Techno-Economic Assessment of Modular Water Electrolysis System Coupled with Heat-Pipe Cooled Microreactor

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1. Introduction

Climate Emergency, selected as the word of the year in 2019, is the best way to describe the global warming issue, which has become one of the most pressing concerns in recent times. To address this issue, countries, with Korea included, have declared their goals to achieve carbon neutrality by 2050 [1]. A hydrogen economy roadmap has been announced in various countries and various companies place ESG (Environmental, Social, and Governance) management at the heart of their operations to pursue long-term sustainable development while taking responsibility for both environment and society. However, this goal looks far from reality as there has been no clear decrease in carbon dioxide (CO_2) emissions, barring the COVID-19 period.

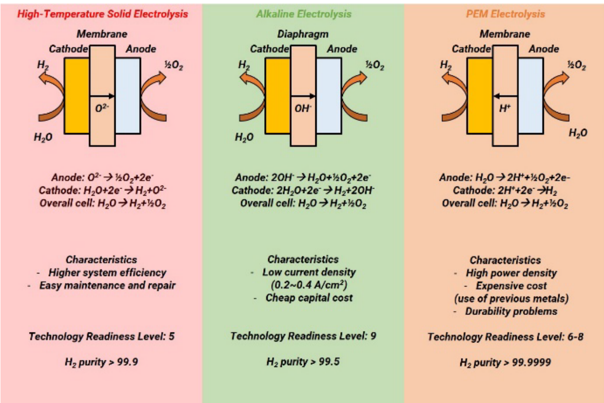


Figure 1. Characteristics of High-Temperature Solid Electrolysis, Alkaline Electrolysis, PEM Electrolysis

Considering this, a transition from the existing carbon economy to the hydrogen economy is considered for carbon neutrality over the coming decades. In Korea, efforts are being made in various fields such as hydrogen production, storage, and usage to realize a hydrogen economy. However, considering that domestic hydrogen production does not show a significant increase at about 2 million tons per year, and even this is mostly gray hydrogen, research on clean hydrogen massive production systems is essential.

Water electrolysis is widely regarded as a green hydrogen production system considering its maturity and high efficiency [2]. Electrolysis varies depending on the reaction in the cell, but the areas being studied in Korea are largely divided into polymer electrolyte membrane (PEM) electrolysis, alkaline electrolysis (AE), and high-temperature steam electrolysis (HTSE) [3].

AE has the advantage of low capital cost, but it also has the drawbacks of low stack efficiency and current density. In contrast, PEM has high power density, current density, and purity (Fig. 1). However, it also has high costs due to the usage of precious metals and durability issues. Both methods have a low operating temperature range, which means that electricity demand takes a much larger proportion than heat demand (Fig. 2). Therefore, total system efficiency has been reduced [4]. Unlike AE and PEM, HTSE has a much higher operating temperature, which decreases the electricity demand and increases the total system efficiency. Although HTSE has the potential for the next-generation clean hydrogen production method, the method has a low technology readiness level (TRL) and still needs many studies for commercialization

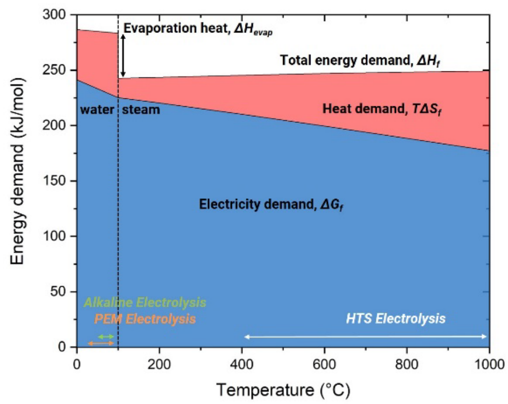


Figure 2. Thermodynamics of electrolysis depending on operating temperature

Besides this, studies about the loss of energy during energy transportation and storage and increased costs due to energy losses were widely reported. Therefore, a modularization system, which could reduce energy losses and additional costs emerged as a solution. Many countries focus on the small modular reactor (SMR) [5]. BloombergNEF predicts that the SMR market will expand by 2,937 GW by 2050 and over 70 SMRs are in development worldwide.

Considering the above, we proposed and evaluated a modular green hydrogen production system coupling the water electrolysis with a heat-pipe microreactor. In here, we selected AE and PEM for the electrolysis method considering the TRL and heat-pipe cooled microreactor considering its inherent safety. After the evaluation and parametric study of the proposed system, we would compare it with the centralized green hydrogen production system in consideration of the hydrogen storage and transportation method.

