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Market Analysis for the Diversification of Nuclear Energy Utilization Using VHTR in Korea

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1. Introduction

Despite the benefits that nuclear energy provides, including reducing inequality among countries in terms of buried energy and lowering greenhouse gas (GHG) emissions (See Fig. 1), the growing concerns over the risks involved in the operation of nuclear power plants and processing of nuclear fuels following the closure and decommissioning of nuclear reactors in the wake of the Fukushima Daiichi nuclear disaster have placed the world in a nuclear dilemma.

Under its 4th Comprehensive Plan for the Promotion of Nuclear Power Production, Korea has actively conducted research for the development of new nuclear hydrogen production technology. Now, the country is pursuing the expansion of its nuclear energy technology as a means of cutting greenhouse gas emissions under its 5th Comprehensive Plan for Nuclear Power Promotion (2017-2021), which is part of an aggressive R&D policy that has been designed to satisfy future energy demand and ensure policy sustainability. As the supply of renewable energy is increasing and gradually replacing nuclear energy, it is imperative that we continue pursuing the development of sustainable nuclear energy technology.

Next-generation nuclear reactors are expected to create new value, and the energy they generate can be used for diverse purposes, such as high-efficiency nuclear hydrogen production using a thermochemical SI process based on very high temperature gas-cooled reactor (VHTR) technology, customized process heat production, and high-temperature electrolysis.

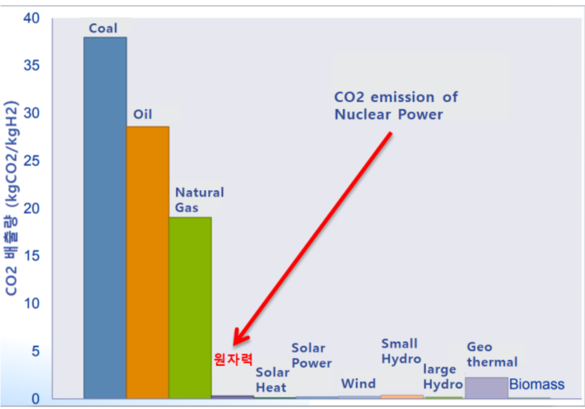

Fig. 1. CO_2 emissions for each hydrogen sources

By analyzing market trends, this study aims to present strategies for entering the nuclear energy market, outline ways of overcoming technological barriers, and achieve cost-effectiveness. .

2. Utilization and Efficiency of Nuclear Hydrogen

Although hydrogen can be obtained relatively easily from fossil fuels, the methods of producing hydrogen from fossil fuels have little to do with lowering GHG emissions. Water splitting into H_2 and O_2 is a hydrogen production method that offers an infinite supply of hydrogen, and is thus viewed as the most ideal hydrogen production method. However, direct hydrous pyrolysis is regarded as one of the poorest hydrogen production methods, because the value of ΔG (energy directly useful for conversion) is too big. It is far better to use electrolysis or thermochemical processes with small ΔG values. Fig. 2 shows that the temperature during direct hydrous pyrolysis needs to reach 4000 K in order to produce only a small amount of hydrogen (when $\Delta G \leq 0$).

Hydrogen production through the "nuclear electric generation + high-temperature steam electrolysis" method is technically useful. In terms of effectiveness, however, it is no better than the "renewable energy power + hydrous electrolysis" method, because power generation for hydrogen production and electrolysis is redundant and the hydrous electrolysis of renewable energy is done to store energy in the energy storage system. Accordingly, direct hydrous electrolysis seems to be the most competitive application of nuclear power.

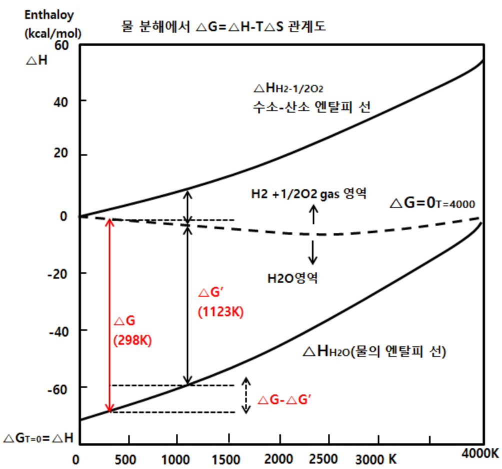

Fig. 2. Relation of $\Delta G = \Delta H - T\Delta S$ in the direct thermal decomposition of water

Theoretically, hydrous electrolysis at low temperatures produces 39.7 kW (68 kcal/mol) of energy per kilogram, but as the electrodes have no overvoltage capacity, the actual energy conversion efficiency is 45 to 60 percent. Fig. 2 shows that in terms of ΔG, hydrous electrolysis at high temperature (1123 K) has more 20 percent benefit than that at room temperature (298 K). Also, Table 1 shows that the SI (sulfur-iodine) process at high temperature is better than hydrous electrolysis at high temperature, in terms of productivity and electricity consumption, and is thus more competitive.

