Preliminary economic study for HTGR coupling with HTSE hydrogen production process

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1. Introduction

The introduction of GHGs (greenhouse gases) into the atmosphere due to the continuous burning of fossil fuels, poses a serious threat to the global environment and consequent climate change [1]. In addition, the demand for energy demand is increasing year on year, which, in turn, is resulting in a year on year increase in the price of fuel. Countries such as the USA, Japan, and the EU are anticipating the creation of a hydrogen economy in that they are nowadays preparing laws, hydrogen supply, and hydrogen national programs.

Recently, Korean government has also begun to anticipate the creation of a hydrogen economy and addressed a hydrogen roadmap. In its roadmap, it has said that it will diversify the hydrogen supply portfolio, increase the hydrogen supply volume to 5.26 million tons in the next 20 years and lower the market price of the hydrogen to less than 3,000 won/kg.

The Korean government's shift toward hydrogen as an energy source is based on hopes of decarbonizing the country's entire transportation fleet and reducing the heavy reliance on imported oil. Because the country relies on oil imports from the Middle East for most of its domestic energy needs. Within the Korean government's hydrogen roadmap, there is a hydrogen supply plan, which involves importing of hydrogen production foothold in abroad and relies on electrolysis. Currently, much research is being conducted into mass hydrogen production in an attempt to solve the problem of hydrogen supply.

Among the many hydrogen production technologies, the HTGR (high temperature gas-cooled reactor) cogeneration system coupled with hydrogen production process is considered the most effective method to produce hydrogen in Korea. Because the heat source from the HTGR can be coupled with hydrogen production facilities such as SMR (Steam Methane Reforming), HTSE (High Temperature Steam Electrolysis), SI (Sulphur-Iodine) thermo-chemical process, and Brayton/Rankine electricity generation facilities. KAERI (Korea Atomic Energy Research Institute) has developed various ways to configure the cogeneration system with a hydrogen production process and electricity production process. Although the HTGR cogeneration system is technically capable of supplying a vast amount of hydrogen, it is uncertain that the HTGR cogeneration system can compete with other hydrogen production technologies. Therefore, it is important to evaluate the economic competitiveness of the HTGR cogeneration system.

In this paper, a preliminary cost evaluation was conducted for an nth-of-a-kind plant comprising a HTGR coupled with a HTSE hydrogen process and electricity generation facilities. The thermal output of the HTGR is 350 MWth, and the outlet temperature of the core is 750 ^{o}C to 950 ^{o}C.

As a result, this paper presents preliminary economic analysis results for the 350 MWth-based HTGR cogeneration system with HTSE hydrogen production and electricity production in terms of hydrogen production cost, electricity generation cost and BC (benefit to cost) ratio. In addition, it presents sensitivity analysis results according to hydrogen price, electricity price, and construction cost.

2. Evaluation Procedures

2.1 Evaluation Model

The cogeneration model mainly comprises of a nuclear power plant, hydrogen production system, and electricity production system. The HTGR supplies thermal heat to the hydrogen production system and electricity production system as shown in Fig. 1. The electricity generated from the electricity production system is supplied to the hydrogen production process, and any surplus electricity can be provided to external users when the need arises.

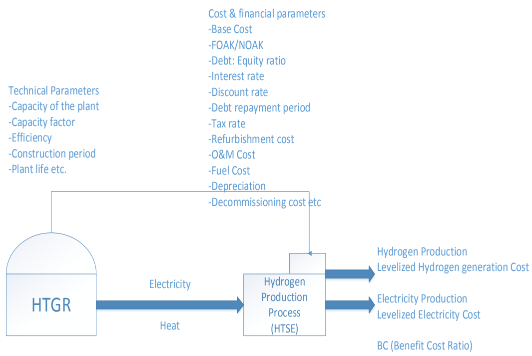

Fig. 1. Economic Evaluation Model and Major Parameters

2.2 Hydrogen and Electricity production rates

For an evaluation of the economic cost value of the hydrogen production cost and electricity production cost, data on the amount of hydrogen electricity energy is essential. The hydrogen production rate for the 350 MWth-based HTGR cogeneration system with HTSE hydrogen production and electricity production is calculated based on preliminary top-tier system requirements for HTGR-based cogeneration. The main strategy is to maximize the hydrogen production, and the electricity generated from the Brayton and/or Rankine cycle is self-consumed for the electricity energy demanded in the HTSE process.

Table 1. Preliminary metrics for HTGR-based cogeneration

HTGR thermal power	350 MW_{th}
HTGR outlet/inlet temperatures	
Very High Temp. Op. (VHTO)	950 ºC /490 ºC (ΔT=460 ºC)
Mid-High Temp. Op. (MHTO)	850 ºC /400 ºC (ΔT=450 ºC)
High Temp. Op. (HTO)	750 ºC /300 ºC (ΔT=450 ºC)
IHX outlet/inlet temperatures	
Very High Temp. Op. (VHTO)	900 ºC /470 ºC (ΔT=430 ºC)
Mid-High Temp. Op. (MHTO)	800 ºC /380 ºC (ΔT=420 ºC)
High Temp. Op. (HTO)	700 ºC /280 ºC (ΔT=420 ºC)
Cogeneration system	Hydrogen and electricity
Hydrogen production process	HTSE
Generator system	Brayton cycle and/or Rankine cycle

Based on Table 1, the primary and secondary helium flow rate can be derived, as shown in Table 2.

