1. Overview

The world's major countries are aggressively preparing national strategic countermeasures in response to climate change, the fourth industrial revolution and tightening environmental regulations.

Korea is also preparing for the new energy paradigm in earnest. The government is working on a full-fledged response through a comprehensive energy transition policy, which includes a reduction in nuclear power usage and an expansion of environmentally-friendly energy. A core goal of these policies is the realization of a low-carbon economy by reducing energy dependence on nuclear power and coal, expanding renewable energy, and establishing energy governance. A variety of new and renewable energy sources such as solar, wind, and hydropower are being considered as part of a plan to in order to achieve a low-carbon society.[1] In this situation, hydrogen can minimize the adverse effects of carbon dependence, such as resource depletion, environmental pollution and global warming as a natural and sustainable alternative energy source. In addition, it is worth considering the benefits of hydrogen in terms of energy security as well.

In his press conference in January, 2019, President Moon Jae-in paid special attention to the possibility of developing a hydrogen fuel cell vehicle as an engine of future economic growth, and the government later identified the "hydrogen economy"[2] in a set of economic revitalization plans. These plans include the support for the further development and commercialization of hydrogen cars, hydrogen buses and hydrogen charging stations as three strategic investment fields for integration with the platform economy[3] through AI, data, block chain technology and the shared economy, with a budget of 500 billion KRW. Additional plans for the activation of the hydrogen

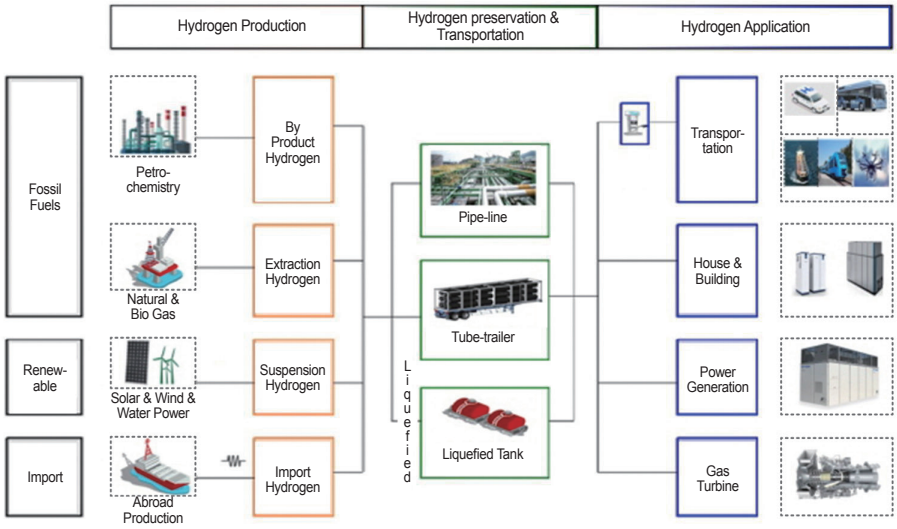
Activating Korea's Hydrogen Energy Industry

1) A low-carbon society refers to a society in which the amount of carbon per unit of mass is reduced, in the order of coal, oil, and natural gas (Jeremy Rifkin, 2003).

2) The hydrogen economy refers to an economy in which hydrogen is used as an important, eco-friendly energy source and a source of economic growth, effected through fundamental changes in the national economy, society as a whole, and people's lives. "Roadmap for Activating the Hydrogen Economy", joint ministry report.

3) The implementation of the platform economy first selects the areas where it is judged that each individual company's investment is somewhat difficult in terms of size and risk of the investment. Government-led strategic investment under this initiative can be seen as a platform economy implementation.

Figure 1. Hydrogen Economy Concept Map



Source: Ministry of Trade, Industry, and Energy.

economy sector are aimed at establishing a step-by-step hydrogen value chain including production, storage, transportation, utilization, and expansion of the demand base for the hydrogen value chain. In addition, the government announced its Roadmap for Activating the Hydrogen Economy in January 2019, with a stated goal of becoming the market leader in hydrogen fuel cells by 2040. Prior to this, in December 2018, the Ministry of Trade, Industry, and Energy (MOTIE) identified the creation of an industrial ecosystem for a hydrogen economy as a priority for 2019. Korea is making earnest efforts bring about a new hydrogen economy.

