Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Technological assessment of residential fuel cells using hydrogen supply systems for fuel cell vehicles

Takahide Haneda [a,b,*], *Yusuke Ono* [a], *Takashi Ikegami* [a], *Atsushi Akisawa* [a]

[a] *Tokyo University of Agriculture and Technology, 2-24-16, Naka-cho, Koganei, Tokyo, Japan*
[b] *Tokyo Gas Co., Ltd, Energy Research Institute, 1-7-7, Suehiro-cho, Tsurumi-ku, Yokohama, Kanagawa, Japan*

ARTICLE INFO

Article history:
Received 8 April 2017
Received in revised form
18 July 2017
Accepted 22 August 2017
Available online xxx

Keywords:
Fuel cell
PEFC
Fuel processor system
Hydrogen production
Fuel cell vehicles

ABSTRACT

Widespread of the fuel cell vehicles (FCV) is one of the essential solutions to CO_2 emission mitigation. However there were only 81 working hydrogen stations distributed in Japan in January 2017. Therefore, it has become increasingly necessary to establish the hydrogen stations. In this study, we focus on the unutilized hydrogen production capacity of a fuel processor system (FPS) incorporated in a residential fuel cell cogeneration system. We proposed a system which the FPS and fuel cell stacks are operated independently at their respective efficient load factors, and which can produce hydrogen for the FCV using the unutilized capabilities of the FPS. An optimum scheduling model for the operation of the FPS and the fuel cell stacks was developed to evaluate annual hydrogen production for the FCV for 24 households. As the results, it was found that all households have the capacity to produce at least 1,040 Nm^3/year of hydrogen, which a FCV can run 8,000 km in a year. Furthermore, we evaluated the primary energy reduction potential were in relation to the different power and hot water demands. As the results, it was found that the primary energy reduction effect slightly increases with increasing hydrogen supply up to about 8,000 km worth of FCV hydrogen.

Introduction

The electrification of mobility is an indispensable element in a wider strategy for achieving the reduction in greenhouse gas emissions. The fuel cell vehicles (FCV), being more efficient than the current internal combustion vehicles owing to the use of a direct energy conversion process [1], are considered the most promising technology next to battery and plug-in hybrid vehicles, and one of the essential solutions for mitigating the carbon dioxide (CO_2) emissions. Their introduction to the market is scheduled in 2015 and the aim was to spread 40,000 units by 2020, 250,000 units by 2025 and 800,000 units by 2030 in Japan [2]. In order to realize this goal, it is necessary to increase the number of hydrogen fueling stations since these stations are essential for operating FCV.

A hydrogen fueling station, which supplies high-pressure hydrogen used as fuel in FCV, requires equipment [3] for charging hydrogen constantly, safely and reliably in about

* *Corresponding author*. Tokyo Gas Co., Ltd, Energy Research Institute, 1-7-7, Suehiro-cho, Tsurumi-ku, Yokohama, Kanagawa, Japan.
E-mail address: haneda@tokyo-gas.co.jp (T. Haneda).

http://dx.doi.org/10.1016/j.ijhydene.2017.08.152

several minutes, while maintaining the quality [4]. As a result of the technical and economical obstacles, the spread of these stations has been delayed and there were only 81 working hydrogen stations distributed across Japan as of January 2017 [5]. Therefore, it has become increasingly necessary for the network of hydrogen fueling stations to grow and it is an urgent issue keeping in mind the goal set by the Japanese government [2], which is to introduce hydrogen fueling stations, 160 units by 2020 and 320 units by 2025 in Japan.

Residential polymer electrolyte fuel cell cogeneration system (residential PEFC system), which generates water, heat, and electricity without emitting pollutants via an electrochemical reaction with hydrogen as fuel and oxygen or air as oxidant [6–8] is considered a promising alternative energy conversion device. It was launched in 2009 [9,10], and more than 150,000 units have been installed in the Japanese market as of 2015 [11]. Moreover, it aims to spread 1.4 million units of residential PEFC systems by 2020 and 5.3 million units by 2030 in Japan [2].

