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Techno-Economic Analysis of Hydrogen Production Using Nuclear Power Plant Electricity Generation in Korea

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1. Introduction

As a part of Republic of Korea's hydrogen policy roadmap, ROK outlines its goal of producing 6.2 million fuel cell vehicle and at least 1200 hydrogen refilling stations [1]. The hydrogen price is targeted to be as low as 3000 KRW/kgH_2 by 2040 [1]. To achieve that goal, stable and cost-efficient hydrogen producing method needs to be identified, including using nuclear power plant generated heat and electricity.

Korea needs to focus on enhancing its hydrogen technology infrastructure, technological status, and R&D budgets to improve their competitiveness [2]. Accordingly, the availability of ROK's nuclear power plant as an energy source to produce hydrogen can be considered as an attractive option. Especially with the government plan to phase out nuclear power that resulted in the reduced capacity factor and availability factor of currently operating nuclear power plant as shown in Fig. 1 [3].

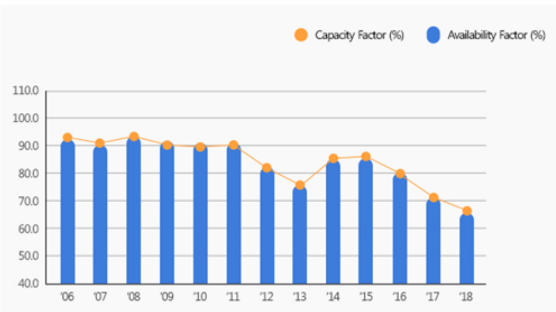

Fig. 1. Capacity and Availability factor of Nuclear power plant in Korea [3]

Therefore, it is important to examine the hydrogen production price using domestically available operating nuclear power plant in order to assess the economic feasibility of hydrogen production infrastructure. The utilization of available nuclear power plants to produce hydrogen could be a good alternative for maximizing the utilization of nuclear power, supplementing renewable intermittency in ROK, and maintaining economic advantage.

2. Methods

Hydrogen Economy Evaluation Program (HEEP) is considered in this study for the preliminary examination. IAEA has developed a software tool to evaluate the economics of promising hydrogen production processes. HEEP considers a large number of input variables affecting the cost of hydrogen production. This program also provides modeling for production, storage and delivery, variable and expandable systems and design database [4].

For using this program, scenarios are needed to be developed according to the Republic of Korea's current electricity generation situation and nuclear power plants. Current specific data of nuclear power plant technical information should be prepared to minimize the uncertainty and represent real-world situations.

2.1 Cost Calculation of Hydrogen in HEEP

HEEP consider various parameters and features to calculate the hydrogen economy [4]. Features contain details of the nuclear power plants, hydrogen generation plants, hydrogen storage plants, and transportation facilities. The various input variables of each category that are considered are shown in Fig. 2.

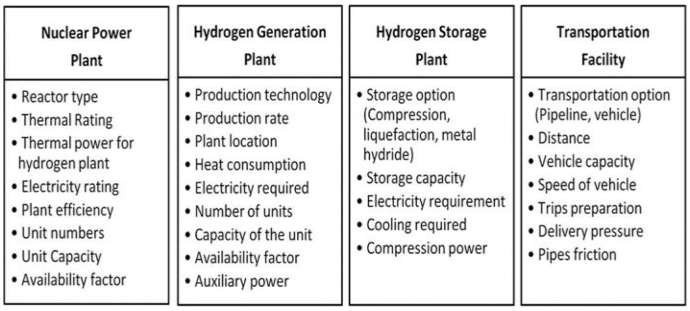

Fig. 2. HEEP input parameters [4]

HEEP analyzes the hydrogen economy through a calculation of the levelized cost of energy delivered by a nuclear power plant with specific information. The cost is calculated by dividing the present value of all expenditures over their lifetime by the sum of the present value of hydrogen generated over their lifetime.

The Levelized cost of nuclear hydrogen generation (LCHG) in HEEP is calculated by the below equations [5].

$$LCHG = \frac{E_{npp}(t_0)+E_{H2GP}(t_0)+E_{H2T}(t_0)}{G_{H2}(t_0)} \quad (1)$$

- ✓ $E_{npp}(t_0)$: Present value of expenditure of the nuclear power plant
- ✓ $E_{H2GP}(t_0)$: Present value of expenditure of Hydrogen plant

- ✓ $E_{H2T}(t_0)$: Present value of expenditure for Hydrogen transport
- ✓ $G_{H2}(t_0)$: Gross generation amount of hydrogen

The present value of expenditures is calculated by using the below equation (2).

$$E(t_0) = \sum_{t=t_{START}}^{t_{END}} \frac{CI_t}{(1+r)^{t-t_0}} + \sum_{t=t_{START}}^{t_{END}} \frac{R_t}{(1+r)^{t-t_0}} + \sum_{t=t_{START}}^{t_{END}} \frac{DC_t}{(1+r)^{t-t_0}} \quad (2)$$

- ✓ CI_t: Capital Investment expenditures at year t
- ✓ R_t: Expenditures towards running the facility in the year t
- ✓ DC_t: Decommissioning expenditures at year t
- ✓ $G_{H2}(t_0)$: Gross generation amount of hydrogen
- ✓ t_0: Base year of comparison
- ✓ r: Real discount rate

2.2 Data Inputs for HEEP

For running the HEEP, the specific nuclear power plant data is needed. First, we set the three types of nuclear power plants to be considered in this study; Shin-Kori, Shin-Wolsung, and Shin-Hanul. Shin Kori and Shin Wolsong are both OPR1000 type reactor, whereas Shin Hanul is an APR1400 reactor type. We assumed that the NPPs are used to generate electricity and produce hydrogen. The value of thermal power, electric power, availability factor and capacity factor is derived from the IAEA Power Reactor Information System (PRIS) [6].