The Hydrogen Council's[4] 2017 report, "A Roadmap towards a Hydrogen Economy",[5] details how the realization of a hydrogen economy will create a market worth 250 billion USD a year by 2050, creating more than 30 million jobs in the process. With regard to the utilization of hydrogen in transportation, the authors of the report expects the market for hydrogen passenger cars to reach 400 million, with an additional five million buses and 20 million trucks, ultimately coming to account for 20 to 25 percent of each sector. The report also projects that 20 percent of the world's energy consumption — including fuel for trains, ships and air freight — will be replaced by hydrogen. If hydrogen energy can serve as an eco-friendly and efficient energy its market potential in the production-transportation-storage-utilization sector (as shown in Table 1) is

4) The committee includes 33 major automakers and energy companies around the world, including Hyundai Motor.
5) McKinsey & Company (2017).

Table 1. Various Uses of Hydrogen Energy

Classification	Contents
Energy Storage-P2G (Power to Gas)	· Hydrogen is available in both power and heat through fuel cells. · P2G is an energy storage and use system · Applied as a means for harmonious integration between renewable energy and existing power systems
Energy Production-V2G (Vehicle to Grid)	· Apply hydrogen electric vehicle to power generation field · V2G uses electric energy of hydrogen electric car as power source. · Respond to unstable power supply
Heat	· Fuel cell system for buildings · Developing fuel cell as power source for next generation housing · Combined cogeneration system that produces electrical energy and thermal energy through chemical reaction between fuel extraction hydrogen and oxygen in the air
Transportation	· Hydrogen fuel cell for transportation · High efficiency of 36% (natural gas vehicle 16%) · Almost no emission of harmful substances and low noise

Source: Convergence Research Policy Center.

virtually unlimited.

There are a number of ways of exploiting hydrogen as an energy source. The most efficient method is to use it as a source of power generation. Hydrogen has occupied the spotlight recently as a way to generate electricity through fuel cells, rather than being used to power turbines. If the internal combustion engine was at the core of the petroleum energy era, fuel cells are one of the most efficient tools for using hydrogen energy in the hydrogen energy era. The development of a fuel cell power generation system can provide an active opportunity to expand the range of applications of hydrogen energy. Fuel cells are devices that produce electricity and heat using oxygen and hydrogen. They are composed of a reformer, a cell, a stack, a power converter. In addition, fuel cells are widely used in automobiles, household and commercial generators and portable appliances and their economic and industrial ripple effects are great, ranging from infrastructure to hydrogen production, storage and transportation.

Another effective application of hydrogen is in the automobile sector. As shown in Table 2 on the next page, infrastructure for hydrogen fuel cell vehicles is still lacking and neither the vehicle nor the fuel to run it is yet cost-effective.[6] However, from a functional standpoint, the technology has many advantages, such as efficiency, mileage, charging speed, life span and acceleration.

In order to facilitate the transition to a hydrogen economy that can vitalize our economy with massive growth potential, it is essential to construct the basic infrastructure of the hydrogen economy and the foundation for an

6) These prices may be somewhat different for consumers receiving government subsidies.

Table 2. Characteristics of Automotive Driving Systems

	Characteristics	ICE (Internal Combustion Engine)	FCEV (Fuel Cell Electric Vehicle)	BEV (Battery Electric Vehicle)
The lower the better	Commercialization price	$	$$$	$$
	Fuel cost	$$	$$$	$
	Maintenance expenses	$$$	$	$
	Infrastructure necessary	$	$$$	$$
	Exhaust emission	●●●	●	●
The higher the better	Efficiency	★	★★	★★★
	Mileage	★★★	★★★	★
	Charge/Fueling speed	★★★	★★★	★
	Life	★★★	★★★	★★
	Acceleration	★★	★★★	★★★

Source: Royal Society of Chemistry.

industrial ecosystem. In addition, efforts should be made to secure R&D investments for technology, leading to improved economic efficiency of the required technologies through continuous research and reinforce linkages in the hydrogen industry.

With the points made above in mind, this report seeks to make clear the implications of hydrogen energy as a next-generation energy source and the ways in which industry can be structured to ensure a smooth transition to a hydrogen economy. To do this, I examine the economic feasibility, technological power and competitiveness of hydrogen energy, and examine the constraints and regulations facing hydrogen energy in our society and economy. Finally, the main purpose of this study is to derive industrial applications and policy implications of hydrogen energy, which is technically complex but possible to produce anywhere.

