Energy 84 (2015) 106–120

Contents lists available at ScienceDirect

Energy

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

Optimal structural design of residential cogeneration systems with battery based on improved solution method for mixed-integer linear programming

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ARTICLE INFO

Article history:
Received 6 December 2014
Accepted 17 February 2015
Available online 26 March 2015

Keywords:
Cogeneration
Battery
Structural design
Operational planning
Optimization
Mixed-integer linear programming

ABSTRACT

An optimal structural design model of residential cogeneration systems with a battery is developed using an MILP (mixed-integer linear programming) approach. A battery is introduced as a device candidate to increase operational flexibility of cogeneration units without electric power export. In this model, the selection from device candidates and multi-period operation of selected devices, in which various operational restrictions are considered, are simultaneously optimized so as to minimize annual primary energy consumption. For a battery, not only charging and discharging losses and an upper limit of charging and discharging electric power but also charging–discharging status and electric power consumption in a built-in bidirectional inverter are uniquely incorporated into the model. In addition, the solution method for this MILP problem is improved using a simple decomposition approach. The developed model is then applied to the structural design of a residential cogeneration system with a battery for simulated energy demands in Japan. The results reveal the effectiveness of the simple decomposition approach and the increase in the energy-saving effect of the residential cogeneration system by the introduction of the battery, as a consequence of the increase in the electric capacity factor of the cogeneration unit by the charge of surplus electric power. Moreover, it is shown that this increase strongly depends on the battery performances.

1. Introduction

1.1. Background of the study

Energy savings are a critical requirement to resolve global environmental problems. An effective solution is to employ distributed energy supply systems, which can reduce transmission and distribution losses and increase efficiency in energy utilization and cost reduction. Recently, distributed energy systems have been utilized not only in industrial and commercial sectors but also in residential sectors due to the development of small-scale, high-performance energy supply technologies, including cogeneration [1] and heat pump [2]. In particular, cogeneration, known as combined heat and power, can supply electric power and heat simultaneously and contribute to an increase in energy utilization efficiency. R-CGSs (Residential cogeneration systems) available in Japan include a 1-kWe GE-CGU (gas engine-based cogeneration unit) [3], a 0.75-kWe PEFC-CGU (polymer electrolyte fuel cell-based cogeneration unit) [4], and a 0.7-kWe SOFC-CGU (solid oxide fuel cell-based cogeneration unit) [5]. In other countries, residential cogeneration units based on micro-gas turbines, micro-Rankine cycles, and thermophotovoltaic generators are under development [6]. However, these cogeneration units are not suitable in temperate climate areas including Japan because they have high heat-to-power supply ratios (greater than six) due to their low generation efficiency, where the heat-to-power supply ratio is defined as the rated heat output divided by the rated electric power output of the cogeneration unit.

The features of the three types of residential cogeneration units available in Japan were presented in Ref. [7], and are summarized as follows: the GE-CGU operates at a constant power output [8] and has the highest heat-to-power supply ratio of the three residential cogeneration units; the SOFC-CGU operates continuously [9] and has the lowest heat-to-power supply ratio; and the PEFC-CGU employs daily start–stop operation [10] and has a heat-to-power supply ratio that falls between those of the other two cogeneration units. Moreover, electric power export from these cogeneration units is not permitted in Japan [11]. Consequently, the

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http://dx.doi.org/10.1016/j.energy.2015.02.056
0360-5442/

Nomenclature

Indices
d subproblems
i cogeneration unit candidates
k sampling times
l peripheral device candidates
m representative days

Binary variables
γ selection of device candidates
$\boldsymbol{w}$ binary variable vector expressing selection of device candidates
δ operating status of device candidates
$\boldsymbol{z}$ binary variable vector expressing operating status of device candidates

Continuous variables
E electric power [kWh/h]
F natural gas consumption [m^3/h]
Q energy flow rate of hot water [kWh/h]
S stored energy [kWh]
$\boldsymbol{x}$ continuous variable vector expressing energy flow rate [kWh/h]
$\boldsymbol{y}$ continuous variable vector expressing stored energy [kWh]

Equations
e linear equation expressing primary energy consumption
$\boldsymbol{f}$ linear equation vector expressing device selection
$\boldsymbol{g}$ linear equation vector expressing constraints
h linear equation expressing installation energy consumption

Objective function
J_{CGS} annual primary energy consumption of residential cogeneration system [MJ/y]

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

Parameters
I Number of cogeneration unit candidates
K Number of sampling times
L Number of peripheral device candidates
M Number of representative days
N Number of days that correspond to representative days in one year
p performance characteristic value [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 hot water
Δt sampling time interval [h]
κ annualized installation energy consumption [MJ/y]
Λ energy loss rate [1/h]
η efficiency
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
BT battery unit
CD performance characteristics of energy conversion devices
CGU cogeneration units
D demand
DS device selection
EB energy balance relationships
OD other devices
P purchased value
PD peripheral devices
SD performance characteristics of energy storage devices

Superscripts
a auxiliary machine
in inlet
O original value
out outlet
SP subproblem
* provisional value

Abbreviations
Case-0 calculation case not considering battery unit as device candidate
Case-1 calculation case considering battery unit as device candidate
Case-2 calculation case setting charging and discharging efficiencies to lower values
Case-3 calculation case neglecting power consumption in inverter
GE-CGU gas engine-based cogeneration unit
MILP mixed-integer linear programming
MINLP mixed-integer nonlinear programming
Method-1 conventional solution method
Method-2 simple decomposition method
PEFC-CGU polymer electrolyte fuel cell-based cogeneration unit
R-CGS residential cogeneration system
SOFC-CGU solid oxide fuel cell-based cogeneration unit

residential cogeneration units must be operated in response to variations in electric power demand within the residence. When the electric power demand is greater than the rated electric power output of the cogeneration unit, supplementary electric power is purchased from the grid. However, if there is a surplus of electric power generated by the cogeneration unit, it must be consumed in an electric water heater [8]. Furthermore, a storage tank for hot water is indispensable because in a residence, hot water demand arises intermittently and is not always synchronized with electric power demand [7,8]. Any shortage in hot water supply from a storage tank is compensated by a gas-fired backup boiler, while heat of surplus hot water is wasted in an air-cooled heat exchanger [9]. Thus, installation of these peripheral devices can improve the benefits obtained by the residential cogeneration units, including energy savings, greenhouse gas emissions reduction, and cost reduction. Recently, installation of a battery unit along with the