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Research Article

Navigating the Hydrogen Economy in South Korea: Marketing Strategies for Success with Licensors

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Abstract: South Korea's ambitious hydrogen economy targets—including annual production of 6.2 million tons by 2040—highlight both significant growth potential and critical technology gaps that necessitate strategic engagement with overseas licensors. (1) Background/Purpose: Despite rapid global expansion of the hydrogen sector, South Korea's domestic hydrogen production technology lags behind leading nations at approximately 60% of their capability level, and R&D investment of USD 2.6 billion (cumulative 2016–2020) falls well short of Germany's USD 22 billion or the USA's USD 32 billion. This business project aims to shift focus from short-term revenue generation to long-term strategic positioning by understanding the domestic hydrogen market, identifying key licensors, and forming strategic alliances to facilitate market entry. (2) Study Design/Methodology/Approach: The study combines literature review of global hydrogen strategies and IEA data with three detailed case analyses—covering liquefied hydrogen plants, hydrogen gas turbine co-firing, and hydrogen fuel cells in the marine industry—to compare domestic Korean capabilities against global benchmarks provided by leading licensors such as Linde, Siemens Energy, and PowerCell Sweden AB. (3) Findings: South Korea's current planned hydrogen production of 30,394 tons/year stands far short of the 6.2 million ton target. Strategic licensor alliances are identified as the most viable pathway for rapid technology transfer, including PSA (Pressure Swing Adsorption), liquefied hydrogen, gas turbine co-firing, and marine fuel cell systems. Case analyses confirm that domestic players such as SK E&S, Hanwha Impact, and HD Hyundai are actively but incrementally bridging this gap through licensed technologies. (4) Originality/Value: This study provides actionable marketing strategy insights for companies seeking to enter or expand within South Korea's hydrogen sector through licensor partnerships, emphasizing sustainable business models that extend beyond government subsidy dependence.

Keywords: hydrogen economy; South Korea; licensor; marketing strategy; steam methane reforming; liquefied hydrogen; hydrogen gas turbine; hydrogen fuel cell; PSA; green hydrogen

1. Introduction

1.1. Business Project Objective

The objective of the business project is to understand the status of the hydrogen market in South Korea and to gain insights that allow for a comparison with the global hydrogen market. Additionally, to enter the hydrogen market, it is essential to identify licensors of hydrogen production processes. By forming strategic alliances with these licensors, the project aims to facilitate a flexible entry into the growing hydrogen market.

- **Strategic Partnerships:** Strategic partnerships with licensors will enable access to advanced hydrogen production technologies, ensuring that the business remains competitive and innovative. These alliances will provide the necessary technical expertise and support to navigate the complexities of hydrogen production, from electrolysis to steam methane reforming and beyond. Collaborating with established licensors will also help mitigate risks associated with technology adoption and implementation.
- **Leveraging Alliances:** Ultimately, the goal is to leverage these strategic alliances to capitalize on the expanding opportunities within the hydrogen market. By aligning with key licensors, the business can position itself at the forefront of the hydrogen economy, ready to adapt to market demands and regulatory changes. Successfully entering the market with licensors and Korean end-users will also facilitate easier entry into the global hydrogen sector. This approach will ensure a sustainable and scalable entry into the hydrogen sector, driving long-term growth and success.
- **Building Global References:** As the hydrogen market is an emerging market, building global references is crucial. This project aims to establish a strong presence and reputation in the global hydrogen sector, which will be essential for long-term success.
- **Sustainability Beyond Government Subsidies:** The objective is to ensure that the business is sustainable beyond relying solely on government subsidies. By developing a robust and adaptable business model, the project aims to create a self-sustaining enterprise that can thrive in the competitive hydrogen market.

1.2. Business Project Background

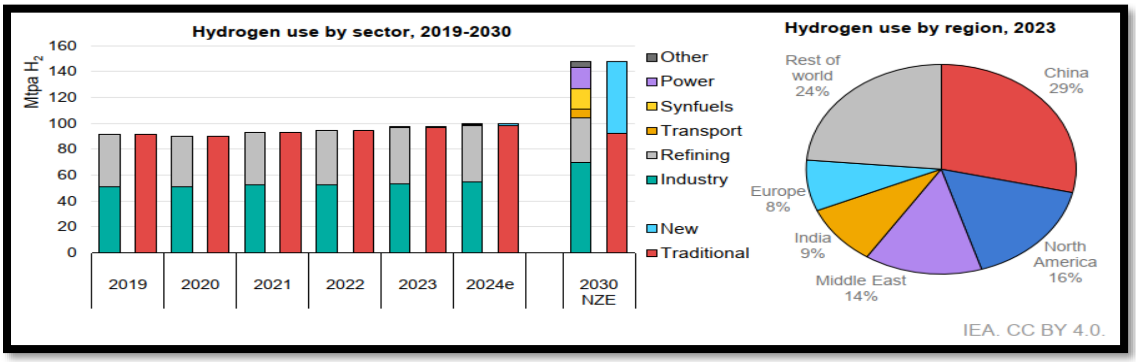
The hydrogen economy is growing rapidly due to global efforts to reduce carbon emissions and transition to sustainable energy. Understanding the increasing demand for hydrogen energy, particularly the rising need for low greenhouse gas emission hydrogen, is essential for developing effective business and marketing strategies. It is crucial to examine the current state of hydrogen technology and its relationship with economic growth. This research will provide valuable insights for stakeholders to navigate the challenges and opportunities in the hydrogen sector.