2. Hydrogen as an Energy Source and its Possibility for Commercialization

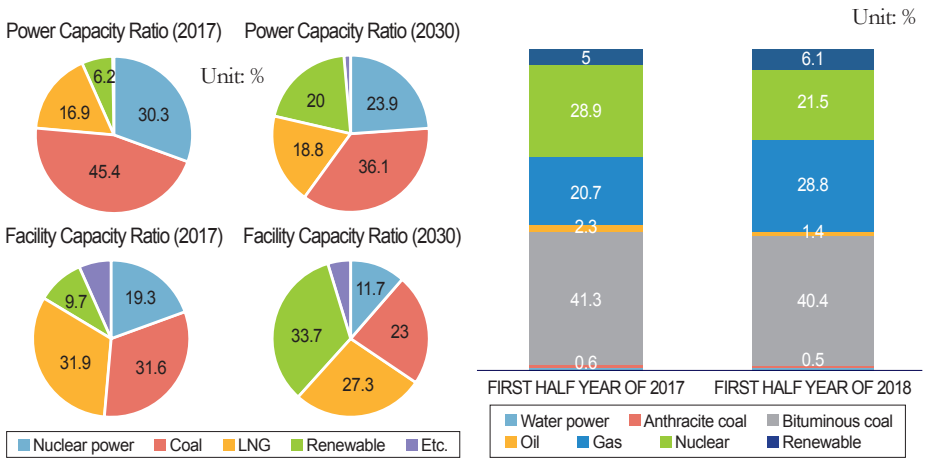
Hydrogen is the most abundant element in nature, element number 1, and is a renewable energy source that generates only water during combustion. Due to the way in which technology and civilization has developed, the current generation is contending with never-before-seen problems of global scale, including the overuse and depletion of fossil fuels, global warming and fine dust. Humanity is in the early stages of attempting to solve these problems through the regulation of carbon dioxide (CO_2) emissions, and hydrogen energy conversion one potential solution to help reduce the use of fossil fuels and thereby reduce the social costs associated with the burning of fossil fuels.

Moreover, Korea depends on foreign imports for more than 95 percent of its energy, and it is well known that the external risks are very high because it is highly reliant on a small number of countries with a locally-concentrated energy supply. Given this, hydrogen has the potential to revolutionize energy security on the Korean peninsula. In addition, a full-scale utilization of hydrogen resources could play an important role in the expansion of industrial sectors through activation of front and rear industries in a new hydrogen industry.

The core of the government's energy transition policy is the realization of a low-carbon economy through the transition to environmentally-friendly energy. A variety of methods have been suggested to bring this to pass, but within the government there are divergent opinions on potential energy transition measures. Discussions revolve around the government's stated goal to achieve 20 percent renewable power generation by 2030, focusing on solar and wind.[7] The plan is controversial because whether or not renewables can both meet Korea's energy demand and be economically viable remains open to question.

In the meantime, thermal power generation must continue (mainly from burning fossil fuels) in order to generate enough electricity to meet current demand. Yet it is inevitable that wind and solar energy sources are brought online and into the energy mix as the energy conversion policy is implemented. But whereas solar, wind, and hydroelectric power plants have problems in terms of installation, site selection, and intermittency, among others,

Figure 2. **Ratio of Power Capacity and Facility Capacity by Energy Source in Korea**



Source: Ministry of Trade, Industry, and Energy and the Korea Electric Power Corporation.

7) According to the Eighth Basic Plan for Electricity Supply and Demand, solar and wind account for 88 percent of total renewable energy capacity.

Table 3. Hydrogen Production Technology Classification

	Method	Raw Material	Energy Source	Technology Level
Fossil fuel	Steam reforming	Natural Gas, LPG, Naphtha	Heat	Commercialized
	Carbon dioxide reforming	Natural Gas	Heat	–
	Partial oxidation	Heavy Oil, Coal	Heat	Commercialized
	Autothermal reforming	Natural Gas, LPG, Naphtha	Heat	Commercialized
	Direct reforming	Natural Gas	Heat	Commercialized
Non fossil fuel	Electrolysis	Water	Electricity	Commercialized
	Thermochemistry decomposition	Water	High Temperature Hear (Nuclear, Solar Heat)	Under Study
	Biological decomposition	Water or Biomass	Heat, Microorganism	Under Study
	Photochemistry decomposition	Water	Solar Photovoltaic	Under Study

Source: Korea hydrogen Industry Association & Maeil Business Newspaper.

