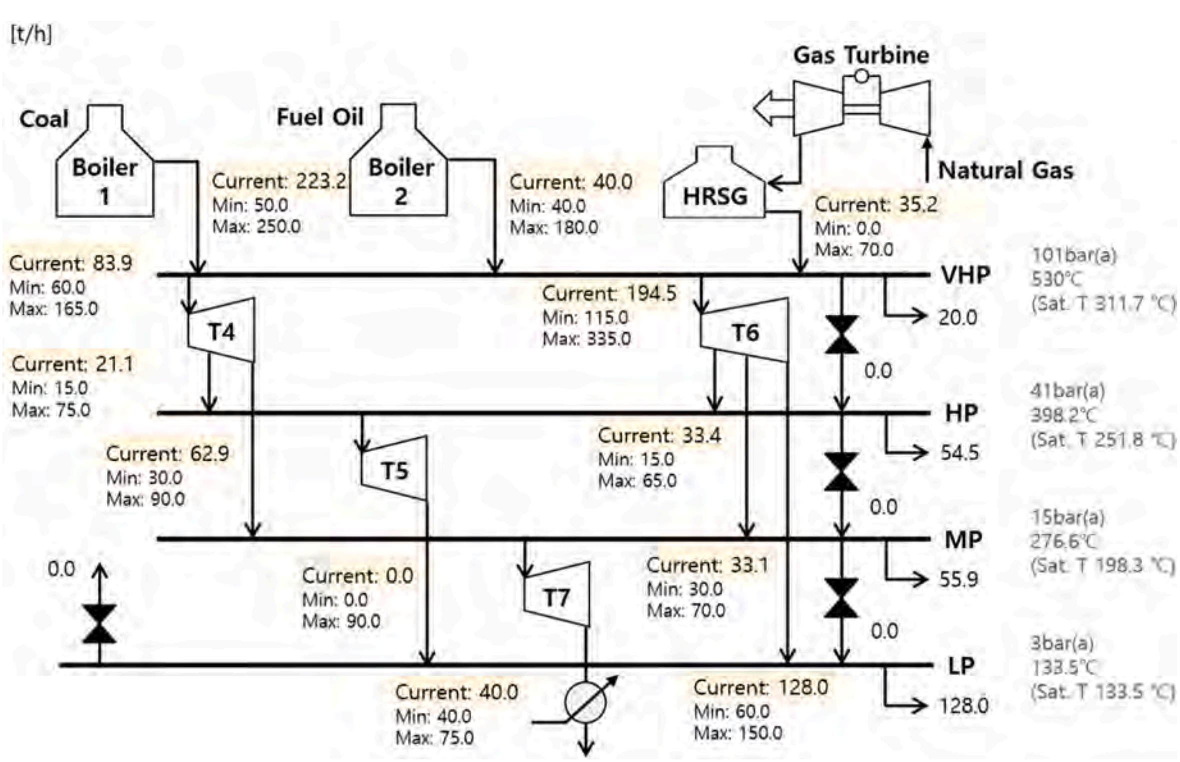


Fig. 4. Optimization results for Case 1.