TABLE II

Nuclear power plants in ROK [6]

Name	Type	Thermal Power (MWth)	Electric Power (MWe)	Availability Factor	Capacity Factor
Shin Kori unit 1	OPR 1000	2825	1044	71.60%	70.60%
Shin Wolsong unit 1	OPR 1000	2825	1048	79.40%	80.40%
Shin Hanul unit 1	APR 1400	3983	1340	-	-

For financial parameters in this analysis to run the HEEP, we assume the discount rate at 5%, the inflation rate as 1%, and the operating years as 60 years [7]. The more detail information about financial parameters in this study is shown in Table III.

TABLE Ⅲ

Financial Parameters

Discount Rate	5%
Inflation Rate	1%
Equity/Debt	70%/30%
Borrowing Interest	10%
Tax rate	10%
Operating (year)	60

For nuclear power plant details, we could not get the real fuel cost data for each nuclear power plant. Therefore, the fuel cost was calculated by using the G4-ECONs code. We assumed that each nuclear power plant in the scenario uses two reactor units for hydrogen production. Scenario 1 belongs to Shin-Kori units 1 & 2, scenario 2 belongs to Shin-Wolsung units 1 & 2, and scenario 3 belongs to Shin-Hanul units 1 & 2.

TABLE Ⅳ

Nuclear Power Plant Details

Scenario	1	2	3
Nuclear power plants	Shin-Kori unit 1 & 2	Shin-Wolsung unit 1 & 2	Shin-Hanul unit 1 & 2
Thermal Rating (MWth/unit)	2825	2825	3983
Number of units	2	2	2
Initial fuel load (kg/unit)	102660	94000	80000
Annual fuel feed (kg/unit)	30390	27060	24000
Fuel cost (KRW/kg)	2.2 million	1.63 million	1.64 million
Capital Cost (USD/unit)	3.16E+9	2.5E+9	4.66E+9

Each hydrogen plant in 3 scenarios is assumed to be co-located with nuclear power plants. For the hydrogen plant detail inputs, we used conventional electrolysis (CE), which is provided in HEEP, as the hydrogen production process. The details of the hydrogen plant are shown Table V.

TABLE Ⅴ

Hydrogen Plant Details

H_2 generation per unit (kg/yr)	2.52E+08
Electricity required (MWe/unit)	1438
Heat consumption (MWth/unit)	0
Number of units	1
Overnight capital	1.01E+12
O&M Cost (% of capital)	4

TABLE VI

Hydrogen storage and hydrogen transportation option

Nuclear Power plant	Distance to hydrogen station
Shin Kori	53 km
Shin Wolsong	45.6 km
Shin Hanul	162 km

Fig. 5. South Korea nuclear power plant location [8]

As shown in Table VI and Figure 5, the location of three nuclear power plants are considered to calculate the hydrogen storage and hydrogen transportation cost. The hydrogen station facility is considered to be in Ulsan, South Korea with the distance from each respective power plant shown in Table VI. Compressed gas, liquefaction, and metal hydrides are used as the hydrogen storage option. The hydrogen then transported using pipe or vehicle as the transport option.

3. Results and Discussion

Figure 6 shows a comparison of Shin Kori (OPR 1000), Shin Wolsong (OPR 1000), and Shin Hanul (APR 1400) nuclear power plants used in this study. The cost difference in Shin Kori and Shin Wolsong's case is due to the difference in the availability factor and plant-specific data in the input, especially the electricity generation related data. Shin Hanul plant-specific data is mostly based on assumption as the power plant is under construction. APR1400 is designed to have higher gross electrical power and thermal power capacity [9].

In terms of cost, the Shin Wolsong nuclear power plant has the highest price compared to others at 4127.7 KRW/kgH2 (USD3.44/kgH2). This result is higher compared to Shin Kori due to the difference in the availability factor and electricity output of the power plant. Shin Kori nuclear power plant produces more electricity and, based on the calculation, affected the cost of electricity generation. Shin Hanul, APR1400, technical data is obtained from the IAEA Aris database then calculated using G4-Econs v2.0 to obtain the input parameter and electricity generation. The estimated cost of hydrogen from the APR1400 is considerably lower compared to Shin Kori and Shin Wolsong (OPR1000). The difference in capital cost among three nuclear power plant also played a part in the hydrogen price calculation.