Description (each co-generation)	HTSE (850℃)	SI (900℃)
VHTR rating (MWth)	250 x 2	250 x 2
Heat consumption	39 MWth	448 MWth
Electricity consumption	179 MWe	33 MWe
Hydrogen production (tons/year)	46,000	49,600
Capital cost (USD 10^6)	572	563
Annual O&M cost (USD 10^6)	52.3	42.2

Table 1. Comparison of HTSE and SI processes (IAEA, 2017)

In the field of renewable energy, however, research on high-efficiency means of producing hydrogen, based on the development of concentrated solar power (CSP) and concentrated photovoltaic (CPV) systems and new materials for electrodes capable of delivering high-voltage/high-density current at high temperatures, has been conducted. Therefore, in order to ensure the sustainability and cost-competitiveness of nuclear power technology, new technology should be developed.

3. Paradigm of a Hydrogen Society

In terms of the future outlook for the hydrogen market, it is of utmost importance that we carefully consider the reasons for becoming a hydrogen society and whether it is actually possible. If reducing GHG emissions and air pollution is our sole goal, we should keep in mind that the current energy industry has been continuously making efforts to find new alternative energy sources. To give an example, technological development in relation to fossil fuels, including steam methane reforming (SMR), clean coal technology (CCT), and carbon capture, storage, and use (CCSU) systems, is currently being carried out with the goal of increasing the sustainability of fossil fuels and is more active than research on hydrogen energy.

We need to become a hydrogen society in order to:

1) ease political concerns over inequality in buried energy;

2) meet the demands of energy-poor nations for economic equality; and

3) formulate aggressive global policies for the reduction of GHG emissions.

Moreover, driven by the commercialization of hydrogen vehicles and fuel cells and rapid advancement of technologies for hydrogen production, delivery, storage, and utilization, the hydrogen economy presents a roadmap for the creation of a hydrogen society through the establishment of hydrogen-related infrastructure and laws.

The strengths of the value chain of the hydrogen industries include:

a) diverse production methods
b) high energy conversion efficiency
c) ease of use
d) use of diverse storage systems
e) diversity in transport and storage
f) eco-friendliness
g) high energy density

These strengths comprise the driving force of the hydrogen economy.

It is expected that the changes in the industrial structure that will be brought about by the emergence of a hydrogen society will inevitably lead to major changes in the large energy companies and modes of energy transport, which have typically been ship, rail, and power cable, and the creation of new industries in each hydrogen-related area. Consequently, new academic disciplines and industrial structure will emerge.

It seems that, in terms of social demands, our transformation into a hydrogen society is both inevitable and reasonable, as knowledge sharing, made possible by the development of information and communications technology, has prompted growing demands for economic equality among nations and the replacement of fossil fuels with more eco-friendly energy sources.

However, it should be noted that the hydrogen economy, the driving force for the emergence of a hydrogen society, will not materialize any time soon, because hydrogen is not yet as efficient or economical as fossil energy or electric power. Accordingly, it is imperative for us to develop a thermochemical SI hydrogen commercialization process that makes it possible to readily introduce cheap hydrogen into the market.

4. Cost Forecast of Nuclear Hydrogen Production

The production cost of nuclear hydrogen varies in accordance with the cost of building and operating a VHTR plant and heat consumption, and this variation is compounded by the fact that each nation calculates efficiency and the cost of building and operating a VHTR plant differently. The various methods by which nuclear hydrogen can be produced, including SMR, thermochemical SI, HTSE, and low-temperature electrolysis, further contributes to the variation in cost according to Table 2.

Institute	Year	Production method	Unit price USD/kg of H_2
DOE	2015	SMR	2.1
	2015	HTGR-electrolysis	3.9
CSIRO	2015	Small PV-electrolysis	9.14 (no battery type)
JAEA	2014	VHTR-SI	2.66
Saudi	2017	Smart-SMR	2.5
	2017	Smart-electrolysis	3.0~3.3 (4.5~5.3 cents/kW of electricity)

Table 2. Comparison of hydrogen production costs [2], [3], [5], [6]

Russia, a nation with a low base price of energy, has proposed an average price of USD 2.0 per kilogram for hydrogen produced via HTGR (LCO H_2)[8], which is significant as it means that the price of nuclear hydrogen can be as competitive in the market as natural gas. This price is likely to become the target price in the long term.