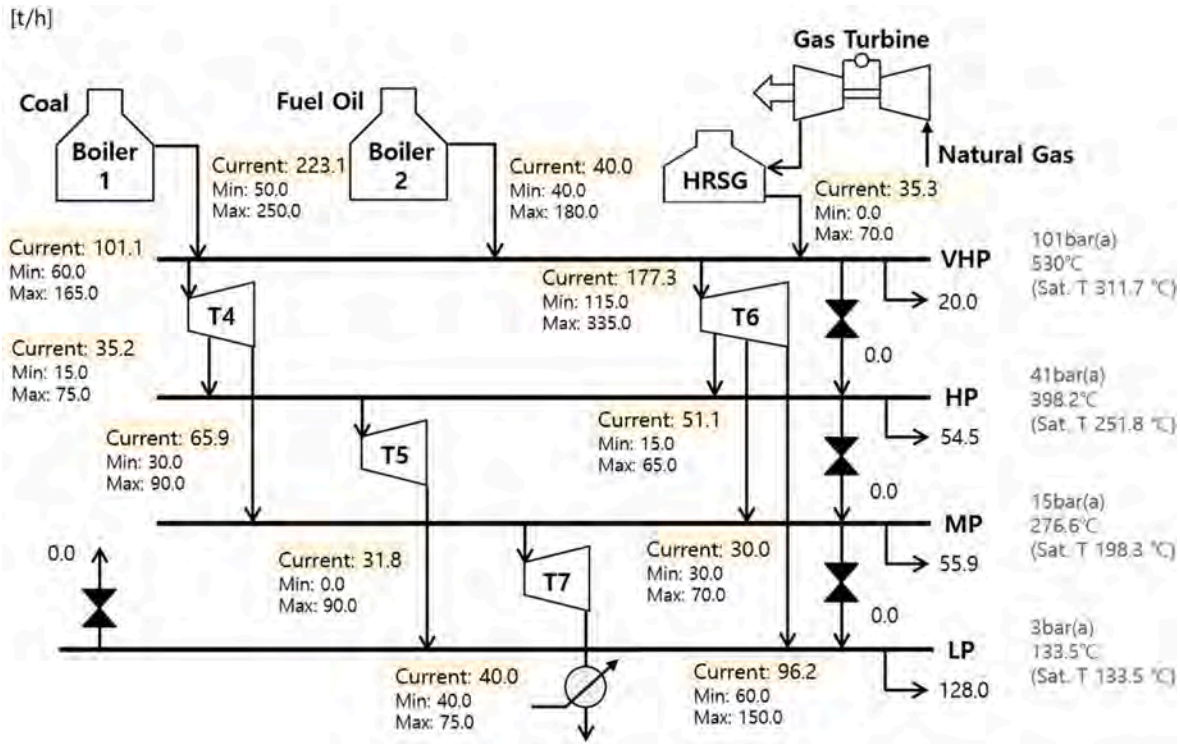


Fig. 5. Optimization results for Case 2.

$$C_R = P_R W_P \tag{29}$$

The objective function of Case 2, $f_{fuel_1,min}$, in Eq. (22) is updated to $f_{fuel_2,min}$ for Case 3 as the purchase and/or sale of the power (C_P) is replaced with the cost of purchasing renewable electricity (C_R). As no CO_2 emissions are assumed for the usage of renewable energy in this study, a cost term related to CO_2 emission tax is the same with Case 2. For Case 3, it is considered to supply some portion of 68 MW_e power demand with external renewable electricity. Due to steam demand from downstream processes, a certain amount of steam must be generated, which is, then, used for power generation within the utility systems. When the supply of renewable electricity exceeds 35 MW_e, the steam demand cannot be met from utility systems in the current utility systems. Therefore, the range of renewable energy to be introduced is set from 0 MW_e to 35 MW_e, and the optimization is carried out with 5 MW_e intervals for the case study. For the purpose of comparison, 68 MW_e import of renewable electricity is considered. Sensitivity analysis is further carried out to understand the impact of CO_2 emissions tax and renewable energy cost on the operational optimization of the utility system. \$30/tCO_2 of the CO_2 emission tax, which is 1.5 times higher than the base cost of \$20/tCO_2, is considered, while additional four levels of renewable energy cost with −10%, −5%, +5%, and +10% of basis cost \$67/MWh, are studied.

The results of optimization and sensitivity analysis are shown in Fig. 6, in which the x-axis represents the amount of power produced by fossil fuels in the utility system and the y-axis is the operating cost. The base case is represented with a dotted circle in Fig. 6, which is the optimal result without using any external renewable electricity import. The cases, in which all the power demand of the system is satisfied with the renewable energy (i.e. 0 value for the x-axis in Fig. 6), showed lower than the base case, except for the case of \$80.4/MWh of renewable energy cost, when the CO_2 emission tax is \$20/tCO_2. This implies that there are additional rooms available for improving the economics of the utility system through the import of renewable electricity over 35 MW_e from the renewable energy system. Even with the current levels of renewable energy cost, it is possible to operate the utility system cheaper than that using fossil fuels only. Further technology advances in renewable sectors, leading to reduction in the price of renewable energy, together with tougher regulations being imposed on greenhouse gas emissions, would provide considerable potential for improving economics of utility systems through renewable integration.