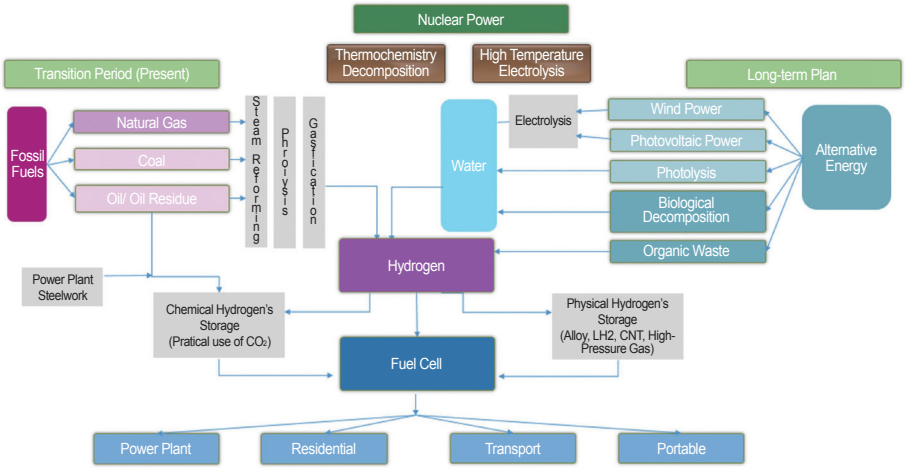
hydrogen energy on the other hand does not suffer those drawbacks to the same degree, all while possessing some additional advantages over other renewables, such as a wide application area. Although there is some controversy over how environmentally-friendly hydrogen energy is, it nonetheless is widely thought to be an essential alternative carbon energy in the future. A critical advantage of hydrogen energy is that no pollutants or greenhouse gases are generated in the process of using it, and the water produced in the course of hydrogen combustion or electricity conversion is possible to reuse.

Unlike fossil fuels, hydrogen energy exists in the form of compounds rather than primary energy, which can be obtained directly through development and mining. Therefore, in order to utilize it as an energy source, it has to undergo a process of decomposition, through techniques such as reforming and oxidation as shown in Table 3.

As shown in the table above, reformed hydrogen and hydrogen oxide, which are currently used to produce hydrogen, are ultimately products of fossil fuels and thus generate CO_2 as a byproduct. The fact that using primary energy sources such as petroleum, coal and gas are being used in the process of energy conversion raises legitimate concerns over whether or hydrogen can become a truly renewable energy source. Hydrogen power sources used by consumers may not produce CO_2 emissions but the production processes of those sources still use fossil fuels.

Hydrogen energy has other problems yet to overcome. These include safety concerns, as hydrogen is highly flammable, doubts over its commercialization prospects due to high production costs, and a lack of hydrogen storage technology. It is thus imperative that policies encouraging continuous R&D be im-

Figure 3. Development Direction of Hydrogen Energy Conversion Process



Source: Convergence Research Policy Center.

plemented to make the technology more viable commercially, offsetting its shortcomings and highlighting its merits.

Already, major countries such as the U.S., Japan, and members of the EU are aware of the importance of hydrogen energy and are carrying out various policies for its expansion and commercialization. Domestic research on hydrogen energy activation and diffusion policies of major countries include the works of Lee Jong Min (2018), Kim Hee Cheol (2017) and Choi Dong Won (2017). Among developed nations Germany is regarded as the leader in energy transition and its implementation technologies and policies. Hydrogen policy in Germany includes measures aimed at establishing infrastructure such as hydrogen filling stations, and founding a leading research institute dedicated to hydrogen and fuel cells. Another noteworthy feature of German hydrogen policy is the use of surplus power from solar and wind power generation to produce hydrogen electrolysis. It is worth noting that the policy links existing renewable energy sources with hydrogen[8], as Germany has prepared power generation and mobile infrastructure, including a micro grid, to utilize renewable energy in preparation for the energy transition. Through these facilities, surplus power from renewable energy is rerouted to be used for hydrogen production and storage. In other words, efforts are being made to ensure the eco-friendliness and economic efficiency of hydrogen energy, by mitigating the intermittency of renewable energy and utilizing waste power.