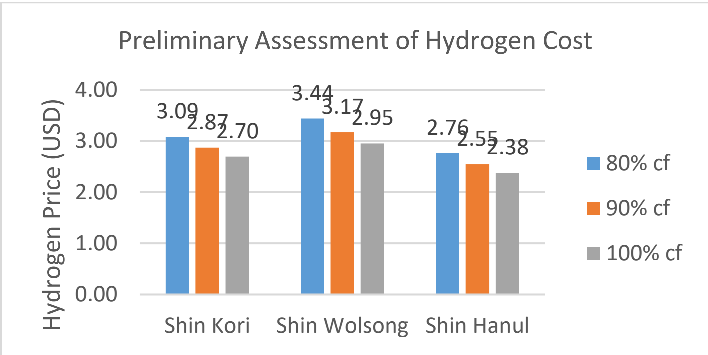

Fig. 6. Preliminary assessment of hydrogen costs case studies

In this preliminary assessment, the hydrogen storage and hydrogen transportation are not included. However, to make the assessment more realistic, hydrogen storage and transportation need to be examined. Compressed gas (CG), liquefaction, and metal hydrides (MH) storage method are available in the HEEP program and are used in this study. The result of the incorporation of hydrogen storage method and its effect on the hydrogen price is shown in Figure 7.

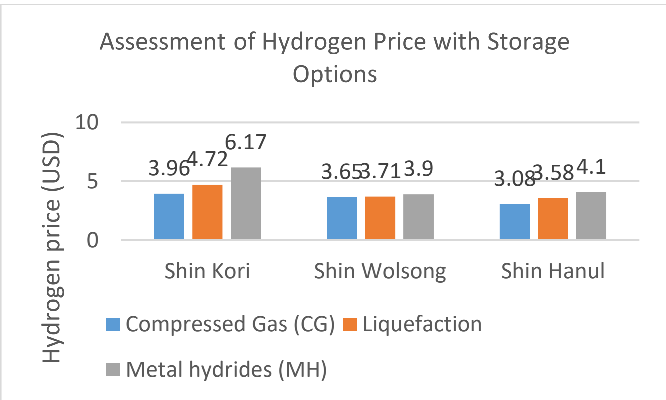

Fig. 7. Hydrogen price variation considering hydrogen storage method

The result in the Figure 7 shows an increase in the hydrogen price about 13.05% on average compared to the hydrogen price in Figure 6. The storage facility technical specification is assumed in the Table VII. The increase in the hydrogen price produced in Shin Kori nuclear power plant is higher compared to the other nuclear power plant. This is due to the needs of storage in this nuclear power plant is higher considering higher production of nuclear hydrogen. The needs of storage occupy 19.25% - 45% cost component of the hydrogen price in the Shin Kori case study. The Shin Wolsong and Shin Hanul hydrogen production only rise below 10% among all the cost components.

The final cost component that needs to be considered is the hydrogen transportation cost. The pipe and vehicle transportation method are considered. The result of the hydrogen cost is shown in Table IX. The result shows 14.18% increase in the hydrogen price on average.

TABLE IX

Example of hydrogen cost component based on Shin Kori nuclear power plant on 80% capacity factor (in USD)

Nuclear Power Plant	Storage & Transportation Method	Price (USD)
Shin Kori	CG-Pipe	4.22
	CG-Vehicle	4.56
	Liquefaction-Vehicle	5.33
	MH-Vehicle	6.77
Shin Wolsong	CG-Pipe	3.78
	CG-Vehicle	4.15
	Liquefaction-Vehicle	4.21
	MH-Vehicle	4.39
Shin Hanul	CG-Pipe	3.18
	CG-Vehicle	3.72
	Liquefaction-Vehicle	4.22
	MH-Vehicle	4.74

The final hydrogen price in three nuclear power plant case studies in Korea is shown in Table IX. The electrolyser used in the case studies is assumed to have same technical specifications. The lowest hydrogen price is obtained from the Shin Hanul nuclear power plant using compressed gas storage method and pipe transportation method at USD3.18/kg H_2. This price is due to the low capital cost regarding the type of the nuclear power plant, compressed gas storage method, and piping. The metal hydrides storage method gave higher hydrogen price compared to other method.

4. Conclusion

The preliminary assessment of the hydrogen production cost scenarios using ROK'S nuclear power plant has been done. Findings on this preliminary assessment suggest that to be able to improve the utilization of ROK's NPP, hydrogen production can be seen as plausible option. According to the results of techno economics analysis on three case studies, the hydrogen cost using nuclear energy range between USD 3.18/kgH_2 to USD 6.77/kgH_2. The cost calculation shows that nuclear hydrogen generation can help reach South Korea's target price for hydrogen, which is 3000 KRW/kgH_2 (USD2.5/kgH_2).

Further analysis should include a realistic and hourly value of ROK's electricity structure to better reflect real world situation. Future work shall include the feasibility study of the cogeneration of electricity and hydrogen in ROK are economically feasible and potentially plausible to be part of ROK transition towards the hydrogen economy. The availability of other energy sources and the viability of a hybrid energy system to produce hydrogen shall be investigated.

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