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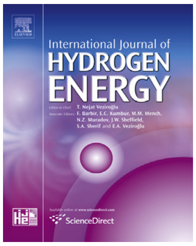

Economic and environmental assessment of residential micro combined heat and power system application in Japan

Hiroshi Ito *

Research Institute for Energy Conservation, National Institute of Advanced Industrial Science and Technology (AIST), 1-2-1 Namiki, Tsukuba, 305-8564, Japan

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A B S T R A C T

In May 2009, residential micro-combined heat and power systems (micro-CHPs) were launched onto the market under the standard name of "ENE•FARM" in Japan. Operation of the latest type released in 2015 was simulated (using commercial software) with the averaged load data from an actual demonstration project in Japan. Simulation results were then used in economic and environmental analysis. Economic analysis revealed that the target cost of a micro-CHP including the back-up boiler is about $6200 under current Japanese grid prices. This target is a capital cost to achieve the economic feasibility within ten years, and is approximately half of the current actual cost. According to environmental analysis, carbon dioxide emission (CDE) reduction with a micro-CHP is reliable even when the CDE factor of the grid electricity is as low as 200 g-CO_2/kWh. Under the current CDE factor in Japan, the application of a micro-CHP would reduce the CDE of the respective home by 19%.

Introduction

Combined heat and power (CHP) systems are energy conversion devices that use a single source of fuel to provide both electricity and heat. A CHP system applied on a residential scale is known as a micro-CHP whose electric output is typically in the range of 0.1–10 kW. A micro-CHP can replace or supplement grid electricity, and can act as a distributed power generation device in a customer's home.

Residential micro-CHP systems are usually designed and operated to meet the residential demand of electricity and heat. Natural gas (NG) is the most common fuel for residential micro-CHPs. There are several options for prime mover of such micro-CHPs, such as an internal combustion engine (ICE), a Stirling engine (SE), a proton exchange membrane fuel cell (PEMFC), and a solid oxide fuel cell (SOFC) [1,2]. Among them, PEMFC has attractive features for residential application, such as high generation efficiency, excellent part-load management, and low emissions. The relatively low operating temperature of PEMFCs (~80 °C) would limit the usage of recovered heat, though it would be favorable under frequent start/stop operation. The recovered heat at this temperature level must be sufficient for residential use of heat, that is, domestic hot water (DHW) and space heating.

To maximize the economic and environmental merit provided by micro-CHP installation, both size and operating strategy are significantly important issues and have been

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* Tel.: +81 29 861 7262; fax: +81 29 851 7523.
E-mail address: ito.h@aist.go.jp.

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Nomenclature

Symbols

C_{CHP}	capital (installation) cost of micro-CHP excluding the cost of back-up boiler, $
P_E	rated power of electricity, kW
P_T	rated power of recovered heat, kW
r_E	electricity price, $/kWh
r_G	natural gas price, $/Nm^3
S_E	share of micro-CHP in electricity
S_T	share of micro-CHP in thermal energy (heat)
α_{CDE}	carbon dioxide emission factor of electricity grid, g-CO_2/kWh
γ_C	capacity factor of micro-CHP
ΔR	annual cost saving in operation, $/yr
η_E	electrical efficiency
η_T	thermal (heat recovery) efficiency
η_{total}	overall (electricity and heat recovery) efficiency
π_{PB}	simple payback period, yr