5. Trend of Energy Consumption in Korea

Korea's rapid industrial development was made possible through the country's promotion of its energy-intensive heavy and chemical industries in the 1980s. With the financial crisis in the mid-1990s, the global financial crisis in 2008, and the consequent oil price fluctuations, however, the nation has seen a major reorganization of its industries, with emphasis on smaller, less energy-intensive industries. As a result, energy use has remained low since 2010, after a modest increase, despite the steady growth of production and added-value indices (See Fig. 2).

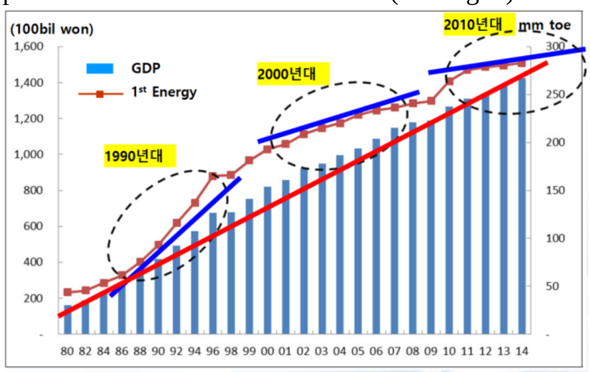

Fig. 2. Consumption trend of primary energy change in Korea from 1984 to 2014, data from ref. [4]

The decline in energy consumption can be attributed to the slowdown of the heavy and chemical industries and the government's efforts to reduce GHG emissions through pollution emission control policy and renewable energy incentives as well as to the improvement in the standard of living, which has led consumers to increasingly prefer clean and efficient energy sources (gas and electricity).

Energy consumption ratio(%)	2001	2005	2010	2015	change
coal	13.4	13.1	14.9	16.0	↑19.4%
oil	61.0	56.6	51.3	49.1	↓20%
LNG	8.7	10.4	11.1	10.1	↑16%
electric	14.5	16.7	19.1	19.0	↑31%
heat	0.8	0.9	0.9	0.7	-
Renew-able	1.6	2.3	2.7	5.1	↑319%

Changes in energy consumption by year and reason
○ Increase in use of charcoal: due to increase in coal power plants
○ decrease in use of oil: due to preference for clean energy
○ Increase in use of gas and electricity: due to preference for efficiency
○ Increase in use of renewable energy: due to financial support from government
○ Heat: stagnation in use of waste energy

Table 3. Consumption trend of primary energy change for each source in Korea, data from ref. [4]

The supply of district energy from 2001 to 2015 showed steady growth, except for the sudden increase in 2010 due to the cold spell and drastic increase in electricity consumption caused by the expansion of combined heat and power (CHP) facilities. In 2001, district energy was used in industrial complexes more than in residential areas, at a ratio of 66:33. By 2015, however, the gap narrowed to 50:46 due to an increase in the supply of CHP to apartment complexes.

According to an analysis of the trends of district energy consumption, the use of CHP for district heating will continue to grow, while that for industrial complexes is expected to show no significant increase, due to the slowdown of the heavy and chemical industries (See Figures 3,4)

(Unit: 1,000 Gcal/year) (1 Gcal = 1.1628 MWth, at full operation)

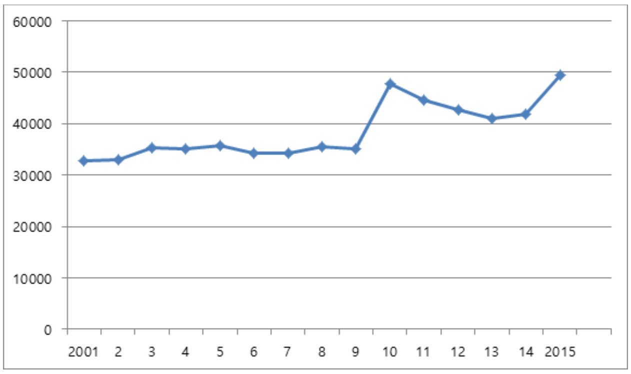

Fig. 3. Trend of district heat consumption in Korea, data from ref. [4]

(Unit: 1,000 MWth/year)

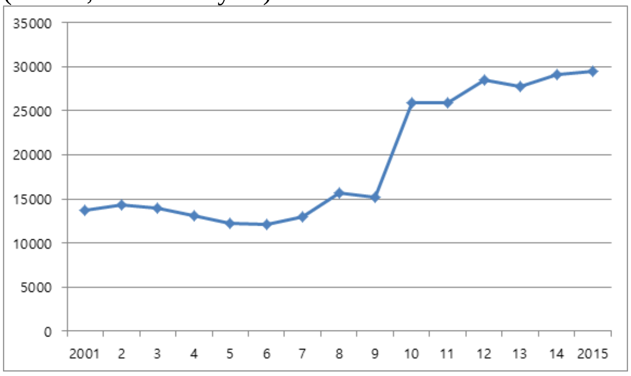

Fig. 4. Trend of district electricity consumption in Korea, data from ref. [4]

Table 4 shows the supply of district energy over the 15-year period from 2001 to 2015.

