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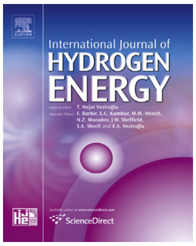

Economic evaluation with sensitivity and profitability analysis for hydrogen production from water electrolysis in Korea

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ARTICLE INFO

Article history:
Received 10 October 2016
Received in revised form
28 December 2016
Accepted 30 December 2016
Available online xxx

Keywords:
Economic evaluation
Water electrolysis
Cost estimation
Sensitivity analysis
Profitability analysis
Steam methane reforming

ABSTRACT

Economic evaluation for water electrolysis compared to steam methane reforming has been carried out in terms of unit hydrogen production cost analysis, sensitivity analysis, and profitability analysis to assess current status of water electrolysis in Korea. For a hydrogen production capacity of 30 $Nm^3\ h^{-1}$, the unit hydrogen production cost was 17.99, 16.54, and 20.18 $\$\ kg\ H_2^{-1}$ for alkaline water electrolysis (AWE), PEM water electrolysis (PWE), and steam methane reforming (SMR), respectively with 11.24, 10.66, and 11.80 for 100 $Nm^3\ h^{-1}$ and 8.12, 7.72, and 7.59 $\$\ kg\ H_2^{-1}$ for 300 $Nm^3\ h^{-1}$. With sensitivity analysis (SA), the most influential factors on the unit hydrogen production cost depending on the hydrogen production capacity were determined. Lastly, profitability analysis (PA) presented a discounted payback period (DPBP), net present value (NPV), and present value ratio (PVR) for a different discount rate ranging from 2 to 14% and it was found that a discounted cash flow rate of return (DCFROR) was 14.01% from a cash flow diagram obtained for a hydrogen production capacity of 30 $Nm^3\ h^{-1}$.

Introduction

Hydrogen has been extensively used in conventional industrial sectors such as petroleum, petrochemical, chemicals, and fertilizer [1–3] to name a few and recent advancements in fuel cell electric vehicles (FCEVs) with CO_2-free emissions have initiated a significant increase of hydrogen demand. Moreover, a newly emerging technology like CO_2 utilization requires the use of H_2 as a reactant to chemically convert CO_2 into useful chemicals such as a synthetic natural gas (SNG) [4,5] and methanol [6,7]. Hydrogen is an energy carrier that should be produced from various sources [8] and numerous methods have been used for hydrogen production such as steam reforming, partial oxidation, water-gas-shift reaction, pyrolysis, plasma reforming, biomass gasification, and water electrolysis (WE) [9–18]. Currently, steam methane reforming (SMR) as shown in Equation (1) is considered as one of the

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http://dx.doi.org/10.1016/j.ijhydene.2016.12.153

Please cite this article in press as: Lee B, et al., Economic evaluation with sensitivity and profitability analysis for hydrogen production from water electrolysis in Korea, International Journal of Hydrogen Energy (2017), http://dx.doi.org/10.1016/j.ijhydene.2016.12.153

most economical processes for hydrogen production and this technology accounts for about 48% of global hydrogen production [19,20].

$$CH_4 + 2H_2O \rightarrow CO + 3H_2 \quad (1)$$

However, because this SMR uses methane or fossil fuels as reactants and produces CO_2 contributing to global warming, more environmentally friendly hydrogen production methods are being sought to meet an increasing hydrogen demand and environmental standards simultaneously. Among many alternatives, WE is considered as the most practical method for the production of hydrogen with no fossil fuels used and no CO_2 produced [8].

In WE, hydrogen is produced from water by splitting water into hydrogen and oxygen via applied electricity (Equations (2)–(4)) and this process is environmentally-friendly with no additional hydrogen purification unit required [21]. Among various WE techniques, alkaline [22–30] and polymer electrolyte membrane (PEM) WE [31–41] are considered as two primary types of WE currently being developed for near-term commercialization.

