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Energetic analyses of installing SOFC co-generation systems with EV charging equipment in Japanese cafeteria

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ABSTRACT

Energetic feasibility analyses were conducted when an SOFC CGS with EV charging equipment is installed in a facility with a high hot-water demand and a high thermo-electric demand ratio. The university cafeteria located on the Hitachi Campus of Ibaraki University in Japan was selected as an installation target because its electric and hot-water demands fulfilled the intended criterion of a high thermo-electric demand ratio. It was made clear that the merits of a co-generation system are not optimal in the case a gas water heater is selected as the backup hot-water supply. To solve the problems contributing to this bad result and to improve the performance, the authors next selected a heat pump water heater as the backup hot-water supply. It was made clear that this system possesses sufficiently high energy savings performance. It was also shown that the coexistence and co-prosperity of the cafeteria and EV charging equipment are successfully achieved. These results reveal that an SOFC CGS with EV charging equipment can be a feasible candidate for a future energy supply system installed in Japanese cafeteria, which is a facility with a large hot-water demand and a high thermo-electric demand ratio, by adopting a heat pump water heater, instead of the usual gas water heater, as the backup hot-water supply.

1. Introduction

Recently, solutions to the problems of global warming and the depletion of fossil fuels have been sought all over the world. To address fossil fuel depletion, many countries have begun to explore the use of unconventional gas resources such as shale gas [1,2]. Since development of dedicated infrastructure was needed to mine these unconventional gas resources, optimal planning and infrastructure development for the shale gas production have been investigated by many companies [3], and now its production is expanding rapidly. Therefore, it is important to develop new technologies that can effectively utilize these types of unconventional energy sources. In addition, those new technologies are useful to promote the introduction of energy saving facilities for solving the problems of global warming and the depletion of fossil fuels.

Among these technologies, fuel cells are promising because of their high energy conversion efficiency. Many researchers have developed a number of types of fuel cells using various electrolytes to date [4,5]. Among them, the SOFC possesses the highest electric power generation efficiency [6]. Previously, since its operating temperature of about 1000 °C was too high for the application to small-scale distributed power supply such as CGS, it was being developed for large-scale concentrated power generation system, and many SOFC combined power generation systems have been proposed. The cycle electrical efficiency was expected to reach 61% (LHV) when the SOFC is combined with micro-gas turbine and organic Rankine cycle [7]. It was shown that the energy efficiency of 76% (LHV) can be achieved when the SOFC is integrated with Stirling engine [8]. An SOFC-gas turbine combined power generation system with CO_2 recovery was also proposed [9]. According to this report, the overall efficiency including the energy consumption for the CO_2 recovery reaches 72% (LHV) by the proposed system.

Recently, the major disadvantage of the SOFC (too high operating temperature) was overcome by development of the intermediate-temperature SOFC with an operating temperature about 700 °C [10,11]. Therefore, SOFCs now attract attention for the application not only to large-scale concentrated power generation system but also to small-scale distributed CGS, and are in active development all over the world.

On the other hand, in order to provide solutions to the problem of global warming, much research and development on solar and wind

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Nomenclature

Variables

e_{cf}	electric demand of cafeteria (W)
e_{ev}	required electricity for EV charging (W)
e_{so}	electric power generated by SOFC CGS (W)
e_{so0}	rated electric output power of SOFC CGS (W)
e_{tl}	total electric power required in system (W)
e_{ug}	electric power from utility grid (W)
h_{cf}	hot-water demand of cafeteria (W)
h_{gs}	hot-water supply output of gas water heater (W)
h_{hp0}	rated hot-water supply output of heat pump water heater unit (W)
h_{sh}	shortage of hot-water supply (W)
H_{tk}	thermal energy stored in hot water storage tank (J)
i	data index of each day
j	data index in each day
n_{hp}	number of operating heat pump water heater units
P_{gs}	total primary energy consumption of SOFC CGS backed up by gas water heater (J)
P_{hp}	total primary energy consumption of SOFC CGS backed up by heat pump water heater (J)
P_{rf}	total primary energy consumption of reference system (J)
r_{gs}	primary energy saving rate of SOFC CGS backed up by gas water heater
r_{hp}	primary energy saving rate of SOFC CGS backed up by heat pump water heater
Δt	monitoring interval of demand data (s)
η_{el}	electric power generation efficiency of SOFC CGS
η_{gs}	thermal efficiency of gas water heater
η_{hp}	COP of heat pump water heater
η_{hw}	hot-water generation efficiency of SOFC CGS
η_{tk}	heat loss rate of hot water storage tank (s^{-1})
η_{ug}	efficiency of purchased electricity from utility grid

