Applied Energy 163 (2016) 118–133

Contents lists available at ScienceDirect

Applied Energy

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

Optimal structural design of residential power and heat supply devices in consideration of operational and capital recovery constraints

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HIGHLIGHTS

- Structural design model for residential power and heat supply devices is developed.
- Various operating constraints of power and heat supply devices are modeled.
- Capital recovery constraint is considered for high-efficient and expensive devices.
- Trade-off between energy savings and initial investment is revealed.
- Sensitivity of recovered capital and initial costs of devices is analyzed.

ARTICLE INFO

Article history:
Received 21 May 2015
Received in revised form 22 October 2015
Accepted 24 October 2015

Keywords:
Cogeneration
Heat pump
Battery
Structural design
Optimization
Mixed-integer linear programming

ABSTRACT

An optimal structural design model of residential power and heat supply devices (R-PHDs), including cogeneration and heat pump units, was developed by considering their operational and capital recovery constraints. The structure of R-PHDs with peripheral devices, sizes of energy storage devices, and their multi-period operation were determined so as to minimize annual primary energy consumption. In addition to various operational constraints for a cogeneration unit and a battery unit, an operable-hours constraint and daily selection of outlet water temperature were newly formulated for heat pump units. The capital recovery by reducing energy cost was also considered in order to select R-PHDs that have high energy-saving effects but are presently expensive. The developed model took the form of a mixed-integer linear programming problem. The model was applied to the structural design of R-PHDs, whose candidates are three types of cogeneration units (gas engine, polymer electrolyte fuel cell, and solid oxide fuel cell), heat pump unit, storage tank, battery unit, and peripheral devices. The result revealed a trade-off between energy savings and initial cost in the optimal structures. A sensitivity analysis of the initial costs of expensive devices was also carried out to clarify their initial cost targets.

1. Introduction

1.1. Background of the study

Reducing energy consumption is considered crucial for resolving global environmental problems. Utilization of distributed energy supply systems is effective for reducing transmission losses and achieving more efficient energy utilization. Distributed energy systems have been widely utilized in the industrial and commercial sectors, and have recently been adopted in the residential sector due to the development of high-performance, residential power and heat supply devices (R-PHDs), including cogeneration units [1] and heat pump units [2].

The following cogeneration units (CGUs) are available for residential applications in Japan: a 1-kWe gas engine-based CGU (GE-CGU) [3], 0.75-kWe polymer electrolyte fuel cell-based CGU (PEFC-CGU) [4], and 0.7-kWe solid oxide fuel cell-based CGU (SOFC-CGU) [5]. In other countries, residential CGUs based on micro-gas turbines, micro-Rankine cycles, and thermophotovoltaic generators are under development [6]. However, these CGUs are not suitable for areas with temperate climate, including Japan, because they have high heat-to-power supply ratios (greater than 6) due to their low generating efficiencies. The features of the three types of residential CGUs available in Japan [7] are summarized as follows: the GE-CGU operates at a constant power output and has the highest heat-to-power supply ratio (2.5) [8]; the SOFC-CGU operates continuously and has the lowest heat-to-power supply ratio (0.91) [9]; and the PEFC-CGU employs daily start–stop operation and has an intermediate

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http://dx.doi.org/10.1016/j.apenergy.2015.10.154
0306-2619/

Nomenclature

Abbreviations
- AC air-cooled heat exchanger
- BTU battery unit
- CGB conventional type gas-fired boiler
- CGU cogeneration unit
- CO conventional energy supply system
- EH electric water heater
- GE-CGU gas engine-based cogeneration unit
- HPU air-source heat pump unit
- LGB latent heat recovery type gas-fired boiler
- MILP mixed-integer linear programming
- MINLP mixed-integer nonlinear programming
- PEFC-CGU polymer electrolyte fuel cell-based cogeneration unit
- R-PHD residential power and heat supply device
- SOFC-CGU solid oxide fuel cell-based cogeneration unit
- ST hot water storage tank

Indices/sets
- $h \in \{1,2,\ldots,H\}$ CGU candidates
- $i \in \{1,2,\ldots,I\}$ HPU candidates
- $k \in \{1,2,\ldots,K\}$ sampling times
- $l \in \{1,2,\ldots,L\}$ peripheral device candidates
- $m \in \{1,2,\ldots,M\}$ representative days
- $n \in \{1,2,\ldots,N\}$ outlet water temperature candidates

Binary variables
- γ device selection (design variable)
- δ operating status

Continuous variables
- A additional capital (yen)
- C energy capacity (design variable) (kW h)
- E electric power (kW h/h)
- P power capacity (design variable) (kW)
- Q energy flow rate of hot water (kW h)
- R reduction in annual energy cost (yen/y)
- S stored energy (kW h)
- V volume (design variable) (m^3)
- X daily energy cost (yen/d)
- Z annual energy cost (yen/y)
- Θ temperature (°C)

Objective function
- J^{E} annual primary energy consumption (MJ/y)
- J^{C} total annual cost (yen/y)

Performance criteria
- α reduction rate of annual primary energy consumption (%)

Parameters
- b base cost (yen)
- c specific heat of water (kW h/(kg °C))
- $\bar{E}^{IN}_{HPU}$ maximum power consumption of selected HPU (kW h/h)
- e_{BTU} unit power consumption in BTU during operation (kW h/(h kW))
- e power consumption (kW h/h)
- g^{P}_{HPU} operable and inoperable hours of HPU
- p lower limit
- q upper limit
- r capital recovery factor
- s_{BTU} upper limit of charging–discharging rate (1/h)
- Δt sampling time interval (h)
- u cost per unit energy capacity (yen/kW h, yen/L)
- v cost per unit power capacity (yen/kW)
- w number of days that correspond to representative days in one year
- η efficiency
- θ temperature (°C)
- ρ water density (kg/m^3)
- ϕ capital recovery rate
- ψ initial cost rate
- $\overline{()}, \underline{()}$ upper and lower limits

Subscripts
- A ambient value
- BTU battery unit
- CGU cogeneration unit
- CO conventional energy supply system
- F feed water
- GB gas-fired boiler
- HPU air-source heat pump unit
- PD peripheral device
- ST hot water storage tank
- SYS selected system

Superscripts
- a auxiliary machine
- COP coefficient of performance
- IN inlet
- L loss
- O other device
- OP value during operation
- OUT outlet
- P purchase value
- S value smaller than upper limit
- SB value during standby
- U value equal to upper limit

heat-to-power supply ratio (1.4) [10]. Moreover, power export from these CGUs is not allowed in Japan [11]. Thus, a CGU is operated in response to the variations in power demand of the residence where the CGU is installed, and any surplus of generated power is consumed by an attached electric water heater [8]. A storage tank (ST) for hot water must also be installed along with a CGU, because hot water demand in a residence is intermittent and is not always synchronized with power demand [7,8]. Any shortage in hot water supplied from an ST is compensated for by a gas-fired boiler, while the heat of the surplus hot water is dissipated to the outdoor atmosphere via an air-cooled heat exchanger [9].

Heat pump water heating units for residential applications are classified as air-source heat pump units (HPUs), ground-coupled heat pump units, and solar-assisted heat pump units [12]. An HPU is the most commonly used unit owing to its simple system configuration and easy installation. Although HPUs using hydrofluorocarbon refrigerants (e.g., R134a [13,14], R407C [15], and R410A [13,16]) have been developed, HPUs that use CO_2 as the working refrigerant [17] are widely used in Japanese residences. This is because CO_2 is an environmentally friendly refrigerant as compared to hydrofluorocarbon refrigerants, and because water can be heated to high temperatures by employing a CO_2 transcritical