It is necessary for Korea to do as Germany and utilize renewable energies such as solar and wind energy as part of greater commer-

8) Germany began construction of the world's largest water electrolysis facility in 2017.

cialization efforts of hydrogen energy, and to consider eco-friendly production methods such as electrolysis. However, existing hydrogen-related policies such as the current Roadmap for Activating Hydrogen Economy, are mainly focused on the demand side, the stage actually using hydrogen energy, and the current discussions on hydrogen are woefully insufficient. As shown in Table 1, even though hydrogen energy has myriad possible uses, published hydrogen policy is limited to hydrogen fuel cell vehicles and heating. It is crucial that the government write more detailed policies that enable hydrogen energy to play a clear role as a universal energy source and expand the scope of the dialogue on hydrogen policy, that take into account fundamental commercialization issues.

In addition to environmental problems and situational feasibility, the economics of hydrogen energy must also be considered. If we look at hydrogen energy in terms of thermal efficiency, the energy-density of hydrogen energy is 142 kilojoules per gram. Hydrogen is three times as energy-dense as natural gas, four times as dense as gasoline; it is an efficient energy source that can produce three to four times as much energy in the same amount of fuel. But it is more expensive than either natural gas or gasoline at the pump. The current price of hydrogen in the domestic market is 8,000 KRW per kilogram, which is higher than gasoline, light oil and LPG. As shown in Table 4, the government set a price target of 6,000 KRW per kilogram by 2022 and 4,000 KRW per kilogram by 2030 and 3,000 KRW per kilogram by 2040. To secure these economic efficiencies, the government should provide reliable policy support, technological development and investment. When hydrogen energy achieves economies of scale due to increased production and grows to become a main energy source in response to changes in supply, it is expected to have an expansionary ripple effect on related industries and a preemption effect in the market.

Given its wide range of potential applications hydrogen is suitable as a future energy

Table 4. Hydrogen Supply and Price Target

	2018	2022	2030	2040
Supply (=Demand)	130,000tons/year	470,000tons/year	1.94million tons/year	5.26million tons/year
Way of supply	① By-production Hydrogen (1%) ② Extracted hydrogen (99%)	① By-production Hydrogen ② Extracted hydrogen ③ Water electrolysis	① By-production hydrogen ② Extracted hydrogen ③ Water electrolysis ④ Abroad production *①+③+④=50%, ②=50%	① By-production hydrogen ② Extracted hydrogen ③ Water electrolysis ④ Abroad production *①+③+④=70%, ②=30%
Price	-	6,000KRW/kg	4,000KRW/kg	3,000KRW/kg

Source: Joint Ministry of Korea.

source, but the road to commercialization is long and paved with difficulties. Economic efficiency, technological development and safety issues must all be addressed. In the next section, we will examine the issues and other constraints on commercialization.

3. Constrains on the Commercialization of Hydrogen Energy

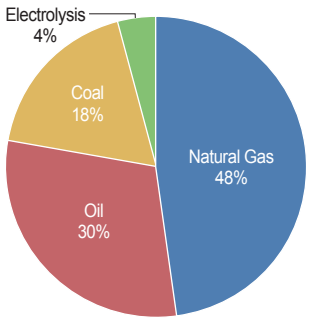
In the early 2000s, hydrogen energy was already thought of as a potential alternative to traditional energy sources such as petroleum amid concerns about resource depletion, high prices, environmental pollution and global warming. At that time, many countries were exhibiting increasing interest in environmentally-friendly energy sources, such as renewable energy and hydrogen energy, and in line with global trends, Korea also announced in 2005 a policy addressing the issue, the Master Plan for the Implementation of an Environmentally-Friendly Hydrogen Economy: Fuel Cell Industry and Mid- to Long-Term Renewable Energy Development Vision.

The U.S. was very much in line with global thinking on the matter and in 2002 announced its National Hydrogen Energy Roadmap. It made early, aggressive investments to become a leader in hydrogen energy and promulgated visionary policy statements including A Hydrogen Economy: To 2030 and Beyond, which promoted clean energy. However, after the Obama administration came into power, the U.S. decided to stop investing in the R&D sector because of the sudden financial crisis and the slow development of fuel cells. At the same time, the hydraulic fracturing technologies for extracting shale gas had become commercially viable and many additional factors, such as the development of crude oil extraction technology and the discovery of new oil reserves, led to a drop in global oil prices and a long-term stabilization period. As a result, development demand for alternative energy has begun to decline somewhat globally.