Abbreviations

BOP	balance of plant
CDE	carbon dioxide emission
CHP	combined heat and power
DHW	domestic hot water
FC	fuel cell
HHV	higher heating value
ICE	internal combustion engine
LHV	lower heating value
LPG	liquefied petroleum gas
METI	Ministry of Economy, Trade and Industry (of Japan)
NEF	New Energy Foundation (of Japan)
NG	natural gas
PEMFC	proton exchange membrane fuel cell
SE	Stirling engine
SOFC	solid oxide fuel cell

evaluated for residential micro-CHP application by several researchers [3–8]. The operation of micro-CHPs installed in residential houses follows the electricity demand and/or heat demand. The demand is determined by a wide variety of parameters, such as floor area, type of building (detached or terraced), the number of residents, climate, and life style. De Paepe et al. [3] and Shaneb et al. [7] simulated both the economic and environmental impact of micro-CHPs installed at different types of residential buildings. Teymouri-Hamzehkolaei and Sattari [9] carried out a feasibility study of micro-CHPs installed in different climate zones in Iran. As for operating strategy, modeling studies have been carried out by Hawkes and Leach [8], Matics and Krost [10], and Oh et al. [11].

Application of a micro-CHP introduces a shift in the energy source from grid electricity to fuel of the CHP (i.e., natural gas). Considering the economic impact of micro-CHPs, prices of both the grid electricity and fuel must be taken into account. Sundberg and Henning [12] clearly presented the effect of fuel price on the economic feasibility of CHPs. Because the prices of grid electricity and fuel significantly differ depending on the region or country, a geographical dependence must also be considered when evaluating the economic merit.

When a micro-CHP is fueled by NG, carbon dioxide emission (CDE) is inevitable even when PEMFC is adapted as a prime mover. In fact, about 190 g of CO_2 per kWh would be emitted even assuming that all the energy from natural gas is converted into useful energy for electricity and heat (i.e., conversion efficiency = 100%). The CDE factor of the electricity grid is lower than this value in some countries (e.g., Canada, Brazil, Norway), though higher in most countries. There is no environmental benefit provided by micro-CHPs fueled by natural gas in such "green" countries. As several previous authors mentioned [3,13,14], the carbon intensity of the grid in the object area needs to be taken into account.

During the past 20 years, research and development (R&D) of residential micro-CHPs has been executed in numerous countries, some via national programs [15]. The R&D of the SOFC-based micro-CHPs has been active recently [16–18], though that of the PEMFC-based has been rather advanced. Napoli et al. [16] presented a techno–economic analysis for the both of PEMFC- and SOFC-based residential micro-CHPs. They suggested that the PEMFC-based type has high potential to reduce the grid (electricity) dependence, while the SOFC-based type is preferable from the view of the reduction of primary energy consumption. Pellegrino et al. [17] discussed the role of policy support for the market-entry of the SOFC-based micro-CHPs. Kupecki [18] developed a mathematical model for predicting the SOFC-based micro-CHP system performance under off-design conditions. Kupecki [18] pointed out that characteristics of balance of plant (BOP) components have a strong effect on the system performance.

In Japan, based on strong interest and support from the government, a large-scale stationary fuel cell demonstration project (hereinafter simply called the "Demo Project") was executed from 2005 to 2009. In total, 17 energy utility (oil or gas) companies and 5 PEMFC suppliers participated in that Demo Project. During that project, a vast amount of data was published [19,20] not only data of the introduced micro-CHPs (efficiency, frequency of trouble, and cost) but also that of the consumers (energy demand, energy share of micro-CHPs in meeting the total demand). These data are invaluable for researchers and developers. Staffell and Green [21,22] used these Japanese data to forecast the capital cost reduction. Due to the effort of energy utility companies and fuel cell suppliers, residential micro-CHPs under the standard name of "ENE•FARM" were launched commercially onto the market in May 2009, just after the Demo Project. The number of installations had been increased year by year, and the cumulative number in the commercial phase exceeded 150,000 by the end of 2015. The capital cost of a CHP unit had been also decreased successfully; the latest model released in 2015 was about one-fifth the cost of that at the beginning of the Demo Project (in 2005) and about half that of the first commercial model (in 2009). These Japanese micro-CHPs entered the phase in which their economic and environmental assessment can be performed based on real field results.

The contributing share of a micro-CHP output to meet the total demand of the site (electricity and heat) is a critical parameter for both economic and environmental assessment.