Rather than solely focusing on short-term revenue growth, it is essential to develop a long-term business plan that aligns with the increasing demand for hydrogen and South Korea's hydrogen roadmap. This approach will ensure that companies remain competitive and innovative in the evolving hydrogen market.

Expansion of Hydrogen Energy Demand

Global hydrogen demand continued to grow in 2023 to reach a new high of more than 97 Mt, a 2.5% increase compared with 2022. Demand has been growing continuously for several decades, with the exception of 2020, when the Covid-19 pandemic led to an economic slowdown. Growth is estimated to continue in 2024, with global hydrogen demand expected to reach close to 100 Mt.

Table 1. Hydrogen Demand by Sector and by Region.



Source: IEA (2024). Global Hydrogen Review, pp. 21–22.

The regional distribution of demand remained largely unchanged from 2022: China was again the largest hydrogen user, accounting for nearly one-third of global demand (close to 28 Mt), more than double that of the second largest user, the United States, with 13 Mt (14% of global demand). Hydrogen demand grew modestly in all major regions, apart from in the Middle East, where growth was much steeper (more than 6% growth year-on-year, due to an increase in demand in refining and methanol production) and India (more than 5% growth year-on-year due to larger demand in refining and the steel sector).

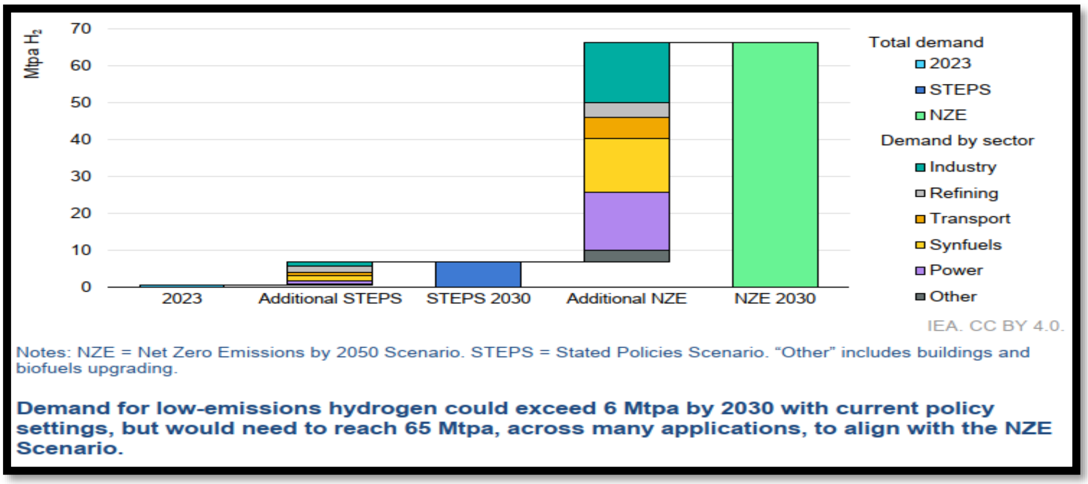
Crucial Role of Low-Emissions Hydrogen

The global energy sector is undergoing a significant transformation as efforts to tackle climate change and enhance energy security drive the shift toward cleaner, more sustainable energy sources. In this evolving landscape, the demand for hydrogen has been steadily increasing. However, there is a growing recognition that low-emissions hydrogen will play a crucial role in the future.

Low-emissions hydrogen is seen as a key solution for decarbonizing sectors where emissions are difficult to reduce and other options are limited, such as heavy industry, shipping, and aviation. The recent global energy crisis has further accelerated the push for low-emissions hydrogen due to its potential to enhance energy security. As a result, governments have intensified their net-zero emission commitments, integrating low-emissions hydrogen into their strategic plans.

