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Technological assessment of PEFC power generation system using by-product hydrogen produced from a caustic soda plant

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ABSTRACT

The potential of an energy system that comprises a hydrogen-fueled PEFC (H2-PEFC), a boiler, and a gas turbine combined heat and power system (GT), using by-product hydrogen produced from a caustic soda plant was evaluated using a mathematical model based on linear programming. Based on the optimization results to minimize the system cost by optimizing the equipment capacity and energy balance of the energy system, the system cost reduction effect and CO_2 reduction effect were calculated in relation to the power generation efficiency and the installation cost of the H2-PEFC. As a result, the conditions for the H2-PEFC where a system cost reduction could be achieved in the PEFC, boiler, and GT system, compared with the boiler system, were clearly shown to be an initial cost lower than 3500 $/kW or a power generation efficiency greater than 50%.

Introduction

Sodium hydroxide (NaOH) is one of the most widely used industrial chemicals, such as in the pulp, paper, alumina, textile, electroplating, detergent, and waste water industries [1]. The global consumption of NaOH is approximately 80 million tons per year and set to expand at nearly 3% compound annual grows rate during 2016–2020 with Asia-Pacific leading all regions with a 50% market share [2]. In caustic soda plants, NaOH is manufactured by the electrolysis of brine (salt solution) consuming huge amounts of electricity [3,4]; in Japan the average electricity for each ton of NaOH produced is 2.5 MWh [5]. Considering the rising cost of electricity, the caustic soda industry needs a technological breakthrough to decrease energy consumption [6].

Hydrogen is also produced as by-product along with NaOH in caustic soda plants and is often discarded as waste or used for heat production, except when a neighboring chemical plant can use the hydrogen as a chemical feedstock [7]. Generating electricity from the by-product hydrogen could substantially reduce electricity costs of a caustic soda plant.

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Polymer electrolyte fuel cells (PEFC) is considered a promising alternative energy conversion device and the best match to the hydrogen flow produced by caustic soda plants because it has the highest power generation efficiency and the best load following capability in the power generator for the hydrogen fuel. These devices generate water, heat, and electricity without emission of pollutants via an electrochemical reaction of hydrogen as a fuel with oxygen or air as an oxidant [8–10]. Residential PEFC cogeneration systems were launched in 2009 [11–13], and more than 150,000 units have been installed in the Japanese market as of 2015 [14]. Additionally, recent interest has increased in the development of large-scale hydrogen-fueled PEFC, with increasing focus on the research and development of hydrogen energy as a renewable resource to eliminate dependence on fossil fuels [10,15,16]. To our Knowledge, Ballard and Nedstack currently have been focusing on hydrogen that is vented into the atmosphere and generating electricity from wasted hydrogen could substantially reduce electricity costs of a caustic soda plant. Ballard Power Systems has announced the installation at the First Energy Generation Corp's Eastlake Plant in Ohio [17] and a 1 MW PEFC unit for wasted hydrogen at a bleach plant in California [17]. NedStack Fuel Cell Technology has put a 1 MW PEFC Power Plant for wasted hydrogen that is vented into the atmosphere into operation at Solvay, in 2011 [17]. However, the amount of wasted hydrogen has been decreasing annually [7] and is much smaller than hydrogen used for heat production that is essential to heat fluids, particularly to achieve NaOH concentrations of 50% [7]; in Japan, the fraction of the wasted hydrogen is 5% while 47% is used for heat production [18]. Therefore, we have focused on hydrogen used for heat production and have proposed the energy system with high efficiency conversion for the hydrogen. The concept of the energy system is that by supplying natural gas to the plant instead of hydrogen for heat production and using the hydrogen that has the high quality with about 1 ppm of NaOH as the only contaminant, for hydrogen-fueled PEFC the exergy of the plant can be vastly improved and the plant's energy consumption and CO_2 emissions can be dramatically reduced. The inferred global production of hydrogen as a by-product from caustic soda plants in 2010 is 16 billion Nm^3 [7]. High efficiency conversion (50% (LHV)) of this quantity of hydrogen could yield around 240 TWh of electricity. At present, the fraction of hydrogen used for heat production could provide 110 TWh of electricity, which is 8% of the plant's electricity consumption.

The objective of this study was to use a mathematical model to evaluate the potential of an energy system that comprises a hydrogen-fueled PEFC (H2-PEFC), a boiler, and a gas turbine combined heat and power system (GT), using by-product hydrogen produced from a caustic soda plant to save energy and CO_2 emissions. The scope of this work was to optimize the equipment capacity and energy balance to minimize the system cost, including the energy cost, maintenance cost and the amortization cost of the energy system. Based on the optimization results, the system cost reduction effect and CO_2 reduction effect were calculated in relation to the power generation efficiency and the installation cost of the H2-PEFC.

Methods

To minimize the system cost of the energy system in a caustic soda plant, the optimum equipment capacity and energy balance of the boiler, H2-PEFC, and GT was calculated based on linear programming.

Mathematical model

The following three energy system cases were constructed for the model for the technological assessment. Figs. 1–3 show the configurations of these energy system cases, which are (a) boiler system, (b) PEFC and boiler system, and (c) PEFC, boiler, and GT system. Table 1 shows the definitions of the symbols used in Figs. 1–3.

(a) Boiler system

The boiler system represents the conventional system and is composed of a boiler. The boiler generates all its steam for the plant from natural gas and by-product hydrogen produced from the plant.

(b) PEFC and boiler system

The PEFC and boiler system is composed of a H2-PEFC and a boiler. The H2-PEFC generates power and hot water from by-product hydrogen produced from the plant. The boiler generates all its steam for the plant from natural gas and the remaining by-product hydrogen produced from the plant that is not consumed by the H2-PEFC.

(c) PEFC, boiler, and GT system

The PEFC, boiler, and GT system is composed of a H2-PEFC, a boiler, and a GT. The H2-PEFC generates power and hot water from by-product hydrogen produced from the plant. The GT generates power and steam for the plant from natural gas and the remaining by-product hydrogen produced from the plant that is not consumed by the H2-PEFC. The boiler generates all remaining steam for the plant from natural gas and any remaining by-product hydrogen from the plant that is not consumed by the H2-PEFC or the GT.

Constraints

The output and energy balance of the boiler, H2-PEFC, and GT were set to satisfy Eqs. (1)–(10), which means all steam was generated in the energy system from natural gas and by-product hydrogen produced from the plant. Hot water generated by the PEFC supplied the boiler with its water supply for preheating, and any remaining hot water was set as waste heat. The mixing rates of by-product hydrogen and natural gas for the boiler and GT were set under 50%.

$$f_3(t) = e_1 \times (f_1(t) + f_4(t) + h_3(t)) \quad (1)$$

$$f_5(t) + f_6(t) = e_2 \times h_4(t) \quad (2)$$