4.4. *Case 4: consideration of both capital and operating costs for the optimization*

In Case 4, economic assessment is made by setting the objective function which additionally considers the capital cost of the utility system, while Cases 1 to 3 only consider the operating cost. As the renewable energy in this work is assumed to purchase electricity from external sources, the capital cost for the fossil fuel-based utility system is only evaluated. The evaluation of capital cost in this study is based on BEC (bare erected cost) level for process equipment, which is based on the multiple-parameter scaling method of Yun et al. [27].

$$\text{Objective Function}, f_{min} = f_{fuel_2,min} + f_{CO_2\ emission,min} + f_{BEC,min} \tag{30}$$

$$f_{BEC,min} = \sum_i SC_i AF_i \tag{31}$$

$$SC = RC_i \left(\frac{SP_i}{RP_i}\right)^{EXP} \tag{32}$$

$$AF = \frac{IR(1+IR)^n}{(1+IR)^n - 1} \tag{33}$$

The optimization results of Case 4 are presented in Fig. 7. Fig. 7(a) shows the change in operating cost, capital cost, and total cost under \$20/tCO_2 of CO_2 emission tax when the amount of power import from renewable electricity is varied with the cost range of \$53.6/MWh and \$80.4/MWh. As the power imported from renewable energy increases from 0 MW_e to 20 MW_e, the electricity generated from the gas turbine and the steam turbine is not necessary, so operating cost related to fuel consumptions and CO_2 emission tax is minimized. For this reason, the