Acronyms

SOFC	solid oxide fuel cell
CGS	co-generation system
EV	electric vehicle
LHV	lower heating value
COP	coefficient of performance

power generation plants have been promoted [12,13]. In addition, EVs are expected to be one of promising transportation technologies with environmental sustainability because EVs generally have advantage to reduce carbon emissions by as much as 30–50% and improve fuel efficiency of about 40–60% [14]. Many automobile companies have already put EVs on the market [15]. EVs, therefore, can be considered to be in the dissemination stage to our society. For wide penetration of EVs, however, a comprehensive network of EV charging stations is socially required along streets similar to petrol stations today. To promote installation of EV charging stations, many methods to determine location of public EV charging stations were discussed [16,17]. In addition, various types of EV charging stations have already been proposed from the social and technological viewpoints [18]. With respect to the design of the EV charging station, its integration with renewable energy was proposed [19,20]. Furthermore, the optimal design of the EV charging station was investigated considering different energy sources such as battery and diesel generator [21]. In addition, there were researches that propose to utilize the EV charging for the demand side management [22].

Considering these research and development trends of SOFCs and EVs, the authors proposed an SOFC CGS with EV charging equipment. In a former study, a feasibility analysis was performed with deployment in a typical Japanese multifamily apartment building [23]. The average annual primary energy saving rate of about 35% was obtained in this study. As for the other research activities on feasibility analysis of SOFC CGS with EV charging equipment, Wakui et al. [24] investigated an SOFC CGS including charging a plug-in hybrid electric vehicle. The energy-saving effect of the combined use of a residential SOFC CGS and a plug-in hybrid electric vehicle was evaluated considering the energy demand of a typical Japanese single-family house. Brouwer et al. [25] investigated how the increased electricity demand of EVs can be fulfilled in households with combined heat and power installations with low cost and low emission for different EV charging patterns using the demand patterns of Dutch single households in 2003. Angrisani et al. [26] researched the interaction between micro combined heat and power system and EV charging in a residential semidetached house. Furthermore, many reports on the installation effects of SOFC CGS without EV charging equipment have been published. For instance, Hawkes et al. [27] researched the installation effects of an SOFC CGS based on the typical residential energy demand in the UK. Lamas et al. [28] calculated the reduction of fuel consumption by using an SOFC CGS fueled by both natural gas and hydrogen generated by renewable energy. In their study, an energy demand of a residence in Japan was used and the primary energy saving rate of about 25% was obtained.

As mentioned above, in previous studies on the installation effects of SOFC CGSs, the energy demands of residences such as single-family houses and multifamily apartments were usually utilized. In these human-living spaces, the thermo-electric demand ratio is relatively low, and the electric demand is usually higher than their thermal demand for hot water. Since an SOFC CGS generates both electricity and hot-water, its installation effects depend on the thermo-electric demand ratio, and the results of conventional studies are considered to be incorrect for facilities with a large hot-water demand and high thermo-electric demand ratio. Therefore, research for such facilities is required in addition to conventional researches. No study, however, has ever been carried out with a facility that satisfies these conditions.

Considering this background, the authors selected the university cafeteria located on the Hitachi Campus of Ibaraki University in Japan as a facility with a large hot-water demand and a high thermo-electric demand ratio, and carried out energetic feasibility analyses if an SOFC CGS with EV charging equipment is installed in the cafeteria. In this paper, the authors demonstrate that an SOFC CGS with EV charging equipment can become a feasible candidate for the future energy supply system installed in the cafeteria, which is a facility with a large hot-water demand and a high thermo-electric demand ratio, by adopting a heat pump water heater, instead of the usual gas water heater, as the backup hot-water supply in the SOFC CGS. The obtained results not only add a new energy saving option for Japanese cafeteria, but also contribute to the spread of socially needed EV charging stations because there are many cafeterias along streets in Japan.

2. Electric and hot-water demands of Japanese cafeteria

To carry out the intended energetic analyses, typical electric and hot-water demand patterns of a facility with a high thermo-electric demand ratio are essential. As a preparatory step of the study, the authors monitored the time sequences of the electric and hot-water demands of the university cafeteria located on the Hitachi Campus of Ibaraki University in Japan because this kind of food service facility in Japan usually consumes a large amount of hot water.

In this section, the authors briefly explain the employed monitoring methods and the monitoring results of the electric and hot-water