Transactions of the Korean Nuclear Society Autumn Meeting
Goyang, Korea, October 24-25, 2019

Preliminary economic analysis of HTGR cogeneration system coupled SMR process considering carbon tax

Taehoon Lee [a*], Juho Lee [a], Changkeun Jo [a]
[a] *Korea Atomic Energy Research Institute Daedeok-daero 989 bungil 111, Yuseong-gu, Daejeon, Korea 34057*
[*]*Corresponding author: leeth@kaeri.re.kr*

1. Introduction

Global warming due to greenhouse gases (GHG) emission, especially carbon dioxide (CO_2) emitted by burning of fossil fuels has become a serious issue [1]. Many countries including the USA, Japan, China recognized that continuous and substantial reduction in the GHGs emission is required to avoid serious climate changes and global temperature rise.

In addition, Recently, Korean government become keenly aware of hydrogen economy and has begun to anticipate the creation of a hydrogen economy and addressed a hydrogen roadmap. The government laid out a roadmap to make hydrogen-related technologies a key new growth engine for Korea. 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.

In order to meet the demand of hydrogen and to solve the problem of hydrogen supply, many technologies have developed to produce mass hydrogen. Among these, 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 economic analysis comparison was conducted for a HTGR coupling with a a SMR hydrogen production process. The thermal output of the HTGR is 350 MWth, and the outlet temperature of the core is 750 ºC to 950 ºC.

As a result, this paper presents preliminary economic analysis results for the 350 MWth-based HTGR cogeneration system with SMR hydrogen production system in terms of amount of hydrogen production, hydrogen production cost, electricity generation cost and BC (benefit to cost) ratio.

2. Evaluation Procedures

2.1 Evaluation Model

The cogeneration model mainly comprises of a nuclear power plant, hydrogen production system such as a SMR 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.

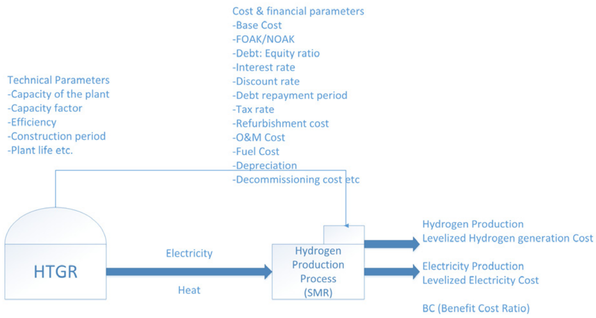

Fig. 1. Economic Evaluation Model and Major Parameters

2.2 Hydrogen and Electricity production rates

The hydrogen production rate for the 350 MWth-based HTGR cogeneration system with SMR hydrogen production is calculated based on preliminary top-tier system metrics 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 SMR process.

Table 1. Preliminary metrics for HTGR-based cogeneration

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

Generator system	Brayton cycle and/or Rankine cycle
Primary/secondary helium flow rate Very High Temp. Op. (VHTO) Mid-High Temp. Op. (MHTO) High Temp. Op. (HTO)	 36,603.1(mol/s) / 39,156.9 (mol/s) 37,416.5 (mol/s) / 40,089.2 (mol/s) 37,416.5 (mol/s) / 40,089.2 (mol/s)

KAERI developed a preliminary HTGR-based cogeneration process flow diagram, and investigated a comparative evaluation for the SMR, HTSE 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 SMR hydrogen production system.

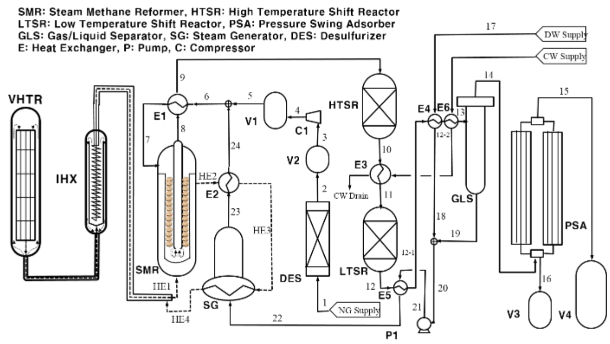

Fig. 2. SMR hydrogen production process flow diagram

Based on the PFD, one can calculate the thermal and electrical energy demands of the SMR 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 SMR hydrogen production system. As a result, it is expected that hydrogen can be produced at a rate of between 92,566 Nm3/h and 143,812 Nm3/h and electricity can be generated at a rate of between 23.8 MWe and 98.3 MWe by the SMR process.

