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Performance of residential fuel-cell-combined heat and power systems for various household types in Japan

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ARTICLE INFO

Article history:
Received 22 March 2018
Received in revised form
6 June 2018
Accepted 8 June 2018
Available online xxx

Keywords:
Residential energy demand
Fuel-cell-combined heat and power
Household characteristics
Energy cost
GHG emissions

ABSTRACT

A residential fuel-cell-combined heat and power (FC-CHP) system is considered a promising low-carbon technology that can reduce residential energy consumption and thus, achieve Japan's greenhouse gas (GHG) emissions reduction targets. However, to consider future directions for the systems' research and development, it is critical to understand the relationships between the performances of FC-CHP systems and residential energy demand profiles, which vary by household characteristic. This study evaluates the effects of applying city gas-fueled FC-CHP systems to Japanese households with different attributes. We compare total costs and GHG emissions for residential energy use between the FC-CHP systems and a conventional system. The economic performance results suggest that the basic PEMFC-CHP systems have an economic advantage only for four-person families with teenage children and further development efforts for low-output FC-CHP systems are required to enable various households save energy costs. The environmental evaluation results show that SOFC-CHP systems can drastically reduce GHG emissions from particularly small-sized households.

Introduction

Combined heat and power (CHP), or cogeneration, is an energy conversion technology that can simultaneously produce electricity and useful heat from a single energy source. Owing to its high energy efficiency, CHP systems have attracted much attention for the conservation of energy resources and mitigation of climate change. Historically, CHP systems have been applied to large-scale power plants and industrial facilities; the world's first CHP power plant was built in Manhattan in 1882 [1], following which CHP technologies have been applied to various manufacturing industries such as food, pulp and paper, chemical, and petroleum refining [2]. In recent years, the installed capacity of CHP systems in commercial facilities and residential dwellings has increased because of the technological improvement and cost reduction in smaller-scale systems whose capacity is generally under 10 MW [3]. In G8+5 countries, CHP systems are expected to provide 24% of total power generation by 2030 [4].

Fuel cell (FC) is a promising energy conversion device that can be applied to residential CHP (also known as micro-CHP) systems as well as automotive power sources and large-scale power plants; this can be attributed to its high power generation efficiency, low heat-to-power ratio, and low operation noises that are desirable for residential use [5,6]. Fuel cells were

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https://doi.org/10.1016/j.ijhydene.2018.06.044
0360-3199/

invented in the early 19th century and used as a power source for spacecrafts under Project Gemini, NASA's second human spaceflight program in the 1960s [7]. Since the 1970s, research, development, and demonstration projects on fuel cell vehicles and power plants have been conducted in the context of increasing environmental awareness and oil crisis [8]. With the proliferating aim to construct microgrid systems and utilize distributed energy resources, in the 1990s, CHP systems for commercial and residential buildings began receiving considerable attention [9]. A series of government-funded demonstration programs of residential FC-CHP systems have been conducted in Europe [10], Korea [11], and Japan [12,13]. Since the release of the world's first residential proton exchange membrane fuel cell (PEMFC) CHP systems in the Japanese market in 2009, new models have been launched every two years and 0.2 million units of residential FC-CHP systems have been installed in Japanese households as of May 2017 [14]. Fig. 1 shows the system price and power output capacity of residential PEMFC-CHP systems in Japan. The current model's price is less than half of the price of the first model released in 2009 as a result of the continuous efforts of system improvement, including the development of a low-output fuel cell stack. The rated power output of the current FC-CHP model in Japan is 0.7 kW. European countries have performed field trials of residential FC-CHP systems whose power output capacities are lower than those of the Japanese models [15].