Table 2. Primary and secondary helium flow rates

Operation mode	$\dot{M}_{primary\ He}$ (mol/s)	$\dot{M}_{secondary\ He}$ (mol/s)
VHTO	36,603.1	39,156.9
MHTO	37,416.5	40,089.2
HTO	37,416.5	40,089.2

KAERI developed a preliminary HTGR-based cogeneration process flow diagram, and investigated a comparative evaluation for the HTSE, SMR and SI processes in terms of hydrogen production efficiency, thermal energy demand, and thermal utilization for each combination of HTGR outlet temperature through 750 ºC to 950 ºC and the hydrogen production process. [2]. Fig 2. shows a PFD(process flow diagram) of a 350 MWth-based HTGR cogeneration system with HTSE hydrogen production and electricity production for each outlet temperature of the core of 750 ºC to 950 ºC.

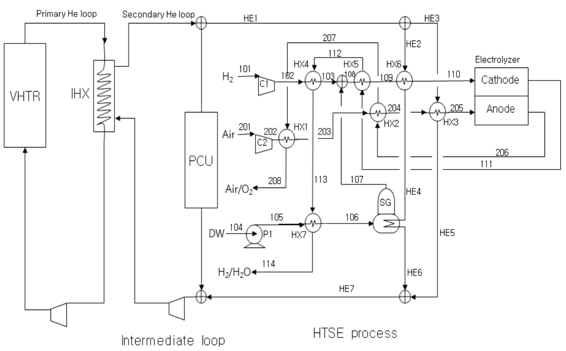

Fig. 2. HTSE hydrogen production process flow diagram

Based on the PFD, one can calculate the thermal and electrical energy demands of the HTSE process components in each operation temperature. With previous studies, KAERI has developed a material balance and heat balance for the 350 MWth-based HTGR cogeneration system with HTSE hydrogen production and electricity generation. As a result, it is expected that hydrogen can be produced at a rate of between 34,854 Nm3/h and 45,228 Nm3/h, and electricity can be generated at a rate of between 138.6 MW_e and 106.8 MW_e by the HTSE process and Brayton cycle as shown Table 4.

Table 4. Cogeneration rate of Hydrogen and Electricity with HTSE

HTGR Outlet Temp.(ºC)	H_2 Productivity (Nm^3/h)	Total Electricity Production (MWe)	Surplus Electricity Production (MWe)
950	45,228	138.6	65.8
850	42,104	129	58.2
750	34,854	106.8	47.5

2.3 Basic input parameters and values

The levelized unit hydrogen production cost and the levelized unit electricity production cost was calculated for the 350 MWth-based HTGR cogeneration system with HTSE hydrogen production and electricity production. We considered technical parameters (such as the capacity of the plant, construction period, and plant life) and economic parameters (such as the debt-to-equity ratio, interest rate, discount rate, O&M cost, and fuel cost). Values for many of the considered parameters were taken from the literature or KAERI's former studies. In some case, such values were modified to meet the capacity size of HTGR, HTSE and electricity facility or particular situations.

The major basic parameters are described in Table 5. [3-6]. The annual operation and maintenance cost are considered with a 3% interest rate. Among the basic parameters, the HTSE capital investment, HTSE O&M cost, and electricity facility capital investment are dependent on the amount of hydrogen produced and the amount of electricity generated. The specific construction investment and annual O&M costs for the HTGR, HTSE and electricity facility are to be presented at a future conference because some numerical values are described in a confidential report.

Table 5. Basic parameters for economic analysis

System	Parameters	Value
HTGR	Capacity factor	90%
	Construction period	5 years
	Number of units	1 or 4
	Capital investment (Constant Price base)	Present at the conference
	Annual O&M	Present at the conference
	Hydrogen generation method	HTSE
	Outlet temperature	750℃~950℃
Hydrogen & Electricity	Capacity factor	90%
	Construction period	5 years
	Number of units	1 or 4
	HTSE Capital investment	Present at the conference
	Electricity Facility Capital investment	Present at the conference
	Annual O&M for Hydrogen Facility	Present at the conference
	Hydrogen Price	5,500 KRW/Kg
	Electricity Price	107.11 KRW/kWh

Finance	Exchange rate	1,100KRW/$
	Discount Rate	5.5%
	Interest rate	2%
	Equity to debt ratio	30%:70%
	Cash flow rate % during construction period	OPR 1000 Reference
	Operating life	60 years

2.4. Economic evaluation results

Based on the HTGR-cogeneration process flow diagram in Fig 2, which serves to maximize the hydrogen productivity in the HTSE hydrogen production processes in conjunction with the helium Brayton and/or reheat Rankine electrical generation systems, one can derive economic analysis results for modules 1 and 4 as shown in Table 8. Economic analysis conducted in terms of the hydrogen production prices and electricity production price and BC ratio. Most cases of modules and outlet temperature combinations are beneficial in terms of BC ratio except modules 1-outlet temperature of 750℃ operations case. The increase in outlet temperature of HTGR leads to a decrease in hydrogen production price and electricity generation price. However, electricity production prices are higher than purchase prices in the case of module 1 operations, which mainly affect the BC ratio decrease for each operation mode.

