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A mixed-integer linear programming approach for cogeneration-based residential energy supply networks with power and heat interchanges

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ABSTRACT

The feasibility on a residential energy supply network using multiple cogeneration systems, known as combined heat and powers, is investigated by an optimization approach. The target residential energy supply network is based on a microgrid of residential cogeneration systems without electric power export, and featured by power and heat interchanges among cogeneration systems and hot water supply network where produced hot water is supplied to multiple residence units through networked pipes. First, an optimal operational planning model is developed on the basis of mixed-integer linear programming, where energy loss characteristics of connecting pipes between storage tanks are originally modeled by considering the influence of hot water retention. Second, a hot water demand calculation model considering energy loss from networked pipes is developed to reduce the solution space of the optimization problem. The developed models are then applied to a residential energy supply network for a housing complex composed of multiple 1-kWe gas engine-based cogeneration systems and 20 residence units. The results show that the energy-saving effect of the residential energy supply network is dominated by the power interchange and decreases with an increase in the number of residence units involved in the hot water supply network.

1. Introduction

1.1. Background and concept of residential energy supply network

Cogeneration systems have been extended to residential sector because of the development of small-scale, high-performance energy-conversion machines [1]. In Japan, a 1-kWe gas engine-based cogeneration system (GE-CGS) [2] and 1-kWe [3] and 0.75-kWe [4] polymer electrolyte fuel cell-based cogeneration systems (PEFC-CGSs) are available for residential use. Recently, a 0.7-kWe solid oxide fuel cell-based cogeneration system (SOFC-CGS) has been released [5]. These residential cogeneration systems (R-CGSs) have different heat-to-power supply ratios and operational restrictions. The GE-CGS has a high heat-to-power supply ratio and must be operated under a constant power output to maintain a high generation efficiency. The PEFC-CGSs have higher generation efficiencies than the GE-CGS; however, they adopt a daily start–stop operation, in which they can be started and stopped up to once a day. This is due to thermal degradation of stacks and input energies for start-up. The SOFC-CGS has the highest generation efficiency and must be operated continuously because its high operating temperature requires a long warm-up time and a high level of input energies. Moreover, in Japan, surplus electric power generated by R-CGSs cannot be exported to commercial electric power systems. Thus, to obtain benefits such as energy savings, CO_2 emission reduction, and cost reduction, R-CGSs must be appropriately operated in response to variations in electric power and heat demands. A storage tank is also indispensable for intermittent hot water supply. However, if energy demands of a residence unit do not match capacity and operational restriction of an R-CGS, then the R-CGS may not fully achieve its potential benefits.

The present study focuses on a residential energy supply network (R-ESN) using multiple R-CGSs to improve the energy-saving effect of R-CGSs. The R-ESN is based on a microgrid [6] of R-CGSs without electric power export; this microgrid is referred to as power interchange. Hot water produced by R-CGSs is stored in storage tanks and stored hot water is interchanged among storage tanks; this is referred to as heat interchange. Moreover, the stored

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Nomenclature

Indices/sets

$f \in F$ floors in housing complex
$h \in H$ residence units involved in hot water supply network
$k \in K$ sampling times on each representative day
$m \in M$ representative days in typical year
$n \in N$ residential cogeneration systems on each floor

Objective functions

J_{ESN} total daily primary energy consumption of residential energy supply network [MJ/d]

Binary variables for mixed-integer linear programming model

$\boldsymbol{z}$ binary variable vector expressing operating status of devices
δ_{IH} operating status of pump for heat interchange
δ_{R} retention status of hot water in connecting pipe
δ_{Rl} retention status of hot water longer than maximum duration time
δ_{Rs} retention status of hot water shorter than maximum duration time