2. Methodology

2.1 System description

The system consists of a water (steam) electrolysis part, a heat source part, and power conversion system (PCS).

The water (steam) electrolysis part consists of stacks, AC/DC inverter, a water (steam) pump, a preheater, and heat exchangers to supply reactants at specific conditions continuously (Fig. 3). The operating conditions were set as shown in the table.1in consideration of the state-of-the-art research.

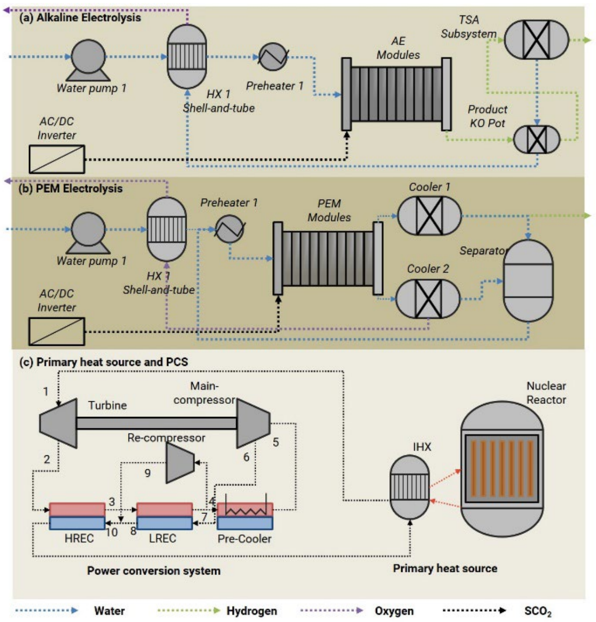


Figure 3. Schematic of (a) Alkaline electrlysis system, (b) PEM elctrolysis system, (c) heat source and PCS

Table 1. Operating conditions and energy usage of each electrolysis system [6, 7]

	Current (2020)		Future (2050)	
	AE	PEM	AE	PEM
Current density [A/cm^2]	0.5	2	2	3
Voltage [V]	1.9	1.9	1.7	1.8
Total Electrical usage [kWh/kgH$_2$]	50	55.8	45	51.4
Stack electrical usage [kWh/kgH$_2$]	47	50.4	42	47.8
BOP electrical usage [kWh/kgH$_2$]	3	5.4	3	3.6
Thermal energy usage [kWh/kgH$_2$]	-	-	-	-
Operating temperature [°C]	70	50	90	80
Cell pressure [bar]	30	30	70	70

For the primary heat source, we selected a heat-pipe cooled microreactor for both electrolysis methods in consideration of modularization system.

For PCS, we selected the SCO_2 recompression cycle for high system efficiency and volume. The SCO_2 recompression cycle has two compressors, a turbine, three heat exchangers, and IHX. We developed in-house code to calculate the temperature and pressure of each point by iteration. We also added the code evaluating the PCHE using the log mean temperature difference (LMTD) method. Using the code we conducted a parametric study about the effectiveness, pressure ratio, and mass flowrate of PCS.

2.2 Economic evaluation

The Levelized Cost of Hydrogen (LCOH) of each system is evaluated and compared. LCOH can be calculated in consideration of the discount rate (r), plant operating lifetime (t_{oper}), construction time (t_{cons}), capital expenditure (CAPEX), operating expenditure (OPEX), and hydrogen production per year (H_t) (Eq.1).

$$\text{LCOH} = \frac{\text{CAPEX}+\sum_{n=t_{cons}}^{t_{oper}}\frac{OPEX}{(1+r)^n}}{\sum_{n=t_{cons}}^{t_{oper}}\frac{H_t}{(1+r)^n}} \quad (1)$$

2.2.1 Water (steam) electrolysis system

The capital cost of electrolysis part was calculated by multiplying the specific cost of each electrolysis system by plant size. The specific cost of each method (C) was calculated according to the plant size (Q) and operating year (V) by interpolating the results of previous studies (Eq.2).

$$C = \left(k_0 + \frac{k}{Q}Q^{\alpha}\right)\left(\frac{V}{V_0}\right)^{\beta} \quad (2)$$

The detailed values of parameters were described in the table. 2.