Table 8. Preliminary economic analysis results for cogeneration with HTGR and HTSE

Analysis Items	Hydrogen production price (won/kg)		Electricity generation price (won/kWh)		BC Ratio	
Modules / Temp	1	4	1	4	1	4
750 ºC	4,911	3,273	153	100	0.914	1.423
850 ºC	4,119	2,763	127	83	1.088	1.681
950 ºC	3,944	2,862	119	78	1.128	1.718

The sensitivity of the input parameter is important to find an optimal plan because it is difficult to specify the values of the process parameters precisely. As shown in Fig 3, the HTGR construction cost mostly affects the BC ratio, and the HTSE facility construction cost is less affective. Nonetheless, the BC ratio is still higher than a value of one in the worst-case scenario, which means that cogeneration with HTGR and HTSE is very profitable.

Fig 4 shows 'hydrogen selling prices' affects the BC ratio the most, whereas 'electricity selling prices' does not influence the BC ratio at all because all of the electricity generated by the HTGR is self-supplied to the HTSE system.

Fig 5 shows that an increase in operating days results in a decrease in both the production cost of hydrogen and the generation cost of electricity: the former is the more affected.

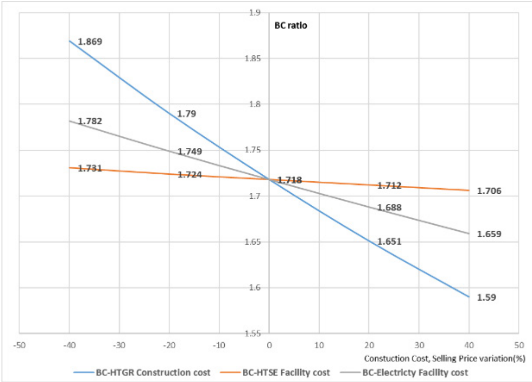

Fig 3. Sensitivity of BC ratio to HTGR, HTSE, and electricity facility construction cost at an outlet temperature of 950 ℃.

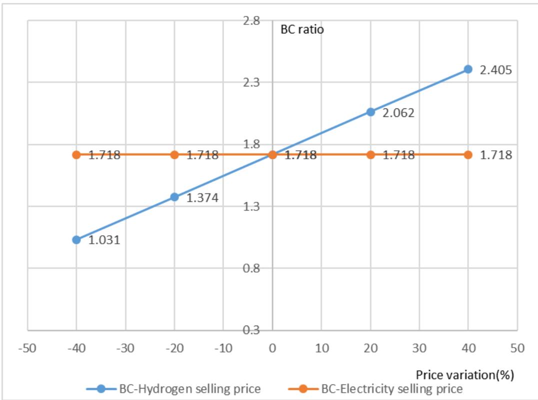

Fig 4. Sensitivity of BC ratio to hydrogen selling price and electricity selling price at an outlet temperature of 950 ℃.

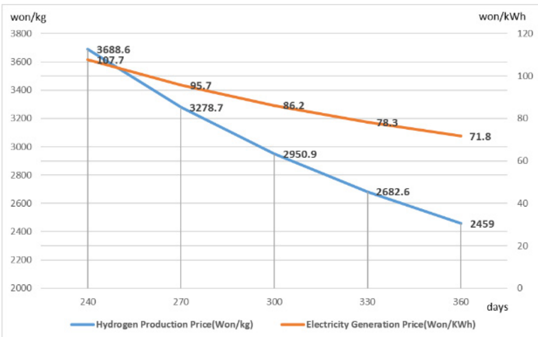

Fig 5. Sensitivity of production cost to operation days at an outlet temperature of 950 ℃.

3. Conclusions

This paper presented preliminary economic analysis results for a 350 MWth-based HTGR cogeneration system with HTSE hydrogen production and electricity generation facility in terms of hydrogen production prices, electricity generation price, and BC ratio.

In addition, a sensitivity study was conducted for major cost parameters that can affect the hydrogen production price, electricity production price, and BC ratio. The results of sensitivity analysis show that 'capacity factor', 'hydrogen selling price', and 'construction cost' are the most influential parameters. However, it is necessary to adjust the parameter values in detail to obtain a more precise economic evaluation. Moreover, since technology development for hydrogen production is in progress, it is need to compare HTGR based-cogeneration system with other hydrogen production methods to select the best option considering energy efficiency and environmental and economic efficiency.

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