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Optimal management of multiple heat sources in a residential area by an energy management system

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ABSTRACT

An energy management system (EMS) that achieves optimal operation by combining heat sources with different characteristics and using energy interchanges between residential dwellings was developed. Commercial fuel cell combined heat and power (FC-CHP) systems and CO_2 heat pump water heaters (CO2HP) with high generation efficiencies have penetrated the Japanese residential market. In this real environment, the types or models of the installed heat sources vary between residential dwellings, and their energy demand is unknown. The EMS predicts energy generation and consumption and develops an optimum operational strategy that it uses to control energy equipment. It also continually revises the strategy and adjusts equipment controls to reflect actual conditions. The EMS is evaluated using a case study of a group of four residential dwellings with two different heat sources. Subsequent quantitative analysis shows that the EMS reduced energy costs by 10%. A sensitivity analysis also confirmed that it operates optimally even when energy prices are changed.

1. Introduction

Energy consumption related to water heating accounts for 27.7% [1] of end-use energy consumption for an average household in Japan. Therefore, to conserve energy, it is essential to reduce water heating related energy consumption in residential dwellings, and many efforts have been made to achieve this based on domestic hot water demand. Some such developments include a system to analyze and improve energy efficiency and performance [2] or an alarm and display system on showerheads to encourage water conservation [3]. The development and penetration of highly efficient heat sources for domestic hot water systems are important; to this end, fuel cells or CO_2 heat pump water heaters (CO2HPs) have been developed and commercialized, and are now being implemented, in Japan.

To date, Japan has been the most active country for fuel cell development and penetration. 180,000 fuel cell combined heat and power (FC-CHP) systems have already been installed in general dwellings [4]. A FC-CHP system consists of a fuel cell stack (proton exchange membrane fuel cells (PEFCs) [5]) or solid oxide fuel cells (SOFCs) [6]), a heat recovery device, a hot water tank, and an auxiliary boiler. The fuel cell stack has a capacity of 0.7–0.75 kW for electricity generation, and heat is recovered as hot water and stored in the tank [7]. Thus, they are used as a combined heat and power (CHP) system, providing high overall efficiency [8]. Adam et al. [9] developed an optimal design modelled on the introduction of micro-CHP systems powered by fuel cells. Japanese gas utilities have been engaged to contribute to the development and penetration of CHP systems [10]. However, there are some challenges regarding their operation. The ratio of electricity and hot water generation does not typically match the demand. This shortfall of hot water must therefore be supplied by an auxiliary boiler. When a hot water tank is filled to capacity, operation of the system ceases, even if there is consumer demand for electricity.

CO2HPs, which provide higher efficiency than conventional electric water heaters or gas-fired boilers using heat pump technology [11], are very popular; more than 5 million units have been installed in Japan [12]. A CO2HP system consists of a heat pump unit that generates hot water and a hot water tank. The rated electricity consumption of a CO2HP is 1.0–1.5 kW, and the hot water generation capacity and coefficient of performance (COP) vary with conditions such as ambient temperature (approximately 2.5–4.0

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Nomenclature

Variables

Obj	Objective function
$Cost(h)$	Energy cost, dwelling h (JPY)
$Cost_e(h)$	Electricity cost, dwelling h (JPY)
$Cost_g(h)$	Gas cost, dwelling h (JPY)
$Buy_e(h,t)$	Electricity purchased from grid, dwelling h, time t (MJ)
$Buy_g(h,t)$	Gas purchased, dwelling h, time t (MJ)
$Buy_{gs}(h,s)$	Gas purchased, dwelling h, price step s (MJ)
$Buy_{gsYN}(h,s)$	Gas purchased or not, dwelling h, price step s (MJ) (binary)
$Sell_e(h,t)$	Electricity sold to grid, dwelling h, time t (MJ)
$Tr_{eb}(h,t)$	Electricity received from other dwelling(s), dwelling h, time t (MJ)
$Tr_{es}(h,t)$	Electricity sent to other dwelling(s), dwelling h, time t (MJ)
$Tr_{hwb}(h,t)$	Hot water received from opposite dwelling, dwelling h, time t (L)
$Tr_{hws}(h,t)$	Hot water sent to opposite dwelling, dwelling h, time t (L)
$FC_e(h,t)$	Electricity generated by FC-CHP, dwelling h, time t (MJ)
$FC_{hw}(h,t)$	Hot water generated by FC-CHP, dwelling h, time t (L)
$FC_g(h,t)$	Gas consumed by FC-CHP, dwelling h, time t (MJ)
$FC_{on}(h,t)$	FC-CHP on/off, dwelling h, time t (binary)
$HP_e(h,t)$	Electricity consumed by CO2HP, dwelling h, time t (MJ)
$HP_{hw}(h,t)$	Hot water generated by CO2HP, dwelling h, time t (MJ)
$BLR_{hw}(h,t)$	Hot water generated by gas-fired boilers, dwelling h, time t (L)
$BLR_g(h,t)$	Gas consumed by gas-fired boilers, dwelling h, time t (MJ)
$HT_{hw}(h,t)$	Hot water supplied from hot water tanks, dwelling h, time t (L)
$HT_{lv}(h,t)$	Stored level of hot water tanks, dwelling h, time t (L)

