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Thermo-environ-economic modeling and optimization of an integrated wastewater treatment plant with a combined heat and power generation system

Seungchul Lee [1], Iman Janghorban Esfahani [1], Pouya Ifaei, Wladimir Moya, ChangKyoo Yoo *

Dept. of Environmental Science and Engineering, College of Engineering, Center for Environmental Studies, Kyung Hee University, Seocheon-dong 1, Giheung-gu, Yongin-Si, Gyeonggi-Do 446-701, Republic of Korea

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ABSTRACT

This study proposes an optimal design method for maximizing the sustainability of an integrated wastewater treatment plant with a combined heat and power generation system. The proposed system is analyzed based on thermo-environ-economic analysis to investigate the effects of the components' efficiencies, temperature differences in the heat exchangers, and pressure ratio of the compressor and gas turbine. The multi-objective genetic algorithm is used to minimize the thermoeconomic and environmental objective functions, which are assumed as the total cost rate and total environmental impact obtained from exergy, annual cost rate, and life-cycle assessment analyses. The optimization results showed that the total cost rate and environmental impacts are decreased by 16.9% and 5.3%, respectively. The power generated by the optimized system can cover 47% of the power demand of wastewater treatment plant as well as the total heat requirement of the system.

1. Introduction

The relationship between water and energy is referred as "water-energy nexus" that has been focused by the scarcities of water and energy due to the climate changes, population increase and urbanization [1]. A huge amount of water is used in all phases of energy generation processes such as extracting primary energy, refining the fuel, and generating electricity [2]. Likewise, potable water for human use requires a lot of energy while extracting and treating raw water, distributing the treated water, collecting wastewater and treating the wastewater prior to discharging to the environment (Fig. 1) [3].

Some problems related to the water-energy nexus also occur in wastewater treatment plants (WWTPs). The environmental standards regarding the effluent discharge of WWTPs is strict because of population growth, urbanization, and the growth of environmental concerns [4]. To satisfy the enforced effluent standards, WWTPs have tried to implement monitoring and control systems [5] or replace old treatment process with advanced treatment processes [6]. However, these efforts increase energy consumption and material usage [7]. For example, if aerobic reactors aeration rate increases to reduce ammonia concentration in effluent, electricity consumption of aeration pump, which is one of the dominant energy users in WWTPs is increased as well [8]. Consequently, more energy should be consumed for better quality of effluent in WWTPs. For solving the water-energy nexus problem in WWTPs, the combined heat and power (CHP) system fueled by biogas generated from anaerobic digestion (AD) process in WWTPs has been proposed as a solution between several technical solutions such as water saving, improving efficiency in water operation and using the resources of the wastewater [9]. Anaerobic digestion is a contradictory process from an energy standpoint because the AD demands a large amount of energy for heating, pumping, and mixing sludge. On the other hand, it can generate methane-rich biogas as a renewable energy source for other processes. For this reason, many researches have attempted to integrate WWTPs and CHP systems with AD (WWTP-CHP-AD). The hybrid renewable energy system configuration was studied by integrating AD, microturbine, fuel cell, wind turbine, and photovoltaic system to develop an energy self-sustainable WWTP in EGYPT [10]. A procedure was proposed to develop a novel WWTP configuration for satisfying high energy demand and nutrient recovery efficiency increase based on the mass balance models under steady state condition. According to the study, 0.24 kW h/m^3 of net energy was generated, 80% of phosphorus in influent was recovered, and 35% of CO_2 emission was reduced compared to the conventional activated sludge

* Corresponding author.
E-mail address: ckyoo@khu.ac.kr (C. Yoo).
[1] The first and second authors have identical collaboration in this research paper.

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Nomenclature

A	area (m^2)
AC	air compressor
ACC	annual capital cost ($/yr)
AD	anaerobic digestion
AFCR	annual fixed charge rate (%)
AOC	annual operating cost ($/yr)
$\dot{B}$	environmental impacts (pts/s)
b	average environmental impacts (pts/kJ)
$\dot{C}$	cost rate ($/s)
CC	combustion chamber
CHP	combined heat and power
CI	cost index
C_P	specific heat capacity (kJ/kg K)
C_{pg}	specific heat capacity of flue gas (kJ/kg K)
cc	cost coefficient
cf	cost factor
$\dot{Ex}$	exergy (kJ)
ex	specific exergy (kJ/kg)
f	exergy factor
H	heat demand (kJ/s)
HRSG	heat recovery steam generator
HX	heat exchanger
h	enthalpy (kJ/kg)
LCA	life-cycle assessment
MGT	micro gas turbine
MOGA	multi-objective genetic algorithm
$\dot{m}$	mass flowrate (kg/s)
N	operating hours at nominal load (h)
N_e	the number of auxiliary equations
n	the number of constituents in the mixture
P	pressure (kPa)
PEC	purchased equipment cost ($)
PH	pre-heater
R	gas constant
r	relative difference
SPECO	specific exergy cost
s	specific entropy (kJ/kgK)
T	temperature (K)
TAC	total annual cost ($/yr)
TIC	total investment cost factor
t	time (day)
U	heat transfer coefficient (kW/m^2 K)
V	volume (m^3)
$\dot{W}$	power (kJ/s)
w	mass fraction
WWTP	wastewater treatment plant
x	mole fraction
Y	exergy ratio
$\dot{Y}$	capital environmental impact (pts/s)
yr	year
$\dot{Z}$	capital cost rate ($/s)

Superscripts

CI	capital investment
cold	cold stream
hot	hot stream
OM	operating and maintenance

Subscripts

AD	anaerobic digestion
a	air
biogas	methane-rich biogas
ch	chemical
CH_4	methane
D	destruction
F	fuel
g	flue gas
hrsg	cost coefficient of heat recovery steam generator
in	inlet stream
k	component
L	loss
m	material
mix	mixture
O	oxygen
out	outlet stream
P	product
ph	physical
R	reference
ref	standard condition

Greek

ΔT	temperature difference (K)
ΔP	pressure difference
η	efficiency (%)
γ	heat capacity ratio
Φ	maintenance/operating factor
ε	exergy efficiency (%)

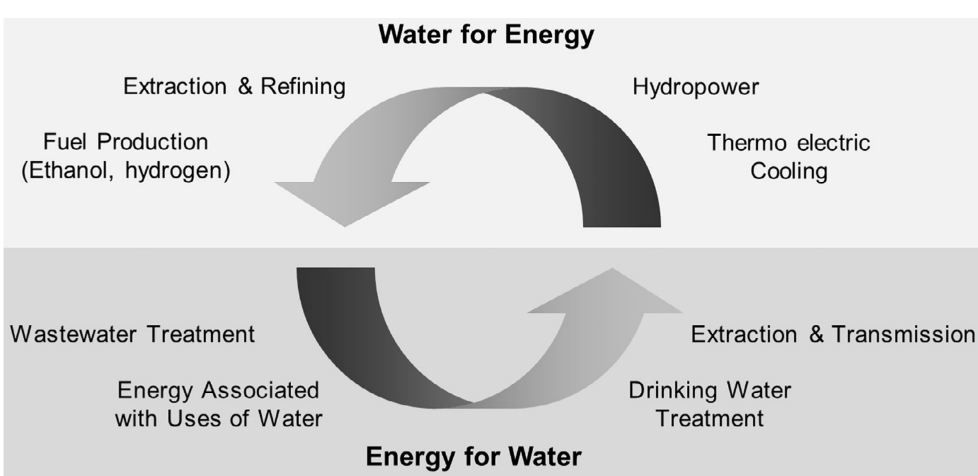

Fig. 1. Relationship between water and energy [3].