Table 2. Factors for evaluating the specific cost of water (steam) electrolysis system

	AE	PEM
α	0.649	0.622

(scaling factor)		
β (Learning factor)	-27.33	-158.9
k_0 (fitting constant)	301	586
k (fitting constant)	11603	9458.2
V_0 (reference year)	2020	2020

The OPEX consists of the Operating and maintenance cost (OM), and reactants cost. Reactants in this system include the water, stacks, and KOH solution (only for the AE system). The OM cost was 3% for the electrolysis system, 2% for the nuclear power plant system. The usage of KOH solution was $2.75*10^{-4}$ kg/kgH_2, and the stack lifecycle was 10.27 years for AE and 6.85 years for PEM, which was calculated by the stack degradation time of the state-of-the-art study.

2.2.2 Reactor and Power Conversion System

The cost for the heat-pipe cooled microreactor was calculated in consideration of specific cost and thermal plant size. The specific cost of the reactor includes fuel and moderator, reactor building, reflector, heat pipes, reactivity control, area based on the previous study.

For PCS, we calculated the cost of each component considering the performance of the components (Table. 3).

Table 3. Equations for calculating the cost for each component; m indicates massflowrate, PR indicates pressure ratio, TIT indicates turbine inlet temperature

	Equation
C_{turb}	$479.34 * m * \frac{1}{0.93 - \eta_{turb}} * \ln(PR) * (1 + e^{0.036*TIT-54.4})$
C_{comp}	$71.1 * m * \left(\frac{1}{0.92 - \eta_{comp}}\right) * \ln(PR) * PR$
C_{HX}	$\rho_{PCHE} * c_{PCHE} * (V_{HREC} + V_{LREC} + V_{Precooler})$
$C_{reactor}$	$P_R * C_{reactor}$

3. Results and discussion

We conducted a parametric study on the proposed system. Figure 4 shows LCOH according to pressure ratio and effectiveness of the heat recuperators in PCS for AE and PEM respectively. Both methods (AE, PEM) showed a similar trend in that LCOH decreases as effectiveness, and pressure ratio increases. This was due to the increased efficiency of the power conversion system, which eventually increased the total system efficiency.

Although the exact values differs, AE showed better LCOH for wide operating range. This phenomena occurs due to the amount of electricity usage and specific cost of electrolysis system. As AE requires less electricity usage than PEM, the total system efficiency of AE was higher than that of PEM.

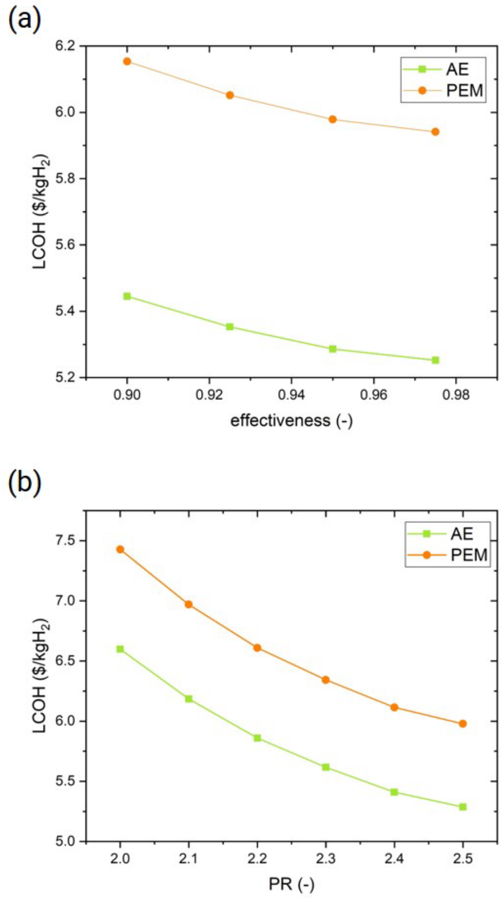


Figure 4. LCOH depending on the (a) effectiveness, (b) PR

Based on the above results, we selected a reference case (PR: 2.5, effectiveness: 0.95, mass flow rate: 24 kg/s) to evaluate the effect of the interest rate. As the interest rate differs from 0.03 to 0.1 in the previous studies, we evaluated the whole range for the reference case (Fig. 5).

Based on the above results, we compared the results of the modular systems with the centralized AE and PEM systems in consideration of the hydrogen storage and transportation methods (Fig. 6).