In addition, it is true that the attention being given to hydrogen energy has recently subsided somewhat given the various commercialization hurdles of the technology. Since the mid-2000s, the Korean government's energy policy was based on demand and supply, and it invested heavily in the technological development of traditional energy sources such as oil and gas. Other additional factors may have played a role in cooling interest in hydrogen energy globally. The decline in international oil prices as well as political issues at home and abroad have slowed the development of hydrogen diffusion technologies and have been a major factor impeding commercialization.

A lack of technology in the hydrogen energy production process is another cause of delayed commercialization. This lack of technology is evident in the fact the overwhelming proportion of hydrogen energy currently produced is made from fossil fuels, as shown in Figure 4. That the production of hydrogen energy re-

Figure 4. Hydrogen Sources



Source: International Renewable Energy Agency.
Note: IRENA based on FCH JU (2016).

quires the use of fossil fuels is becoming a major cause of controversy, creating skepticism of hydrogen energy's eco-friendly credentials. When hydrogen energy was first being popularized conceptually in the early and mid-2000s, the production of hydrogen energy through water electrolysis technology was highlighted as particularly environmentally-friendly. But nearly two decades later the technology has not been able to enter the commercialization stage due to the high production unit price, and it is expected that it will take considerable time to secure economic efficiency.

Even the fuel cell sector, which is considered to be the most economical among current hydrogen energy utilization measures, still has difficulties in securing economic efficiency. The price of a 1-kilowatt residential fuel cell sells on the market for 32.5 million KRW. Consumers pay 9.57 million KRW and an installation fee of 22.75 million KRW. It is clear that the fuel cell does not yet possess cost competitiveness with household electricity and gas. But some progress is being made. In Japan, Tokyo Gas set the goal of lowering the individual unit prices of its Enefarm hydrogen fuel system and introducing 5.3 million units by 2030 through an active supply policy. Japan is also expected to play lead energy-saving efforts through active expansion of fuel cells. However, until economies of scale are achieved and carbon taxes are realized, it will remain difficult to answer the questions of economics regarding hydrogen energy and its potential for universal commercialization.

Yet economics are ultimately second to the stability problem of hydrogen, the most important issue and a precondition for hydrogen diffusion and industrial revitalization despite the various advantages and necessities of hydrogen energy mentioned above. Hydrogen is a flammable gas with explosive potential, and its volatility is 12 times that of gasoline and 4 times that of natural gas, so there are legitimate safety concerns. On the other hand, some argue that it is comparatively safe, as

hydrogen quickly evaporates in the event of a leak.[9]

Currently, Korea is making an effort to revitalize the hydrogen fuel cell vehicles industry, centered on Hyundai Motor Company. Hyundai is planning to start full-scale production of hydrogen cars at its Chungju plant, but must manufacture its own hydrogen supply. This is related to the institutional problems of the hydrogen industry in Korea, such as the licensing of hydrogen charging stations. Institutional and regulatory mitigation is essential to foster a new hydrogen sector. However, the activation of the hydrogen industry being delayed by safety problems. Building more charging stations is indispensable if the hydrogen sector is to grow field, but safety issues limit aggressive expansion. These safety issues have in turn led to a perception problem. In other words, policies that mitigate the NIMBY and PIMFY phenomena are also required for the activation of the hydrogen industry.

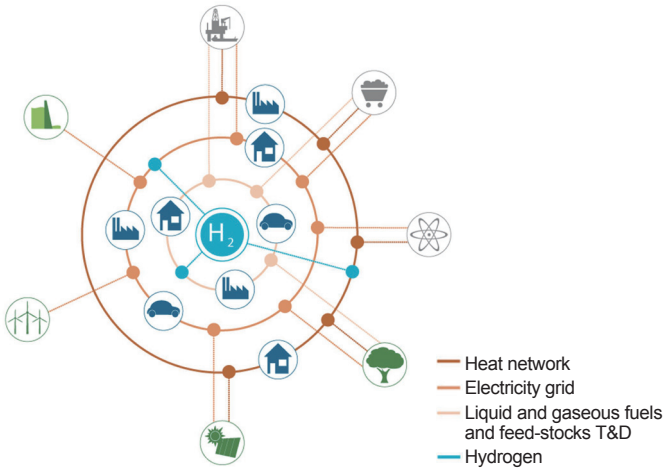
4. Challenges and Implications for Activating Hydrogen Energy

