Energy 64 (2014) 719–733

Contents lists available at ScienceDirect

Energy

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

Optimal structural design of residential cogeneration systems in consideration of their operating restrictions

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ARTICLE INFO

Article history:
Received 29 May 2013
Received in revised form
22 August 2013
Accepted 2 October 2013
Available online 22 November 2013

Keywords:
Cogeneration
Optimization
Structural design
Operation planning
Energy savings
Residential use

ABSTRACT

An optimal structural design model of a residential cogeneration system, known as combined heat and power, considering various kinds of operating restrictions is developed from the energy-saving viewpoint. As principal operating restrictions of cogeneration units, a constant power output operation, a daily start–stop operation, and a continuous operation are focused on. The developed model results in a mixed-integer linear programming problem and the selection and multi-period operation are simultaneously optimized. Moreover, the model is applied to the structural design of a residential cogeneration system, consisting of a cogeneration unit and its peripheral devices, for simulated energy demands in a Japanese residence. The candidates for a cogeneration unit are a gas engine employing a constant power output operation, a polymer electrolyte fuel cell employing a daily start–stop operation, and a solid oxide fuel cell employing a continuous operation, and the candidates for peripheral devices are an electric water heater and an air-cooled heat exchanger. The optimization results reveal that the selection of the cogeneration unit is influenced more by their operating restrictions than by the consistency in the heat-to-power ratios of the cogeneration unit and energy demands. In addition, it is found that the selection of the peripheral devices varies with the selected cogeneration unit and energy demands.

1. Introduction

1.1. *Background of the study*

Energy savings is strongly required not only in industrial and commercial sectors but also in residential sector for global environment and resources. Cogeneration, which is known as combined heat and power, is an effective energy supply method to achieve energy savings and cost reduction. Recently, small-scale, high performance cogeneration units have been developed for residential use [1]. In Japan, following a 1-kWe gas GE-CGU (engine-based cogeneration unit) [2] and a 0.75-kWe PEFC-CGU (polymer electrolyte fuel cell-based cogeneration unit) [3], a 0.7-kWe SOFC-CGU (solid oxide fuel cell-based cogeneration unit) was released [4]. A 1-kWe Stirling engine-based cogeneration unit and a 1-kWe Rankine cycle-based cogeneration unit are also available in other countries [5]; however, these two types of cogeneration units have heat-to-power supply ratios higher than six and are not appropriate for residential use in Japan where the heat-to-power demand ratio is generally low.

The three types of residential cogeneration units released in Japan have different heat-to-power supply ratios and operating restrictions. The GE-CGU has the highest heat-to-power supply ratio among them and must be always operated under the rated power output in order to maintain a high generation efficiency. The PEFC-CGU has a higher generation efficiency than the GE-CGU and adopts a daily start–stop operation, in which they can be started and stopped up to once a day. The latter is due to thermal degradation of the stacks [6] and the input energies for start-up. The SOFC-CGU has the highest generation efficiency among them; however, it must be operated continuously because its high operating temperature requires a long warm-up time and a large amount of input energies. Moreover, the electric power export from residential cogeneration units to commercial electric power systems is not permitted in Japan. Thus, to obtain benefits including energy savings, CO_2 emission reduction, and cost reduction, residential cogeneration units must be appropriately operated in response to variations in residential energy demands. However, the PEFC-CGU and SOFC-CGU may have minimum electric power outputs because of the decrease in their generation efficiencies. Furthermore, a storage tank must be installed along with the residential cogeneration units to meet the mismatch between production and demand [7]. If the electric power export from residential cogeneration units can be conducted, residential

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http://dx.doi.org/10.1016/j.energy.2013.10.002

Nomenclature

Indices/sets

$i \in I$	candidates of cogeneration unit
$k \in K$	sampling times
$l \in L$	candidates of peripheral devices
$m \in M$	representative days
$n \in N$	divided parts for input–output relationship

Binary variables

γ	selection of candidates of system components
δ	operating status of candidates of system components
δ^{L}	stored status lower than upper limit
δ^{STA}	migration from standby state to operating state
δ^{STO}	migration from operating state to standby state
δ^{U}	stored status equal to upper limit