In this study, Pohang (South Korea) was set as the hydrogen production point and LA (USA) as the hydrogen consumption point, where the route covers 9,530 km by sea and 1000 km by land for centralized systems. For modular systems, we considered only 300 km by land. It is assumed that ships are used for sea routes, and rails and trucks are considered for land routes. For the storage method, we considered compression, liquefaction, and ammonia. The costs for the storage and transport was calculated in consideration of specific cost, which also depends on the storage method, reported in a previous study, and the data from the centralized system was selected from the National hydrogen roadmap in Australia (In this study, the discount rate was assumed to be 0.07).

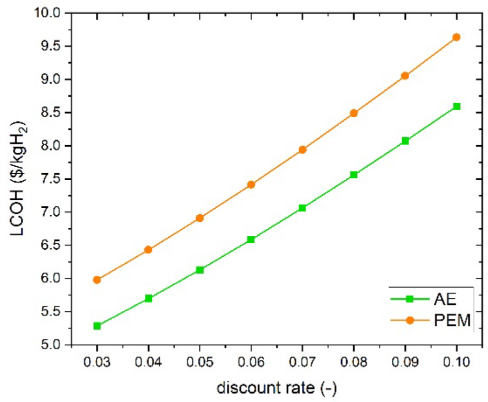
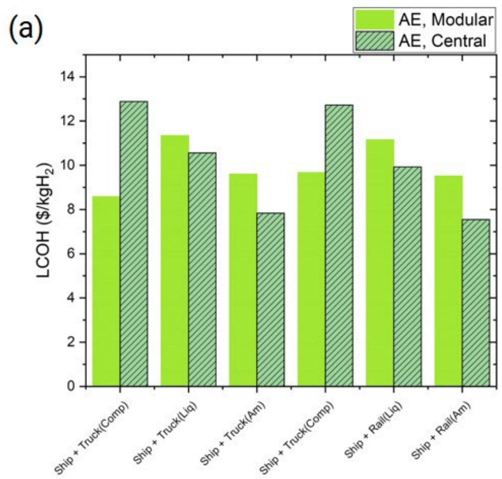


Figure 5. LCOH depending on the discount rate; orange indicates PEM and green indicates AE

Although the centralized system showed better LCOH than the modularized system. The modular system shows better LCOH in some cases. The optimal case of modular system with AE was using truck with compression whereas that of centralized system was using ship and rail with ammonia as storage method. Similarly, for PEM method, the optimal case was using truck with compression whereas that of centralized system was using ship and rail with ammonia. This results indicates that the using ammonia is appropriate for long-distance transport whereas using compression with truck is appropriate for the short-distance transport. For optimal cases, the difference of modular and centralized system was only 0.61 $/kg$H_2$ for PEM, 1.03 $/kg$H_2$ for AE respectively.



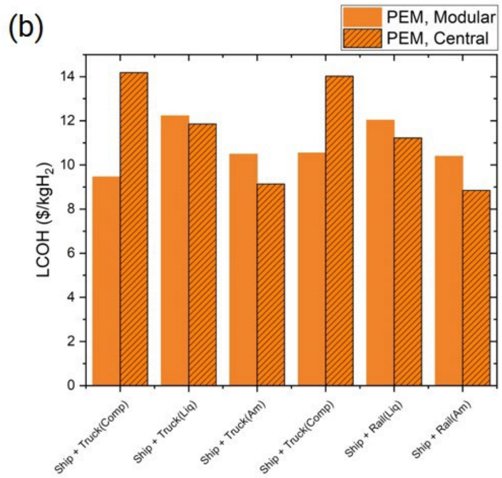


Figure 6. LCOH including storage and transportation for centralized, modular system for (a) AE, (b) PEM method

4. Conclusion

We proposed the modular green hydrogen production system using electrolysis coupled with a heat-pipe cooled microreactor. We also used the SCO_2 recompression cycle as PCS. We developed in-house code using MATLAB to evaluate the system efficiency and LCOH of the proposed system. We conducted a parametric study for PR, effectiveness and discount rate on the LCOH. Based on the reference cases, we compared the proposed modular system with centralized system. Although the optimal case was better for centralized system at given condition, the difference was only 0.61 kg/H_2, 1.03 $/kg$H_2$ for PEM, AE respectively. Considering the learning rate and technology readiness level of current system, the modularized green hydrogen production system coupled with heat-pipe cooled microreactor could be an alternative method for the upcoming hydrogen economy.

5. Acknowledgement

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