(Heat unit: 1.000 Gcal/year, Electricity unit: MWth/year)

Consumer	Energy	2001	2005	2010	2015
Residential	Heat	12,179	16,517	19,386	19,670
	Electricity	3,364	4,098	9,402	17,441
Industrial	Heat	20,617	19,151	28,388	27,684
	Electricity	10,343	8,163	16,539	11,695
Both	Heat	-	-	1,794	2,015
	Electricity	-	-	289	308
Total	Heat	32,796	35,668	47,724	49,368
	Electricity	13,707	12,261	25,941	29,443

Table 4. Trend of heat and electricity consumption in Korea, data from ref. [4]

6. Target Market of Nuclear Heat in Korea

While the strategy for realizing the nuclear hydrogen market focuses on supplying hydrogen at low prices, the strategy for realizing the nuclear process heat market aims to secure the necessary demand. For instance, although petrochemical complexes have the highest demand for district energy, the majority of these facilities have been designed to maintain a balance between supply and demand by using their own fuels, making it unnecessary for a large quantity of energy to be supplied from external sources. In terms of district heating, apartment complexes and non-petrochemical industrial complexes have little surplus energy and, accordingly, have potential to serve as a market for nuclear energy.

In Korea, the introduction of emissions trading, as a means of reducing GHG emissions, prevents cheap fossil fuel energy from entering the market, and as permit trading is expected to gradually increase paid-in allocation (10 percent by 2025), Korea is likely to see an increase in its burden of cost.

In this respect, nuclear process heat, which is largely excluded from emissions trading, has potential for market entry.

Table 5 below summarizes the plan for the operation of the emissions trading scheme that has been drawn up by the Korean government.

Classification	1st Period (15~17)	2nd Period (18~20)	3rd Period (18~20)
Emissions trading allocation	GF (quote of past achievements) Free of charge, voluntary participation	BM (facility efficiency) 3% of allocation at a cost Obligation to purchase more than the allocated emissions	BM (methods for improvement) 10% of allocation at a cost Obligation to purchase more than the allocated emissions
Reduction of external projects	Vitalization of external projects	Promotion of emissions reduction overseas	Materialization of allowable emissions trading range overseas
Inspection and certification	System establishment and increase in experts	Global standards of emissions statement	Introduction of international certification
Emissions trading market	Launch of carbon trade exchange	Periodical auction	Third-party participation in the market
International cooperation on industrial support	Financial support and tax relief for the reduction facility support project	Reinvestment of carbon revenue	Vitalization of emissions trading through international cooperation

GF: grandfathering BM: benchmark

Table 5. Operation plan for the Korean government's emissions trading scheme

Northern Europe, Eastern Europe, and the post-Soviet states, where the supply of district energy has increased, need to undertake projects designed to replace their old heating facilities and pipes with new ones. However, the rise in the fuel price (gas) and consequent negative profitability have made it difficult to carry out such projects.

Therefore, the district energy project can enter the market only when it is capable of guaranteeing GHG emission reductions and profitability.

7. Cost Forecast for District Heat

Regarding the use of nuclear heat for district heating, a comparison of the costs of various types of energy is necessary. Table 6 shows a comparison of the sale prices of heat as of February 2018.

Classification	Use	Basic rate	Unit rate
Residential	Heating	KRW 52.4/m^2	KRW 64.35/Mcal
Industrial	Heating	KRW 396.79/Mcal	KRW 83.55/Mcal
Public	Heating	KRW 361.98/Mcal	KRW 72.97/Mcal

Table 6. Sales costs of district heat from the KDHC

According to a report by the INL in 2012, the cost of building a 600-MWth plant was roughly USD 1.165 billion (including a reserve fund of 22 percent), and the operation and maintenance cost was USD 60 million per year [7]. Based on these information, the resultant cost of heat is KRW 53.85/Mcal. As the estimated construction cost includes all expenses for possible risks, the actual construction cost is expected to be lower.

The cost of heat is KRW 71.4/Mcal when the sale price of medium-pressure steam (12kg/cm^2) is KRW 45,000/ton.

8. Conclusion

Nuclear energy can be used in diverse ways in the future. In particular, nuclear hydrogen is expected to be more competitive than renewable energy-electrolysis hydrogen in the market thanks to its economical, direct hydrogen (thermochemical SI) production method, which does not employ electrolysis. In addition, a strategy is needed for the use of nuclear energy for non-petrochemical industrial complexes and district heating in residential areas.

To compete in the market, nuclear energy needs to be price competitive and free from the problems associated with nuclear reactor safety.

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