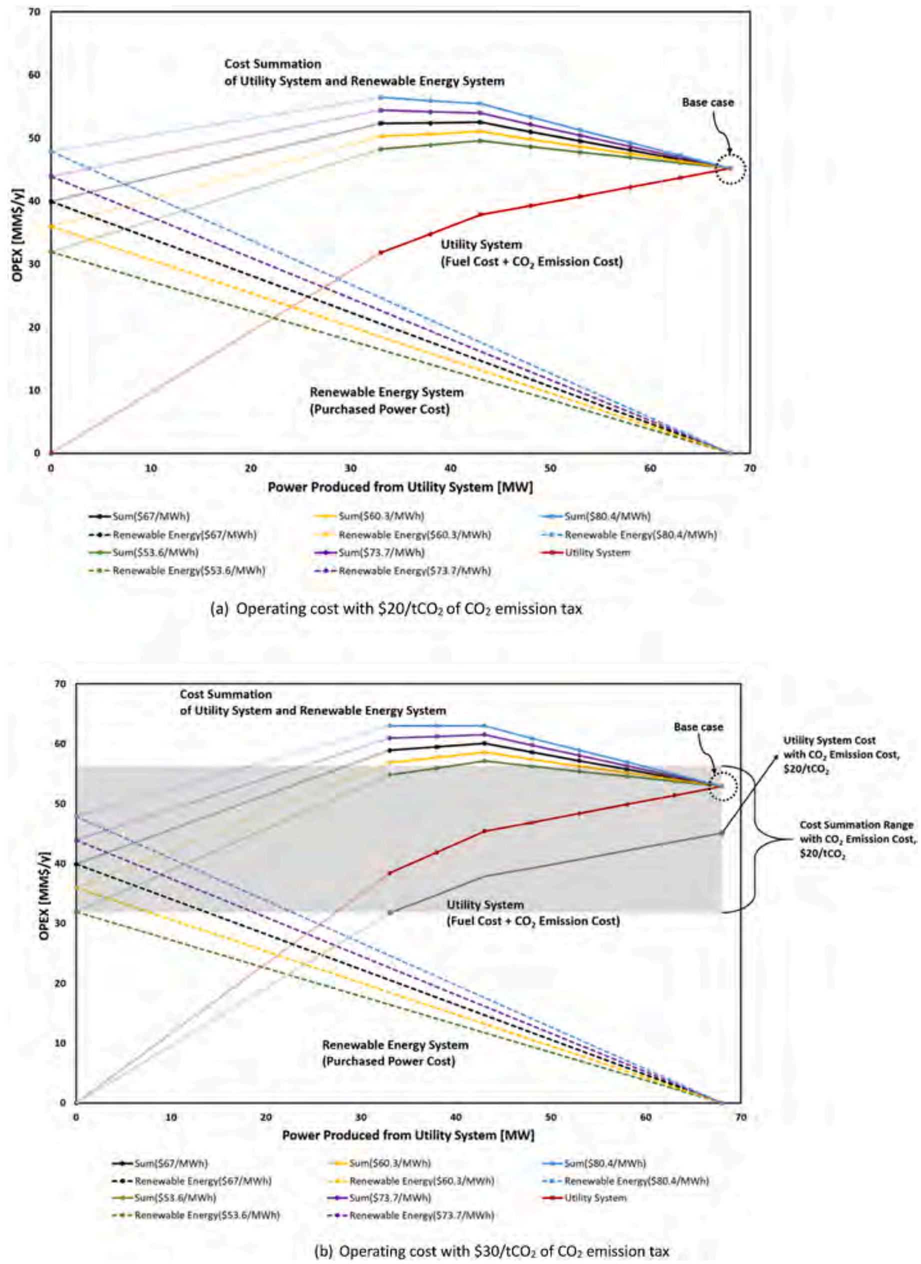


Fig. 6. Results of sensitivity analysis for Case 3.

more renewable energy imports, the less fuel consumption. However, due to the trade-off between the decrease in CAPEX and the increase in OPEX, the degree of changes in total cost is relatively small, compared to other cases.

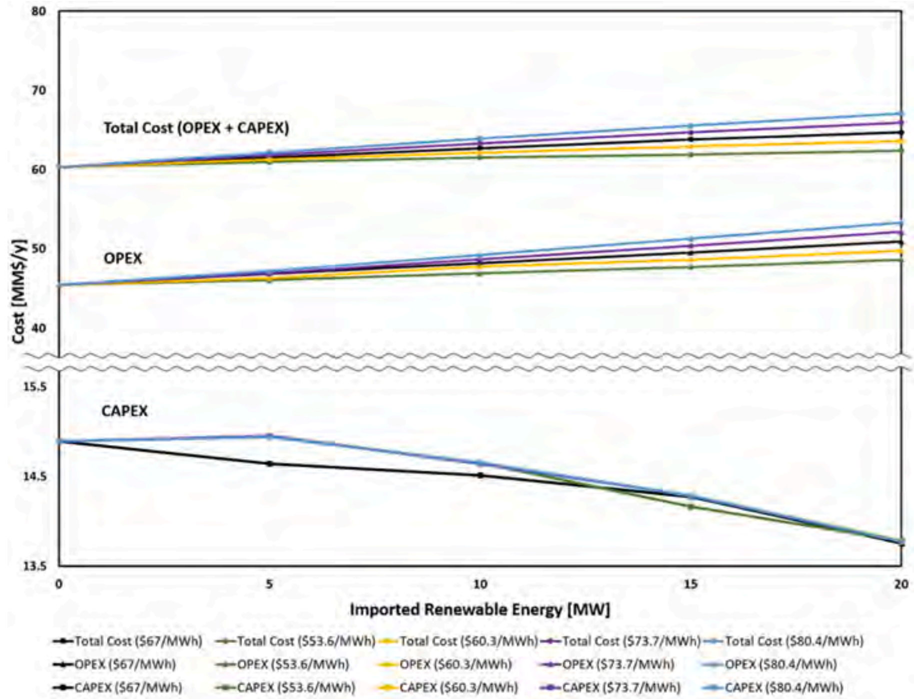
The sensitivity of CO_2 emission tax on the total cost is evaluated with the variation of CO_2 tax from \$ 10 to \$ 50. Total cost, which is the summation of CAPEX and OPEX, increases with the CO_2 emission tax as given in Fig. 7(c). Also, when the purchase price of renewable electricity is varied, a similar degree of variation in the total cost, subject to the amount of imported renewables. As shown in Case 3 and Case 4, when 20 MW_e of renewable energy among the total energy demand of 68 MW_e is imported, the decrease in CAPEX is not sufficient to compensate for the considerable increase in OPEX, resulting in a rise of total cost. On the other hand, if renewable energy over 20 MW_e were introduced, both CAPEX and OPEX would be reduced. The cost reduction in the CAPEX of utility systems is related to the increase in the supply from renewable energy, as discussed with Case 4. The cost reduction in the OPEX results mainly from economic gains of less CO_2 emitted as explained in Case 3.