In parallel with their development and demonstration, the economic and environmental benefits of residential FC-CHP systems have been evaluated over the past few decades [16]. Peacock and Newborough [17] and Hawkes and Leach [18] investigated the effects of applying 1 kW CHP systems using Stirling engines, gas engines, and fuel cells in single UK dwellings. They suggested that FC-CHP systems should have a large potential to both save energy costs and reduce carbon dioxide (CO_2) emissions. With the aim of finding the optimal design and operation strategy for residential FC-CHP systems, many studies have developed simulation models for FC-CHP systems using mathematical programming [19–24], system dynamics [25–29], and building simulation [30–32]. Through case studies based in Japan, Ren and his colleagues evaluated

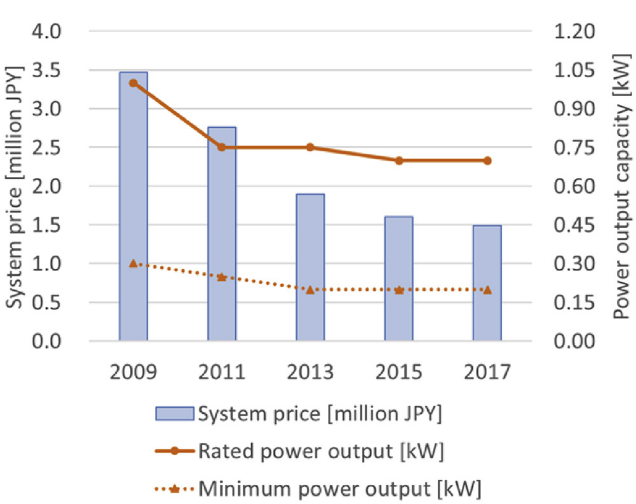

Fig. 1 – System price and power output capacity of residential PEMFC-CHP systems in Japan.

the economic and environmental performances of the FC-CHP systems with varying output capacities and employed different operation modes [21,22]. Ito [33] performed an economic and environmental assessment of FC-CHP systems using operation data on actual usage collected through a demonstration project in Japan [12,34]. While residential FC-CHP systems are assumed to provide electricity and heat only to a single household in most studies, there are only a few studies that investigated the effect of sharing electricity and heat produced from FC-CHPs with neighboring households [35–37]. Economic and environmental analysis have also been applied to integrated energy systems which combine FC-CHP and other residential energy technologies, such as battery [38–42], heat pump water heater [40,43], solar photovoltaics [42,44], solar thermal collector [45] and wind turbine [46].

The performance of residential CHP systems depends on residential energy use conditions and the technological specifications of CHP systems [36,47,48]. Wakui and his colleagues [40,41,49] developed a model for residential energy devices including FC-CHP and evaluated residential energy costs and primary energy consumptions considering various residential energy use conditions. They found that the optimal selection of residential energy devices depends on the number of household occupants who affect residential energy demand profiles. To evaluate the effect of residential energy technologies under different attributes, Ozawa et al. [50] developed a demand simulation model that can estimate the energy demand profiles of various household types and quantitatively revealed the influences of the number of occupants and their age on residential energy demand profiles.

Given the demographic changes in Japan, small families and elderly households account for a major part of the residential sector. Japan's birth rate has remained at a low level for many years and the population shows a declining trend from 2008. In addition, it is estimated that the Japanese population should decrease from 128 million in 2010 to 116 million in 2030 [51] and the average number of household members in Japan will decrease from 2.42 persons/household in 2010 to 2.22 persons/household in 2030 [52]. At the same time, Japan's life expectancy at birth has increased owing to medical advances and the average life expectancy of Japanese men and women is expected to extend from 79.6 to 86.3 years in 2010 to 82.4 and 88.7 years in 2030 [53]. Thus, by 2030, about 40% of the all households will be “elderly households” (households with heads aged over 65 years) [52]. It becomes important for the future to evaluate residential technologies for these households to reduce energy consumptions and GHG emissions from residential sector.

Hydrogen and fuel cell technologies are expected to play a key role in Japan's energy strategy [54]. According to Japan's road map for hydrogen and fuel cells [55], 5.3 million units of residential FC-CHP systems should be installed by 2030 to achieve Japan's Intended Nationally Determined Contributions (INDC; a 26% reduction of total greenhouse gas (GHG) emissions by FY 2030 compared with those in FY 2013). To consider future directions for the research and development of residential FC-CHP systems, it is important to understand the relationships between the performances of FC-CHP systems and residential energy demand profiles that vary by household characteristic—a topic which has not been fully

Please cite this article in press as: Ozawa A, Kudoh Y, Performance of residential fuel-cell-combined heat and power systems for various household types in Japan, International Journal of Hydrogen Energy (2018), https://doi.org/10.1016/j.ijhydene.2018.06.044