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Development of an energy management system for optimal operation of fuel cell based residential energy systems

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ABSTRACT

Residential fuel cell based combined heat and power (FC-CHP) systems have been commercialized and are penetrating the marketed in Japan. In order to utilize FC-CHP systems efficiently, operational strategies are required. Energy interchange among consumers improves efficiency by allowing flexible operation of equipment. An energy management system (EMS), which is installed at the consumer dwelling, can integrate the control and management of energy equipment by using an optimized planning approach that incorporates the energy interchange and can operates equipment whilst adjusting to real conditions. An EMS has been developed, which achieves optimal operation of FC-CHP systems with energy interchange between dwellings in a residential area. Case studies were performed to evaluate the EMS model by using evaluation indices including energy costs, CO_2 emissions, and primary energy consumption. The results showed that 1) energy management and energy interchange were effective and contributed to cost reductions, CO_2 mitigation, and reduction of primary energy consumption and 2) the developed EMS model achieved optimal operations.

Introduction

Energy consumption related to water heating accounts for 27.7% [1] of end-use energy consumption for an average household in Japan. To conserve energy, it is therefore essential to reduce water heating related energy consumption in residential dwellings [2–4]. Residential fuel cells have been commercialized and are now being implemented in Japan. To date, Japan has been the most active country for fuel cell penetration into the market, and 150,000 units had been installed by 2015 [5]. These units include proton exchange membrane (PEM) fuel cells or solid oxide fuel cells [6,7] that are used as a combined heat and power (CHP) system [8,9] to supply electricity and hot water while providing for high overall efficiency [10].

In order to utilize the fuel cell CHP (FC-CHP) systems efficiently, operational strategies are needed. This includes not only improvements to the FC-CHP system hardware, e.g.,

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Nomenclature

Variables

Obj	Objective function
$Cost(h)$	Energy cost of 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
$Sell_e(h,t)$	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 the FC-CHP system, dwelling h, time t, MJ
$FC_{on}(h,t)$	FC-CHP on/off, dwelling h, time t (binary)
$BLR_{hw}(h,t)$	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

Given parameters

$P_{eb}(t)$	Electricity price for purchase from grid, time t, JPY/kWh
$P_{es}(t)$	Electricity price for selling to grid, time t, JPY/kWh
P_g	Gas price, JPY/Nm^3
Tp_{HT}	Temperature of stored hot water in hot water tanks, JPY/kWh
Tp_{hwt}	Temperature of consumed hot water, °C
$Tp_{in}(t)$	Temperature of incoming hot water, time t, °C
FC_{max}	Maximum electricity generation of the FC-CHP system, kW
FC_{min}	Minimum electricity generation of the FC-CHP system, kW
BLR_{max}	Maximum hot water generation of gas-fired boilers, L
HT_{max}	Maximum storage level of hot water tanks, L
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 the FC-CHP system per electricity generation, basement portion, MJ
C_{fcRe}	Fuel consumption of the FC-CHP system per electricity generation, variable portion
C_{fcBh}	Fuel consumption of the FC-CHP system per heat generation, basement portion, MJ
C_{fcRh}	Fuel consumption of the FC-CHP system per heat generation, variable portion
C_{eMJ}	Conversion factor, electricity, MJ/kWh
C_{gMJ}	Conversion factor, gas, MJ/Nm^3
C_{MJkcal}	Conversion factor, heat, kcal/MJ
$Dem_e(h,t)$	Electricity demand, dwelling h, time t, W
$Dem_{hw}(h,t)$	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
Te	Start time of the optimization period
Ts	End time of the optimization period

improvements in the generation efficiency [11,12], but also management software that will achieve optimal operations and provide the best overall performance. Many previous studies have been conducted on this subject [13–15]. To date, studies have mostly focused on control of the CHP systems [16]. Hawkes and Leach analyzed the operation of residential CHP systems, including FC-CHP systems, in order to minimize energy costs [17]. Utilization of hot water is critical for the efficient operation of an FC-CHP system; if consumers do not have sufficient hot water demands, the FC-CHP system cannot be operated, even if consumers have high electricity demands [18]. Wang and Nehrir conducted studies on fuel cells as distributed generation sites from the viewpoint of the power system [19,20]. Studies on combining the technology with other distributed generation sites such as those that use photovoltaic power have been conducted in recent years [21–23].

Most studies on the control of FC-CHP systems are based on optimization by mathematical models [24], which analyze the potential of FC-CHP systems [25]. Ren et al. analyzed the potential of a residential micro CHP system [14,26], and Merkel et al. conducted an analysis on the capacity of various micro CHP systems in the UK [27]. However, the mathematical models cannot simulate FC-CHP system operations in real environments. All data, including energy demands, must be given in advance and uncertainty cannot be considered. Furthermore, the time resolution of such models is limited so that the models can be solved in a certain period of time.

In addition, one of the most critical issues concerns how the optimized solution should be used for real operations. The energy demand or state of the equipment is always changing and typically differs from that used as an input for the optimization model. In the real world, hot water flows as a faucet is opened, and electricity is supplied as an appliance is turned

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