Table 2. Cogeneration rate of Hydrogen and Electricity for SMR process

Rx Outlet Temp	H_2 Productivity (Nm^3/h)	Total Electricity Production (MWe)	Surplus Electricity Production (MWe)
750	143,812	23.8	9.5
850	143,121	52.4	42.9
950	92,566	87.3	82.2

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 SMR 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, SMR and electricity facility or particular conditions.

The major basic parameters are described in Table 3. [3-7]. The annual operation and maintenance cost are considered with a 2% interest rate. Among the basic parameters, the SMR capital investment, SMR 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, SMR and electricity facility are to be presented at a future conference because some numerical values are described in a confidential report.

Table 3. 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	SMR
	Outlet temperature	750℃~950℃
Hydrogen & Electricity	Capacity factor	90%
	Construction period	5 years
	Number of units	1 or 4
	SMR Capital investment	84,929 Mwon
	Electricity Facility Capital investment	Present at the conference
	Annual O&M for Hydrogen Facility	0.03 $/Nm^3$
	Hydrogen Price	5,500 Won/Kg
	Electricity Price	107.11 Won/kWh
	Methane Price	415.6 USD/ton
Finance	Exchange rate	1,100 Won/$
	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 without carbon taxes

Based on the HTGR-SMR cogeneration process flow diagram in Fig. 2, which serves to maximize the hydrogen productivity in the SMR 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 4. Economic analysis conducted in terms of the hydrogen production prices and BC ratio. All case of modules and outlet temperature combinations are beneficial in terms of BC ratio. However, the increase in outlet temperature from 850 ºC to 950 ºC of HTGR leads to a decrease in hydrogen production price and BC ratio due to the thermal pinch effect in line 7 and line 8.

Table 4. Preliminary economic analysis results for cogeneration with HTGR and SMR

Analysis Items	Hydrogen production price (won/kg)		BC Ratio	
Modules / Temp	1	4	1	4
750 ℃	3,691	3,295	1.484	1.676
850 ℃	3,079	2,637	1.791	2.061
950 ℃	3,496	2,811	1.673	2.083

2.5. Economic evaluation results considering carbon tax and natural gas price trend

A carbon tax is a tax levied on the carbon content of fuels and, like carbon emissions trading, is a form of carbon pricing. As of 2018 at least 27 countries and subnational unit have implemented carbon tax. The SMR process is a chemical synthesis for producing syngas (hydrogen and carbon monoxide) from hydrocarbon such as natural gas. It means that we need to consider carbon tax in term of economic view. According to the SMR process material balance, 5.3 kg of carbon dioxide is produced per one kg hydrogen production by HTGR coupled with SMR process. In addition, imported natural gas prices are not fixed price, but are expected to increase in accordance with the state of the economy.

Table 5 shows carbon tax and hydrogen production price based on HTGR-4modules operating under 850 ℃ coupled with SMR if carbon tax is applied. Fig. 3 shows a series of price forecast for natural gas using data of KOSIS(Korea Statistical Information Service) and IEA (International Energy Agency). It has five scenarios such as reference case, high economic growth case, low economic growth case, high oil price case and low oil price case.