$$\text{Cathode } (-)\text{: } 2H^+ + 2e^- \rightarrow H_2. \quad (2)$$

$$\text{Anode } (+)\text{: } 2H_2O \rightarrow O_2 + 4H^+ + 4e^-. \quad (3)$$

$$\text{Overall reaction: } 2H_2O \rightarrow 2H_2 + O_2. \quad (4)$$

One of the most promising areas for H_2 produced from WE is a H_2 fueling station for FCEVs. Fig. 1 shows a process flow diagram for a H_2 fueling station using alkaline water electrolysis (AWE), high pressure PEM water electrolysis (PWE), and SMR. Basically, a produced H_2 from WE is stored and then dispensed to FCEVs while the one from SMR should be purified using pressure swing adsorption (PSA) to meet strict requirements for FCEVs before being sent for storage and dispenser. Contrary to AWE and SMR requiring a compressor to pressurize the produced H_2 for dispenser, no compressor is necessary for high pressure PWE due to the production of pressurized H_2 enough for a dispenser. Zeng and Zhang [22] reported a comprehensive review for AWE examining the current status of the technology and identifying the R&D areas to be addressed for the commercialization of AWE. In addition, future research directions focusing on electrode materials, electrolyte additives, and bubble management, etc. were extensively discussed. A lot of works have been focused on the development of efficient electro-catalysts for hydrogen evolution reaction or oxygen evolution reaction [24,26,28]. Moreover, Egelund et al. [30] demonstrated a low cost method for electrode manufacturing and reported a metallic composite electrode material to improve oxygen evolution reaction at high temperature in commercial AWE. For PWE, Carmo et al. [37] presented a state-of-the-art PWE technology showing higher current density and better partial load range compared to AWE. At the same time, some challenges still existing for PWE such as cross-permeation phenomenon, thicker membranes, and expensive materials and components were identified in order to provide future research directions. Clarke et al. [32] constructed a stand-alone PWE system operating at up to ~4 kW input and the system was self-pressurizing and fail-safe. Millet et al. [33] also reported their recent advances in PWE technology including electro-catalyst, membrane electrode assemblies, cell efficiency, safety, stack design and optimization, etc. for electrolyzers with a hydrogen production capacity of 5 $Nm^3\ h^{-1}$. Grigoriev et al. [35] investigated the possible safety issues related with high pressure PWE operating at pressure up to 130 bar and pointed out that hydrogen concentration in the oxygen gas and vice versa were the most influential risks. They also proposed possible solutions to reduce contamination levels such as the use of thicker membranes, membranes with low gas permeability, and external catalytic gas combiners. Rahim et al. [39] developed mass transport model suitable for PWE and discussed several issues encountered in PWE model.

In addition to technical reports mentioned above, economic analysis for WE at various capacities has been reported. Genovese et al. [42] performed a comprehensive economic analysis for both AWE and PWE based on state-of-the-art technology of WE in the US and estimated a base-case H_2 production cost in 2009 of 5.20 \$ kg H_2^{-1} for a forecourt refueling station with a H_2 capacity of 1500 kg H_2 d^{-1} and 3.00 \$ kg H_2^{-1} for a central production facility with a H_2 capacity of 50,000 kg H_2 d^{-1}. For PWE, Ainscough et al. [43] estimated respective H_2 production costs of 5.14 \$ kg H_2^{-1} and 5.12 \$ kg H_2^{-1} in 2013 for a forecourt (1500 kg H_2 d^{-1}) and a centralized production (50,000 kg H_2 d^{-1}) of H_2 based on Hydrogen Analysis version 3 (H2A v3) in the US. They also projected reduced H_2 production costs of 4.23 \$ kg H_2^{-1} and 4.20 \$ kg H_2^{-1} in 2025 for a forecourt and centralized production, respectively. Parthasarathy and Narayanan [44] summarized H_2 production costs of 0.75 \$ kg H_2^{-1} for SMR, 0.92 \$ kg H_2^{-1} for coal gasification, 1.21–2.42 \$ kg H_2^{-1} for biomass gasification, 2.56–2.97 \$ kg H_2^{-1} for electrolysis, and 4.98 \$ kg H_2^{-1} for a photocatalytic process from various sources based on several studies. In addition, Gim and Yoon [45] performed comparative economic analysis for on-site hydrogen refueling stations in Korea using AWE and SMR. For a H_2 production capacity of 30, 100, and 300 $Nm^3\ h^{-1}$, they reported a unit hydrogen production cost in 2012 of 14.6, 10.0, and 7.8 \$ kg H_2^{-1} (AWE) and 17.2, 10.7, and 7.1 \$ kg H_2^{-1} (SMR), respectively. Their results showed that AWE is more economical for a H_2 production capacity $\leq$100 $Nm^3\ h^{-1}$ while SMR is more feasible for a H_2 production capacity $\geq$300 $Nm^3\ h^{-1}$ based on economy of scale.

With growing interests in WE worldwide including Korea as a practical and environmental-friendly method to meet increasing hydrogen demand, it is a timely approach to investigate the economic feasibility of WE while reflecting its current status in Korea. To assess an economic status of WE in Korea, an economic analysis targeting hydrogen production capacity of 30, 100, and 300 $Nm^3\ h^{-1}$ was carried out through unit hydrogen production cost calculations based on cost data obtained from a commercial supplier (EM Korea) and

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