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Framework for establishing the optimal implementation strategy of a fuel-cell-based combined heat and power system: Focused on multi-family housing complex

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HIGHLIGHTS

- A framework for establishing the implementation strategy of FCCHPS was developed.
- Primary energy saving (PES), LCC & $LCCO_2$ were used to select the optimal strategy.
- IS_PLF_500 kW was determined as the optimal implementation strategy in terms of PES.
- IS_HLF_200 kW was determined as the optimal strategy in terms of LCC & $LCCO_2$.
- The framework can be used as a guideline for establishing the government subsidy.

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ABSTRACT

The fuel-cell-based combined heat and power system (FCCHPS) is attracting attention as a new/renewable energy system with great potential for coping with climate change. However, a FCCHPS has not been actively applied to building sector in South Korea. Therefore, this study aimed to develop a framework for establishing the optimal implementation strategy of a FCCHPS for multi-family housing complex (MFHC). The implementation strategy of a FCCHPS consists of the operating scheme and operating size. To verify the feasibility of the proposed framework, 'O' MFHC located in Seoul, South Korea was selected as a case study. 'O' MFHC was assessed from the perspective of primary energy saving (PES), and life cycle cost (LCC) and life cycle CO_2 ($LCCO_2$). In terms of PES, IS_PLF_500 kW was determined as the optimal implementation strategy of a FCCHPS, where the operating scheme was power load following (PLF) and the operating size was 500 kW. PES and its saving ratio were determined at 1476.8 TOE/year and 54%, respectively. In terms of LCC and $LCCO_2$, IS_HLF_200 kW was determined as the optimal implementation strategy of a FCCHPS, where the operating scheme was heating load following (HLF) and the operating size was 200 kW. The net present value, its saving ratio, and break-even point were determined at US$ 3,823,091, 15.7%, and 3 year, respectively. The proposed framework can be used for establishing the optimal implementation strategy of a FCCHPS depending on the energy demand of a given building and the government subsidy in introducing a FCCHPS to the building sector.

1. Introduction

According to *the worldwide trends in energy consumption and efficiency* of International Energy Agency (IEA), building sector accounts for 36% of the worldwide energy consumption [1]. Among several measures for the primary energy savings in the building sector, interest in a new and renewable energy (NRE) has increased in recent years [2–10]. Also, with the advances in the NRE-related technologies, practical applications are gradually increasing [11–17]. IEA forecasts that the NRE power generation will increase to 40 percent by 2017, compared to that in 2011, and it will account for 33 percent of the overall power supply by 2035 [18–21].

Among the several NRE systems, a fuel-cell-based combined heat and power system (FCCHPS) is currently being promoted as a core green technology by the South Korea government owing to various advantages [22,23]: (i) all-weather power generation

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Nomenclature

Abbreviations	
FCCHPS	fuel cell-based combined heat and power system
mCHPS	microcombined heat and power system
IS_FPCO_100 kW	implementation strategy (IS) with the operating scheme of full power capacity output (FPCO) and the operating size of 100 kW
IS_PLF_100 kW	implementation strategy (IS) with the operating scheme of power load following (PLF) and the operating size of 100kW
IS_HLF_100 kW	implementation strategy (IS) with the operating scheme of Heating Load Following (HLF) and the operating size of 100 kW
PES	primary energy saving
LCC and $LCCO_2$	life cycle cost and life cycle CO_2
MEU_E	monthly energy usage of electricity (kW h)
MEU_G	monthly energy usage of gas (kW h)
MED_E	monthly energy demand of electricity (kW h)
MED_H	monthly energy demand of heat (kW h)
$MFES_E$	monthly FCCHPS energy supply of electricity (kW h)
$MFES_H$	monthly FCCHPS energy supply of heat (kW h)
MFU_G	monthly fuel (gas) used in a FCCHPS (kW h)
MES_E	monthly energy saving of electricity (kW h)
MES_G	monthly energy saving of gas (kW h)
H_R	heat rate (kJ/kW h)
H_{RE}	heat recovery efficiency (%)
Greek letters	
Φ	boiler efficiency
Ω	pipe-loss coefficient
Δ	boiler load-loss coefficient

system; (ii) minimum installation area per unit power generation; and (iii) high efficiency in electricity generation of fuel cells (about 90%). Furthermore, in case that a hydrogen infrastructure will be established, the potential of a FCCHPS will be more increased [24,25].