Continuous variables

E	electric power [kWh/h]
E_{D}	electric power demand [kWh/h]
E_{P}	purchased electric power [kWh/h]
E^{a}	electric power consumed in auxiliary machines [kWh/h]
F	natural gas consumption [m^3/h]
Q	heat flow rate of hot water [kWh/h]
Q_{DH}	hot water heating demand [kWh/h]
Q_{DS}	hot water supply demand [kWh/h]
$Q_{\mathrm{ST}}^{\mathrm{in}}$	heat flow rate of hot water stored into storage tank [kWh/h]
$Q_{\mathrm{ST}}^{\mathrm{out}}$	heat flow rate of hot water supplied from storage tank [kWh/h]
S	stored energy [kWh]
S^{L}	stored energy lower than upper limit [kWh]
S^{U}	stored energy equal to upper limit [kWh]
X	flow rate of input energy [kWh/h]
Y	flow rate of output energy [kWh/h]
ξ	continuous variable to linearize nonlinear term

Objective function

J_{CGS}	annual primary energy consumption of residential cogeneration system [MJ]

Performance variables

J_{CO}	annual primary energy consumption of conventional energy supply system [MJ]
α	reduction rate of annual primary energy consumption by utilizing residential cogeneration system [%]

Parameters

a, b	performance characteristic values [–, kWh/h]
c	specific heat of water [kWh/(kg °C)]
E^{aSB}	standby electric power consumed in auxiliary machines [kWh/h]
E^{STA}	electric power to start up [kWh/h]
F^{STA}	natural gas consumption to start up [m^3/h]
p, q, s, u	performance characteristic values [(kWh/h)/(m^3/h), kWh/h, (kWh/h)/(m^3/h), kWh/h]
r_{E}	ratio of varied annual demand to original annual demand for electric power
r_{Q}	ratio of varied annual demand to original annual demand for heat
Δt	sampling time [h]
V	storage tank volume [L]
W	number of representative days in typical year
θ	temperature [°C]
κ	installation energy [MJ]
Λ	energy loss rate [1/h]
ρ	water density [kg/m^3]
ϕ_{E}	conversion factor for primary energy of purchased electric power [MJ/kWh]
ϕ_{G}	conversion factor for primary energy of natural gas [MJ/(m^3)]
$\overline{()}$, $\underline{()}$	upper and lower limits

Subscripts

CGU	cogeneration unit
F	feed water
PD	peripheral device
ST	storage tank

Superscripts

O	original value

Abbreviation

GE-CGU	gas engine-based cogeneration unit
PEFC-CGU	polymer electrolyte fuel cell-based cogeneration unit
SOFC-CGU	solid oxide fuel cell-based cogeneration unit

cogeneration units can operate in response to variations in heat demand; it is called heat demand following operation [8,9]. However, in a residential cogeneration unit without electric power export, its heat output varies in response to its electric power output that follows the electric power demand [10]. Because heat demand in a residence is not always synchronized with electric power demand and intermittently arise as shown in Ref. [11], the surplus heat output generated by the residential cogeneration unit must be stored in the storage tank. On the other hand, if instantaneous heat demand exceeds the heat output of a residential cogeneration unit, the shortage in the heat must be supplemented from a storage tank [5]. In light of these features of residential cogeneration units without electric power export, peripheral devices may also be required, including an air-cooled heat exchanger to waste surplus hot water [10], an electric water heater to consume surplus electric power [11], and a gas-fired boiler to compensate for the shortage in hot water supply from a storage tank [10,11]. Combining these peripheral devices with the above-mentioned residential cogeneration units increases the flexibility of the system structure; thus, an optimal design of the residential cogeneration systems, consisting of cogeneration units and their peripheral devices, for various energy demands is strictly required to archive their potential benefits.

1.2. Review of previous works

The previous works for the optimal design of energy supply systems including the residential cogeneration systems were broadly classified into the optimal sizing and the optimal structural design.

1.2.1. Optimal sizing of energy supply systems

In the optimal sizing, the system structure was previously defined and the sizes of system components including the cogeneration units are determined so as to maximize the above-