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Economic feasibility studies of high pressure PEM water electrolysis for distributed H_2 refueling stations

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ABSTRACT

In this paper, we report economic feasibility studies focusing on profitability analysis of high pressure polymer electrolyte membrane (PEM) water electrolysis for distributed H_2 refueling stations in Korea. From capital and operating costs, a unit H_2 production cost of 6.24 $ kgH_2^{-1} was obtained for a H_2 capacity of 700 $m^3\,h^{-1}$, which is equivalent to handling about 300 fuel cell electric vehicles. Based on cost estimations, profitability analysis using cash flow diagrams was performed to assess the economic feasibility of high pressure PEM water electrolysis and various key economic indicators like net present value (NPV), discounted payback period (DPBP), and present value ratio were obtained for both different discount rates and capacity factors. In conclusion, employment of high pressure PEM water electrolysis was found to be economically profitable showing reasonably high NPVs (16–52 MM$) and short DPBPs (4–7 years).

1. Introduction

Hydrogen (H_2) widely used in various industry such as petrochemical, petroleum refining processes, fertilizer, fuel cell stacks, fuel cell electric vehicles (FCEVs), and chemicals [1–3] has taken the spotlight as an eco-friendly energy carrier that can possibly replace a current fossil fuel based energy production. H_2 has been produced so far through various methods such as steam methane reforming (SMR) [4–6], oil/naphtha reforming [7–9], coal gasification [10–12], and water electrolysis (WE) [13–15]. Most (about 96%) of H_2 production has been from fossil fuels and in particular SMR is the most widely used method for H_2 production accounting for about 48% in a world-wide H_2 production [16]. However, SMR also produces CO_2, a greenhouse gas requiring the development of an eco-friendly H_2 production method to replace this SMR. Among many potential candidates, WE has gained much attention as a CO_2-free H_2 production method. In addition to pure H_2 production, recent studies showed that power to gas (P2G) and power to liquid/fuel (P2L/P2F) technology are also feasible to convert H_2 produced from WE into useful products like methane, methanol, dimethyl ether (DME), etc. via surplus electricity from wind turbine or solar cells [17–20].

With applied electricity, water is decomposed into H_2 and O_2 in WE as shown in Eqs. (1)–(3). The types of WE that are under active development are alkaline water electrolysis (AWE) [21–24], polymer electrolyte membrane (PEM) water electrolysis (PWE) [25–28], and solid oxide electrolyzer cell (SOEC) [29–32].

$$\text{Cathode } (-):\ 2H^+ + 2e^- \rightarrow H_2 \quad (1)$$

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

$$\text{Overall reaction: } 2H_2O \rightarrow 2H_2 + O_2 \quad (3)$$

AWE is a water electrolysis method using an alkaline electrolyte (20–30% KOH, NaOH solution) and a separation membrane to split H_2 and O_2. AWE has advantages of convenient construction and operation at high pressure, but it has relatively low current density and efficiency due to low operating temperature and requires high maintenance cost because of membrane corrosion from electrolyte solution [33–35]. In contrast, PWE has high current density and efficiency [36–38] and can be operated at a higher pressure than AWE enough to possibly eliminate the use of compressor to pressurize produced H_2. SOEC under

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Nomenclature

AWE	Alkaline water electrolysis
CEPCI	Chemical engineering plant cost index
CFD	Cash flow diagram
CRF	Capital recovery factor
DDB	Double declining balance
DME	Dimethyl ether
DPBP	Discounted payback period
FCEV	Fuel cell electric vehicle
FCI	Fixed capital investment
MACRS	Modified accelerated cost recovery system
NPV	Net present value
P2F	Power to fuel
P2G	Power to gas
P2L	Power to liquid
PA	Profitability analysis
PEM	Polymer electrolyte membrane
PVR	Present value ratio
PWE	Polymer electrolyte membrane water electrolysis
SA	Sensitivity analysis
SF	Stream factor
SL	Straight line
SMR	Steam methane reforming
SOEC	Solid oxide electrolyzer cell
TEA	Techno-economic analysis
US DOE	United States Department of Energy
WE	Water electrolysis
WCI	Working capital investment

development can be operated at a high temperature due to the usage of thermally stable solid oxide and has high conversion efficiency and low electricity consumption [39–41].

Fig. 1 shows a schematic of a H_2 refueling station for FCEVs using high pressure PWE currently being developed in Korea. Compared to AWE, a compressor is not required for high pressure PWE thus leading to possible cost savings in capital and operating costs. The H_2 production capacity considered in this study is 700 $m^3 h^{-1}$ from PWE under capacity factors from 20 to 80% load that can handle about 300 FCEVs a day (estimated from 14 FCEVs a day with 30 $m^3 h^{-1}$).