From Case 3, it was observed that the profiles of operating cost steadily increase with the degree of renewable electricity integration. For Case 4, the capital cost of utility systems is minimized when 20 MW_e of renewable electricity is imported, due to economies of scale. Accordingly, further reduction in total cost is feasible when the contribution of renewable electricity imports is bigger than that of power generated through the combustion of fossil fuels.

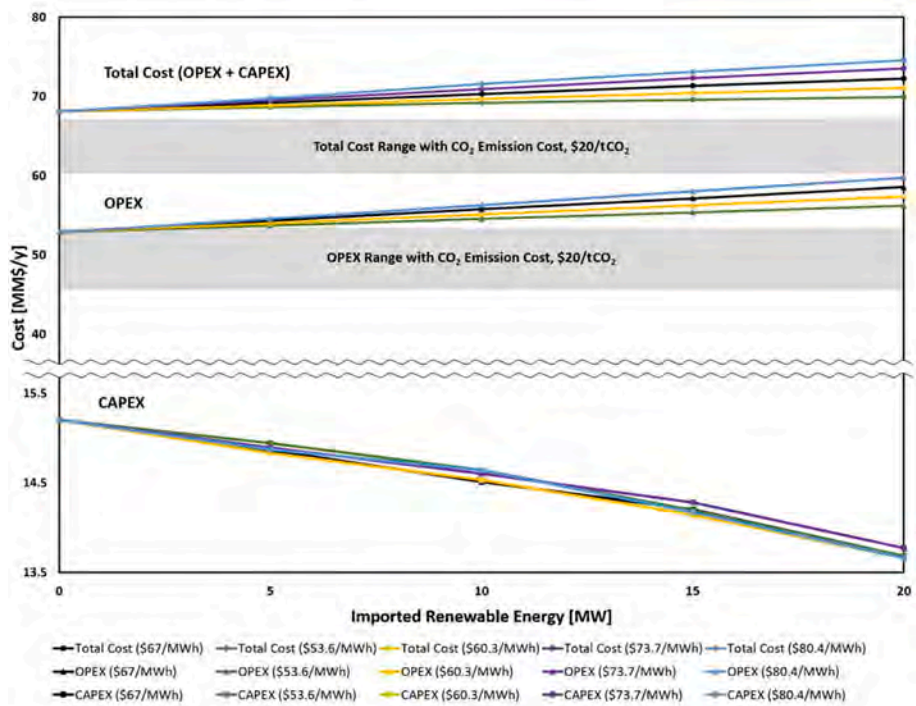
5. Conclusion

Considerable attention is being paid to the environmental impact associated with CO_2 generated by the usage of fossil fuels, which led to the introduction of legislations for regulating the combustion of fossil fuels. As fossil fuels are currently a main energy source for industrial utility systems, focus on this study is made to investigate renewable energy integration to the conventional steam and power generation.

The environmental impact of the utility system is interpreted with the accounting of CO_2 tax, which is then incorporated into economic