The World Energy Organization (IEA) had already designated hydrogen as a future energy source to replace fossil fuels in 2015. In addition, the use of hydrogen as an energy source will be a key factor in the operation of the future low-carbon energy system that connects transmission and distribution networks of different energy sectors. The world is facing a big change in energy transition, and full-fledged conversion to the hydrogen economy is justified in the time and direction of such energy conversion. Also, due to the diversity of hydrogen production methods and the necessity of eco-friendly energy sources in accordance with the development of technology, each country has continued efforts in various fields to actively utilize hydrogen. Korea is also in the process of drafting and implementing various policy measures for the transition to the hydrogen economy. The construction of a related industrial ecosystem for the hydrogen economy through the production of hydrogen energy, the securing of technologies, and the activation of the demand industry will contribute to the stabilization of the energy supply at the national level in the long term. In addition, it is necessary to nurture the hydrogen energy field as it can provide opportunities for cultivating new industries and securing additional growth engines.

On the other hand, when we look at the ways of activating hydrogen energy in Korea, we can see some limitations. But in order to realize a genuine hydrogen economy, hydrogen energy activation schemes must be linked organically in the life-cycle of production, distribution, storage and utilization. In addition, there is a need to establish and maintain an industrial

9) According to the Institute of Physical Properties (DIPPR) of the American Chemical Society, the relative risk of hydrogen is analyzed in the order of gasoline (1.44) > propane (1.22) > methane (1.03) > hydrogen (1).

Figure 5. Hydrogen's Potential Role in the Energy System



Source: International Energy Agency.

ecosystem by systematically linking the forward and backward industries at every point in the hydrogen life-cycle.

Korea produced the world's first commercial hydrogen vehicles and is a technological power in the field of fuel cells. Yet owing to the fact that related industrial ecosystems are still relatively immature, hydrogen-related industries are not yet proliferating in earnest, and hydrogen technologies fail to reach widespread commercial viability. To break this cycle, it is necessary expand hydrogen production stage by stage and upgrade the technology for doing so. At the same time, it is critical to draft a step-by-step framework for the entire development cycle of the hydrogen industry and to lay the foundation for expanding the demand industry by improving technological competitiveness. The importance of front-to-back linking industries is increasing, and in the main manufacturing sector of Korea, a hydrogen industrial ecosystem can play a role as a vital agent. This will enable the country to pioneer new markets as a leading country in hydrogen, a new industry.

Another obstacle to the creation of ecosystems for hydrogen and associated industries is the opposition of residents who doubt the safety of hydrogen. In 2018, the government organized the Hydrogen Product Safety Support Center for Hydrogen Generation, which selected regions for hydrogen industrial development with the support of local governments. In support of this project, holding a town-hall style meeting with local residents was essential to eventually earning wider public acceptance. Yet despite its success, stern NIMBY opposition made even hosting the town hall difficult. Therefore, it is also necessary to continue to strengthen government efforts to

resolve conflicts with the residents.

Since 2018, the government has announced the implementation of a hydrogen expansion strategy and is making efforts to improve the system by taking measures to relax regulations on hydrogen infrastructure. These include the announcement of special criteria for the construction of fusion, hybrid-type and package charging stations, regulations regarding the maintenance of the pressure vessel related at hydrogen charging stations, permissions to install composite hydrogen storage vessels and the registration exemption for products manufactured abroad. In order to facilitate the transition to the hydrogen economy in this way, it is necessary to establish related legal system and further deregulation efforts.

In addition, there is a need to systematically promote and manage the hydrogen energy sector through preparation of investment and activation policies in various fields. There is also a need for energy governance capable of realizing such a transition. In Korea, there are private organizations for the promotion of hydrogen, including H2KOREA and Hynet, but it is very important to maintain consistency in the direction of implementation by establishing representative control towers as the world leaders in hydrogen do.

In order to achieve a successful energy transition in a country where the energy dependency ratio is as high as 95 percent, it is necessary to make policy efforts and design support measures to address the supply-demand conditions, needs and role of each energy source. If it can demonstrate energy independence, Korea will be able to meet advanced countries on its own terms in the realm of energy security.

Sun Kyung Huh
Researcher
Center for Growth Engine Industries
skhuh@kiet.re.kr