Table 5. Carbon tax and hydrogen production price

Carbon tax	Expected value (won/kg)	Hydrogen production price with carbon tax(won/kg)
Average	367.2	3004.2
Maximum	1118.5	3755.5
Minimum	21.2	2658.2
Median	217.4	2854.4

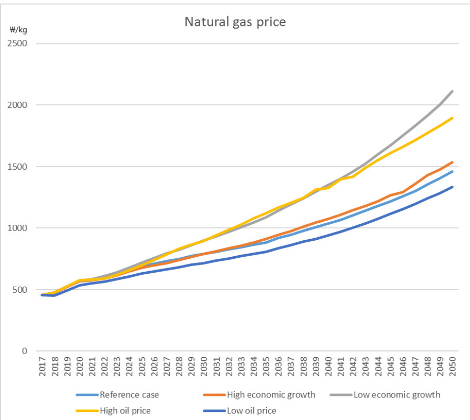

Fig. 3. Time series forecast of natural gas

Fig. 4 summarizes the economic analysis results of the HTGR coupling with SMR process for each economic growth scenarios, reflecting the carbon tax in Table 5 and the time series forecasts of natural gas in Fig. 3. Fixed price in fig 4 means LNG supply cost is constant whereas natural gas disposition reflects natural gas supply scenarios. The BC rate of all cases is still above 1 and cogeneration process can be judged to be economically sound. However, if the economic growth slows or the crude oil price rises, the BC rate will fall sharply.

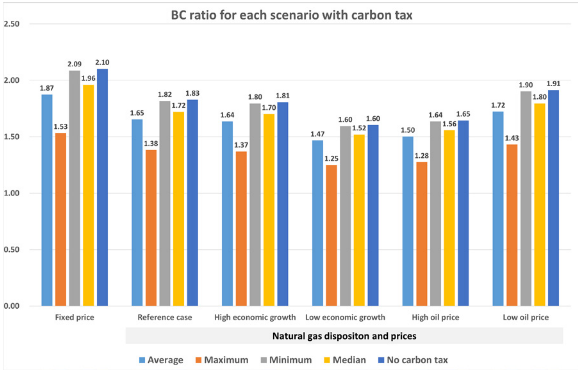

Fig. 4. BC ratio for each economic growth and oil price expectation scenario with carbon tax

3. Conclusions

This paper presented preliminary economic analysis results for a 350 MWth-based HTGR cogeneration system with SMR hydrogen production and electricity generation facility in terms of hydrogen production prices and BC ratio considering various economic growth scenarios and natural gas price.

The impact of carbon taxes on the hydrogen production prices was not greater than expected. We think that this is because the commercial SMR process uses natural gas as a heat source and generates a large amount of carbon dioxide, whereas the SMR hydrogen production process coupling with HTGR uses HTGR as a heat source required for hydrogen production.

Nevertheless, since HTGR coupled with SMR hydrogen process still generates carbon dioxide continually, the hydrogen production in this method needs to be reconsidered in light of its environmental impact.

On the other hand, the impact of BC rate on natural gas supply due to economic growth and crude oil price fluctuations was greater than carbon tax. In scenarios where economic growth has deteriorated or high oil prices persisted, the rate of decrease in the BC rate is relatively large.

Finally, the variables in this paper are used for approximate economic analysis. It is necessary to refine the input variables and reflect accurate data obtained through investigating market status for precise economic analysis. Moreover, because the technology for HTGR and SMR is currently under development, the results of economic potential for HTGR cogeneration system may change according to the future situation change.

ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. 2017M2A8A1014757).

REFERENCES

[1] Shizo Saito, Role of nuclear energy to a future society of shortage of energy resources and global warming, Journal of Nuclear Materials, 398 pp.1-9, 2009

[2] T.H. Lee et al, Process analysis for a HTGR-based High Temperature Thermal Energy Utilization, KAERI/TR-6996/2017, KAERI, 2017

[3] W.J. Lee et al, The Study of Economic Analysis and Demonstration Research Plan for HTR Business, KAERI/TR-5891/2015

[4] Phillip Mills et al, High Temperature Gas-Cooled Reactor Projected Markets and Preliminary Economics, INL/EXT-10-19037, INL, 2010

[5] A.M. Gandrik, Assessment for HTGR Capital and Operating Costs, INL, 2012

[6] Leon Basye Shiva Swaminathan, Hydrogen Production Costs – A survey, DOE/G0/101780-778, 1997

[7] Willard Lawrence Quon, A Compact and Efficient Steam Methane Reformer for Hydrogen Production, University of Houston, Dissertation, 2012