Exogenous variables and constants

$P_{eb}(t)$	Electricity price of purchase from grid, time t (JPY/kWh)
$P_{es}(t)$	Electricity price of sale to grid, time t (JPY/kWh)
$P_{gs}(s)$	Gas price, price step s (JPY/Nm^3)
$Buy_{gsv}(s)$	Monthly gas consumption, price step s (Nm^3/month)
Tp_{HT}	Temperature of stored hot water in hot water tanks (°C)
Tp_{hwt}	Temperature of consumed hot water (°C)
$Tp_{in}(t)$	Temperature of incoming water, time t (°C)
$Tp_{amb}(t)$	Ambient temperature, time t (°C)
FC_{max}	Maximum electricity generation of FC-CHP (kW)
FC_{min}	Minimum electricity generation of FC-CHP (kW)
HP_{max}	Minimum electricity consumption of CO2HP (kW)
BLR_{max}	Maximum hot water generation of gas-fired boilers (kWh/h)
HT_{maxFC}	Maximum storage level of hot water tanks of FC-CHP (L)
HT_{maxHP}	Maximum storage level of hot water tanks of CO2HP (L)
η_{HP}	Coefficient of performance (COP) of CO2HP
η_{BLR}	Efficiency of gas-fired boilers
η_{trhw}	Heat loss of hot water interchange
η_{HT}	Heat loss of hot water tank
C_{fcBe}	Fuel consumption of FC-CHP per electricity generation, basement portion (MJ)
C_{fcRe}	Fuel consumption of FC-CHP per electricity generation, variable portion
C_{fcBh}	Fuel consumption of FC-CHP per heat generation, basement portion (MJ)
C_{fcRh}	Fuel consumption of FC-CHP per heat generation, variable portion
C_{HP1}	Coefficient for COP of CO2HP, ambient temperature
C_{HP2}	Coefficient for COP of CO2HP, incoming water temperature
C_{HP3}	Coefficient for COP of CO2HP, outgoing hot water temperature
C_{HP4}	Coefficient for COP of CO2HP, constant term
C_{md}	Number of days per month
C_{eMJ}	Conversion factor, electricity (MJ/kWh)
C_{gMJ}	Conversion factor, gas (MJ/Nm^3)
C_{MJkcal}	Conversion factor, heat (kcal/MJ)
C_{eco2d}	CO_2 intensity, electricity, daytime (7–23 h, CO_2-g/kWh)
C_{eco2n}	CO_2 intensity, electricity, nighttime (23–27 h, CO_2-g/kWh)
C_{gco2}	CO_2 intensity, city gas (CO_2-g/MJ)
C_{ep}	Primary energy consumption, electricity (MJ/kWh)
$Dem_e(h,t)$	Electricity demand, dwelling h, time t (kW)
$Dem_{hw}(h,t)$	Hot water demand, dwelling h, time t (L)
$HT_{init}(h)$	Initial stored level of hot water tanks, dwelling h (L)

Others

h	Dwelling number
h^*	Dwelling number of opposite dwelling (interchange hot water)
H	Number of dwellings
t	Time
Ts	Start time of the optimization period
Te	End time of the optimization period
s	Price step of gas consumption
S	Number of price steps of gas consumption

[13]). They are usually only operated late at night, when electricity is cheaper. All hot water required for the following day must be heated in advance because the system has no back-up boiler and it takes time to produce hot water.

To ensure efficient utilization of FC-CHPs or CO2HPs, many previous studies have researched optimal operational strategies. Hirvonen et al. [14] analyzed energy sharing among buildings with CHP systems assuming that a local heat network had been introduced and utilizing premade (not measured) energy demand data. Ren et al. [15] analyzed the optimal operation of a standalone FC-CHP system in residential dwellings, assuming a specific type of dwelling, a time-of-use electricity tariff, and utilizing statistical energy demand data. Rosato et al. [16] conducted a dynamic analysis of a combustion based micro-CHP system with an auxiliary boiler, used in a multi-family building, by considering the shared use and effectiveness of hot water. Yokoyama et al. [17] performed a detailed numerical analysis of the operation of a CO2HP system, analyzing the influence of a daily change in hot water demand