Techno-economic analysis (TEA) to evaluate both technical and economic analysis is essential to determine the feasibility of a process of interest [42,43] and various research groups reported TEA studies regarding PWE. Tremel et al. [25] performed TEA for the synthesis of methanol, diesel, DME, synthetic natural gas, and ammonia from hydrogen production through WE and concluded that methanol production is the best option based on its feasibility to implement. Kopp et al. [44] carried out technical and economic analysis of 6 MW PEM electrolysis and reported the calculated efficiency of the P2G plant based on three options, which are electricity purchased at the European power exchange, surplus electricity from a marketing company, and participating in the control reserve market. Ferrero et al. [45] performed techno-economic assessment of P2G using H_2 obtained from variable renewable electricity storage through alkaline, PEM, and SOEC WE and estimated H_2 costs in 2030 scenario of 2.0–2.3 € kg^{-1} for mobility and 1.0–1.2 € kg^{-1} for grid injection. In our previous studies [3,46], comprehensive economic analysis though a unit H_2 production cost, sensitivity analysis (SA), profitability analysis (PA) employing a discounted cumulative cash flow diagrams (CFDs), and uncertainty analysis using a Monte-Carlo simulation method targeting various H_2 production capacities for H_2 refueling stations in Korea was conducted. Unit H_2 production costs of 17.99, 16.54, and 20.18 $ kgH_2^{-1} were estimated for AWE, PWE, and SMR for a H_2 refueling station with a H_2 production capacity of 30 $m^3 h^{-1}$. The main difference of a unit H_2 production cost from the work by Ferrero et al. [45] can be ascribed to a lower H_2 production capacity. With these unit H_2 production costs, discounted cumulative CFDs were constructed to provide discounted payback periods (DPBPs, a period required to recover all fixed capital investment (FCI)) for different discount rates of 2, 6, 8, 10, and 14%. Furthermore, uncertainty analysis using a Monte-Carlo simulation method showed significantly changeable unit H_2 production costs and provided useful economic guidelines to properly take economic fluctuations into account.

Extending our previous TEA studies coupled with Korean government's recent plan to construct about 200 H_2 refueling stations by 2025, here we report the economic feasibility of high pressure PWE for H_2 refueling stations in Korea with a H_2 production capacity of 700 $m^3 h^{-1}$, which is considered as distributed H_2 production by US DOE [47]. In particular, a unit H_2 production cost based on capital and operating costs, SA to determine the most influential economic factors, and discounted cumulative CFDs to obtain DPBP, net present value (NPV, net profit at the end of the process), and present value ratio (PVR, ratio of negative cash flows and positive cash flows) were analyzed to properly evaluate techno-economic feasibility of high pressure PWE under active development in Korea.

2. Method

2.1. Unit H_2 production cost

Economic analysis methods employed in this paper were based on the work of Turton et al. [48] and a unit H_2 production cost for 700 $m^3 h^{-1}$ was estimated from our previous data for 30, 100, and 300 $m^3 h^{-1}$ [3]. Total costs are the sum of capital costs and operating costs. Capital costs include H_2 production equipment, storage, compressor, pump, dispenser, construction, and supplement while operating costs consist of electricity, labor, maintenance, other operating cost, water, land rent, and natural gas. All economic data were adjusted to 2015 by using chemical engineering plant cost index (CEPCI) of 547.2 as of October 2015. To convert capital costs into annualized ones,

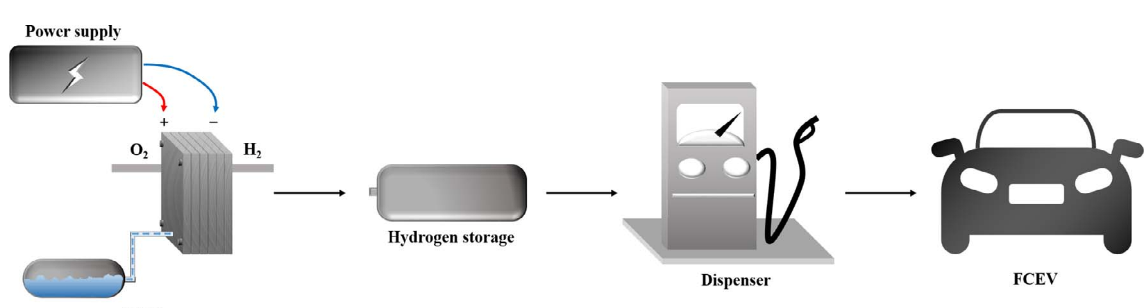

Fig. 1. Schematic of a H_2 fueling station using high pressure PEM water electrolysis (PWE).