A residential PEFC system consists of a fuel processing system (FPS), fuel cell stack, grid connected inverter, an auxiliary boiler, storage tank for hot water, and so on. The FPS, comprising desulfurization, steam reforming and CO shift reactors, reforms the city gas into hydrogen and this hydrogen reacts with oxygen in the fuel cell stack to generate electricity and heat. The electricity generated is converted into AC power by a grid connected inverter, and the converted electricity is supplied to support the electrical load. The heat energy generated by the FPS and the fuel cell stack is collected and stored in a storage tank as hot water in order to meet the demand for heat. Because a residential PEFC system operates based on the hot water demand in a house, it is known that these systems can experience long stopping times, particularly in the summer and late at night when demand for hot water is low; and when the system is stopped, the FPS is stopped as well [12]. In this research, we focus on the hydrogen production function of the residential PEFC system and propose an energy system that produces hydrogen as fuel for FCVs using the hydrogen production capacity available during times when the PEFC system is not operating or is operating only partially. The residential solid oxide-type fuel cell cogeneration system (residential SOFC system) can be considered conceptually similar to this approach, but as the residential SOFC system doesn't have any CO removing system, such as the CO shift reactors [13,14] present in the FPS of a residential PEFC system, it has more difficulty producing hydrogen for FCV use. Additionally, residential PEFC systems are being more widely introduced into the market than residential SOFC systems are. Therefore, in this study we focus on a residential PEFC energy system which is expected to be the best equipped to provide FCV fuel in place of hydrogen fueling stations until such infrastructure can be fully developed.

The objective of this study was to use a mathematical model to evaluate the hydrogen supply potential of the residential PEFC system with hydrogen supply function for FCV (PEFC system with hydrogen supply) by conducting a simulation for multiple households with varying power and hot water demands. In addition, this work aimed to optimize the operation schedule to minimize the energy costs, including electric power costs and city gas costs, of the PEFC system with hydrogen supply for households with different demands. Based on the optimization results, the primary energy reduction potential were calculated in relation to the different power and hot water demands.

Mathematical model

Nomenclature

Table 1 show the definitions used in this paper, including symbols used in Fig. 1 and in Equation (1)–(32).

System model

A residential PEFC system produces hydrogen from city gas using a FPS, generating both hot water and electric power simultaneously with a fuel cell stack fueled by the generated hydrogen. A residential PEFC system is composed of a FPS, a fuel cell stack, a tank for hot water, and an auxiliary gas boiler for additional hot water production in case the heat from the fuel cell stack cannot cover the hot water demand [12]. Conventional residential PEFC system (conventional PEFC system) produce the amount of hydrogen necessary so that the FPS and the fuel cell stack are operated at interlocked load ratios. It is known that the power generation efficiency of the fuel cell stack is higher at lower load [15], but on the other hand, the reforming efficiency of the FPS is higher at higher load [16]. For this reason, the proposed PEFC system independently operates the fuel cell stack at a low load and the FPS at a high load, enabling operation that is more efficient. Additionally, in a conventional PEFC system, excess hydrogen is supplied to the fuel cell stack to prevent local deterioration due to hydrogen shortage [17] and avoid a reduction in the power generation efficiency of the fuel cell stack [18]. The excess hydrogen that is not used as fuel for power generation by the fuel cell stack is returned to the FPS, where it is used as fuel to provide the heat of the reforming reaction. When a hydrogen production function is added to a conventional PEFC system, it is possible to operate the system more efficiently using additional city gas instead of excess hydrogen for reaction heat in the FPS. Considering the above concept, in this study the authors designed an optimized PEFC system with a hydrogen supply, adding a hydrogen production function to the conventional power generation and hot water supply cogeneration functions. Notably, this PEFC system with hydrogen supply makes it possible to decouple the load of the fuel cell stack from the FPS, functionally operating these systems independently by allowing excess generated hydrogen to be stored in an installed tank. Additionally, this system uses the city gas supply instead of excess generated hydrogen as fuel for the heat of the reforming reaction in the FPS. The system components, as well as the electricity, heat, hydrogen, and city gas flows targeted in this study, are shown in Fig. 1.

Calculation conditions

In the proposed system, electric power is supplied by both the power grid and the fuel cell stack, while hot water is supplied