Continuous variables for mixed-integer linear programming model

$\boldsymbol{T}$ continuous variable vector expressing duration time of hot water retention
$\boldsymbol{x}$ continuous variable vector expressing energy flow rates of inputs and outputs of energy conversion devices
$\boldsymbol{y}$ continuous variable vector expressing energies stored in energy storage devices
E_{PC}^{B} electric power purchased in bulk [kWh/h]
G_{CGU} natural gas consumption in cogeneration unit [m^3/h]
G_{GB} natural gas consumption in gas-fired backup boiler [m^3/h]
Q_{IH} energy flow rate of interchanged hot water [kWh/h]
Q_{L} energy flow rate lost from connecting pipe [kWh/h]
Q_{ST}^{in} energy flow rate of hot water stored to storage tank [kWh/h]
Q_{ST}^{out} energy flow rate of hot water supplied from storage tank [kWh/h]
S_{ST} stored energy [kWh]
T_{R} duration time of hot water retention [h]
ζ_{IH} continuous variable to linearize nonlinear term
ξ_{R} continuous variable to linearize nonlinear term [h]

Equations for mixed-integer linear programming model

$\boldsymbol{g}_{CD}$ linear equation vector expressing input–output characteristics of energy conversion devices
$\boldsymbol{g}_{EB}$ linear equation vector expressing energy balance and supply–demand relationships
$\boldsymbol{g}_{ST}$ linear equation vector expressing input–output characteristics for storage tanks
$\boldsymbol{h}_{CP}$ nonlinear equation vector expressing input–output characteristics for connecting pipes

Variables for hot water demand calculation model

g_{d} mass flow rate of hot water at each residence unit [kg/h]
g_{PP} mass flow rate of hot water in hot water pipe [kg/h]
Q_{d} hot water demand at each residence [kWh/h]
Q_{SP} energy flow rate of hot water at supply point [kWh/h]
S_{PP} energy of hot water in hot water pipe [kWh]
S_{PP}^{R} energy lost from hot water pipe [kWh]
U_{PP} overall heat transfer coefficient of hot water pipe [kW/(m^2 °C)]
η_{PP}^{S} hot water supply efficiency
θ_{PP} hot water temperature in hot water pipe [°C]
θ_{PP}^{S} hot water temperature in hot water pipe during hot water supply [°C]
τ_{PP} time constant during hot water retention [h]

Parameters

c specific heat of water [kWh/(kg °C)]
d_{IS}^{o} outside diameter of insulator [m]
d_{PP}^{i} inside diameter of hot water pipe [m]
d_{PP}^{o} outside diameter of hot water pipe [m]
E_{CGU}^{R} rated electric power output of cogeneration unit
L ength of hot water pipe [m]
s_{IH} hot water energy added during heat interchange [kWh]
Δt sampling time [h]
T_{R}^{M} maximum duration time of hot water retention available for heat interchange [h]
V_{PP} volume of hot water pipe [m^3]
W weighted number of representative days for each month
α_{i} heat transfer coefficients inside hot water pipe [kW/(m^2 °C)]
α_{o} heat transfer coefficients outside hot water pipe [kW/(m^2 °C)]
η_{IH} heat interchange efficiency of connecting pipe
η_{ST} energy loss rate from storage tank
θ_{A} ambient temperature [°C]
θ_{F} feed water temperature [°C]
θ_{S} hot water supply temperature [°C]
θ_{ST} hot water temperature in storage tank [°C]
λ_{IS} heat conductivity of insulator [kW/(m °C)]
λ_{PP} heat conductivity of hot water pipe [kW/(m °C)]
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

Performance criteria

J_{CO} total daily primary energy consumption of conventional energy supply system [MJ/d]
J_{SE} total daily primary energy consumption of separate operation of each residential cogeneration system [MJ/d]
P_{E} electric capacity factor of residential cogeneration systems [%]
R_{E} electric power supply rate [%]
R_{IH} interchanged hot water rate [%]
R_{Q} hot water supply rate [%]
γ_{ESN} reduction rate of primary energy consumption for residential energy supply network relative to that for conventional energy supply system [%]