(a) Overall cost with $20/tCO$_2$ of CO_2 emission tax

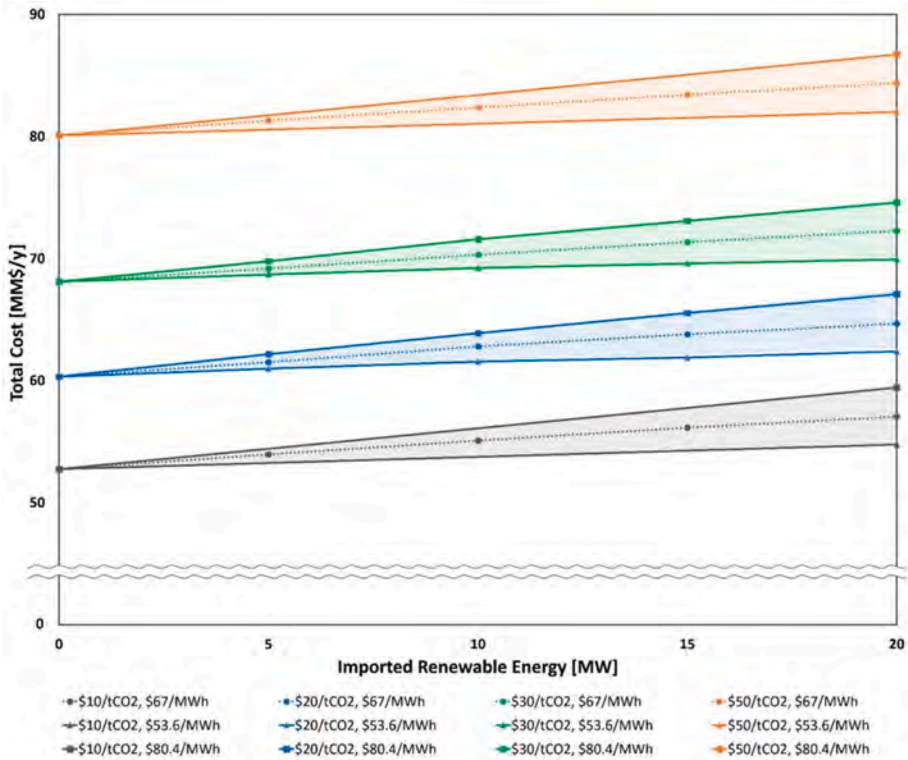


(b) Overall cost with $30/tCO$_2$ of CO_2 emission tax

Fig. 7. Results of sensitivity analysis for Case 4.

values in terms of operating cost and capital investment. The techno-economic impact of renewable energy integration is studied by building a process model of utility systems with the simulator, which is then optimized to find the most economic operating conditions, subject to design constraints. The optimization framework developed in this work was applied to four different cases, with which conceptual insights related to the integration of renewable electricity to the industrial site are gained.

As the import of renewable energy to the industrial site is systematically considered subject to CO_2 emission tax, the study conducted contributes to the knowledge for the realization of carbon neutrality for industrial heat and power systems as well as provides operational



(c) Sensitivity of overall cost subject to different CO_2 emission tax

Fig. 7. (*continued*).

guidelines for improving economics in site-wide energy management under the transition of fossil fuel-based system to electrified system. The sensitivity analysis by changing the CO_2 emission tax and renewable energy cost was performed, which also enhances our understanding on the impact of environmental regulations and the possible price fluctuation in renewable energy on the design and operation of site utility systems. With the model proposed in this study, we are able to predict the trend of cost change related to energy production, under variation in renewable energy cost and practical limitations in confidence.

Over 10% of reduction in fossil fuel consumption, compared to the base case, is achieved through the optimization framework, which demonstrates the importance in selecting the most appropriate operating conditions for site utility systems. In Case 2, 35 t/h of VHP steam production can be further saved, compared to the design suggested from Varbanov et al. [7], which was enabled through operational optimization of steam generation and its distribution, simultaneously considering the CO_2 emission tax.

Regardless of the cost of electricity from renewable energy systems, the most economic scenario in Case 4 was found when no renewable energy is imported. From Case 3, when the renewable electricity cost is varied and the site-wide overall electricity demand is met with renewable energy only, the minimum operating cost is found to be 43.9 MM $/y, which achieves 3% reduction, compared to that of the case under no import of renewable electricity. The minimum operating cost of 43.9 MM$/y for Case 3 is obtained under the purchase price of $73.7/MWh for renewable electricity, although this purchase price is much higher than the present value.

Also, when the price of renewable energy is reduced by 10% i.e. $53.6/MWh, the operating cost of the system can be reduced by about 30%. Therefore, the overall operating cost of the utility system decreases with the degree of electricity import from renewable sources. This reduction further increases, and the maximum reduction is observed at the CO_2 emission tax of $30/t$CO_2$. Hence, the tougher regulation for the CO_2 emissions as well as the further reduction in the cost of renewable electricity generation, the higher competitiveness for the implementation of renewable energy with conventional industrial utility systems.

Credit author statement

Haryn Park: Conceptualization, Methodology, Investigation, Validation, Software, Writing- Original draft preparation. Jin-Kuk Kim: Methodology, Investigation, Validation, Writing-Reviewing and Editing. Sung Chul Yi: Conceptualization, Supervision, Validation, Writing-Reviewing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data used in the study are included in the manuscript.

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