Nevertheless, the distribution of a FCCHPS in South Korea was lower than that of the other types of NRE system. As of 2011, the amount of electricity supplied by a FCCHPS was 63,644 TOE, which was 32% of the amount of electricity supplied by a photovoltaic system (158,095 TOE). Furthermore, 4.3% of 63,644 TOE (2614 TOE) was introduced to the building sector [26]. The lower distribution of a FCCHPS in the building sector was attributed to the following reasons: (i) the FCCHPS market structure focused on polymer electrolyte membrane fuel cells (PEMFC) and solid oxide fuel cells (SOFC), which were 0.7–1.0 kW products suitable for single-family housing; (ii) the high initial investment cost for the FCCHPS such as PEMFC and SOFC; and (iii) the lack of framework for establishing the optimal implementation strategy of a FCCHPS in the building sector.

To address these challenges, this study aimed to develop a framework for establishing the optimal implementation strategy of a FCCHPS. First, this study selected a building type that was expected to be highly affected by the introduction of a FCCHPS. In South Korea, the energy consumption in buildings accounted for 25% of the national energy consumption and 42% of the national CO_2 emissions [27–30]. The ratio of residential building was the highest (66.5%), followed by commercial buildings (16.8%) and others (16.7%) [31] (Fig. S1 of supplementary data). Also, the ratio of multi-family housing complex (MFHC) among the residential buildings was the highest (58.8%) in South Korea [32] (Fig. S2 of supplementary data). Thus, the improvement of the energy efficiency in MFHC will make a substantial contribution to the national energy efficiency. Therefore, this study selected MFHC as the main target of the FCCHPS market. Second, this study selected the FCCHPS type that was expected to be suitable for MFHC. In Japan and the European Union, the ratio of single-family housing was the highest in residential building types [33,34]. Thus, PEMFC and SOFC, which were suitable for single-family housing, were mainly distributed [35,36]. In South Korea, however, the ratio of MFHC was the highest in residential building types. Thus, it is necessary to select a FCCHPS type which can be applied to the central heating system of MFHC at a low cost. Since the molten carbonate fuel cell (MCFC), which is the second-generation technology, has a low heat rate (Table S1 of supplementary data), it is more suitable for residential buildings where progressive tax is applied. Also, MCFC occupies over 90% of the FCCHPS market in South Korea [37]. Therefore, this study selected MCFC as the FCCHPS type which can be applied to the central heating system of MFHC at a low cost.

2. Literature review

Previous research conducted to evaluate the economic and environmental effects of a FCCHPS from three perspectives: (i) which type of a FCCHPS is implemented; (ii) which operating scheme of a FCCHPS is applied; and (iii) how much operating size of a FCCHPS is [38–54].

First, the types of FCCHPS can be categorized based on the type of electrolyte used in the FCCHPS stack. According to the types of FCCHPS, the heat rate and the heat to power ratio can differ, which affect the economic and environmental effects of a FCCHPS. Liso et al. [49] analyzed the impact of the heat to power ratio for a SOFC-based microcombined heat and power system (mCHPS) in single-family housing under different climate regions in Europe. It was determined that a SOFC-based mCHPS of 0.5–1.5 kW can only achieve the demand for electricity and heat energy during warm seasons. Onovwiona and Ugursal [50] reviewed various types of a FCCHPS such as PEMFC, MCFC and SOFC to select the most appropriate type for residential building. It was determined that MCFC was suitable for residential building of more than 100 kW.

Second, the economic and environmental effect of a FCCHPS depends on its operating scheme. Wakui et al. [51] analyzed the operating scheme of a SOFC-based mCHPS for residential building in terms of primary energy saving (PES). It was found that the power load following scheme was superior to the heating load following scheme in terms of PES in Japan. Arsalis et al. [52] proposed the improved operating scheme that was combined with the power load following scheme and the heating load following scheme. A PEMFC-based mCHPS was applied to Danish single-family housing using the proposed operating scheme. It was concluded that the proposed operating scheme can make it possible to maintain high efficiency of a FCCHPS and to avoid heat dumping.

Third, the operating size of a FCCHPS should be considered in introducing it to the building sector. Accordingly, the excessive installation of a FCCHPS can be prevented, and its initial investment cost can be minimized. Wakui and Yokoyama [53] analyzed the energy-saving effects of 14 different scales of a SOFC-based mCHPS (0.2–1.5 kW) for single-family housing in Japan. A SOFC-based mCHPS of 0.6 kW was determined as the optimal operating size, resulting in annual PES of 17% in Japan. Mahlia