Several major economies have recently introduced new industrial policies that prominently feature hydrogen technologies. Despite this progress, the adoption of low-emissions hydrogen is still in its early stages, and significant challenges remain to fully realize its potential. Given the increasing demand for hydrogen, it is essential to focus on low-emissions hydrogen as a critical agenda item. This approach will not only help in achieving decarbonization goals but also ensure a sustainable and secure energy future. By prioritizing low-emissions hydrogen, companies can align with global trends and contribute to the broader efforts to combat climate change and enhance energy security.

Table 2. Low-Emission Hydrogen Demand by Sector in 2023.



Source: IEA (2024). Global Hydrogen Review, pp. 23–25.

The classification of hydrogen production based on energy sources and the type of colors helps define low-emissions hydrogen. This table categorizes hydrogen types like grey, blue, and green hydrogen by their energy sources and associated carbon emissions. Understanding these classifications is essential for identifying sustainable hydrogen production methods and supporting global decarbonization efforts.

Table 3. Types of Hydrogen Production.

Type	Raw Material	Process	Output	Carbon Emissions	Notes
Brown	Coal, Lignite	Gasification	H2 + CO2	≥10 kg/kgH2	Highest emissions
Gray	Natural Gas	Steam	H2 + CO2	9.2~11.1	Most common currently

Type	Raw Material	Process	Output	Carbon Emissions	Notes
		Reforming		kg/kgH2	
Blue	Natural Gas	Steam Reforming + CCUS	H2 + CO2	1.2~3.9 kg/kgH2	CCS reduces emissions
Green	Renewable Energy	Electrolysis	H2 + O2	0.3~1.0 kg/kgH2	Lowest emissions
Pink	Nuclear Elec. + Heat	Electrolysis	H2 + O2	Small amount	Nuclear-powered

Source: Korea International Trade Association, Green Transition Team (2023). Policy research for strengthening hydrogen industry competitiveness: Policy comparison of major countries for eco-friendly hydrogen production. p. 4.

South Korea's Hydrogen Vision for 2040 and Beyond

South Korea's vision for 2040 includes increasing the number of hydrogen refuelling stations (HRSs). In 2019, the Hydrogen Energy Network (HyNet) was launched with an initial investment of $119 million, aiming to grow the number of HRSs from around 24 in 2019 to 310 by 2022 and 1,200 by 2040. Additionally, by 2040, South Korea plans to install 15 gigawatts of utility-scale fuel cells.

According to the Ministry of Trade, Industry and Energy, by 2030 the country will produce 3.9 million metric tons (mt) of hydrogen annually. This includes 940,000 mt of grey hydrogen, 750,000 mt of blue hydrogen, and 250,000 mt of locally sourced green hydrogen, while also importing 1.96 million mt of green hydrogen from abroad. Currently, South Korea does not generate any clean hydrogen; all 220,000 mt produced in 2020 was grey hydrogen derived from fossil fuels.

By 2050, South Korea aims to produce 27.9 million mt of hydrogen each year, comprising 3 million mt of green hydrogen and 2 million mt of blue hydrogen, while importing 22.9 million mt of green hydrogen from overseas, eliminating grey hydrogen from its production mix.

2. Theoretical Background

2.1. Hydrogen Economy: National Hydrogen Strategies and Policies

The number of countries with a hydrogen strategy has increased, with 19 new strategies published in the past year, mainly in emerging markets and developing economies (EMDEs). These strategies, driven by goals of decarbonization, energy security, domestic industrial development, and export potential, are primarily seen in Europe, Africa, and ASEAN countries. Notably, all new strategies focus on strong exports and domestic industry growth, with no plans for hydrogen imports. Currently, countries responsible for 84% of global energy-related CO2 emissions have a hydrogen strategy in place.

Table 4. Comparison and Analysis of Hydrogen Production Policies in Major Countries.

Country	Strategy	Budget	Rep. R&D Programs	Gov. Body	Key Focus	Notes
Germany	Promote domestic green H2 production; secure overseas supply chains	$22B (~'30)	H2Giga, H2Mare, TransHyDE, H2Atlas Africa, HySupply	BMMK, BMDV, BMBF	Green H2 production	—
USA	Activate market; reduce production costs via large-	$32B (~'32)	Clean Hydrogen Electrolysis, Clean H2 Manufacturing & Recycling, H2Hub	DOE	Market activation	—

Country	Strategy	Budget	Rep. R&D Programs	Gov. Body	Key Focus	Notes
	scale subsidies					
UK	Reduce production costs; expand overseas supply chains simultaneously	$6.5B (~'30)	Low Carbon Hydrogen Supply 2, Hydrogen BECCS innovation, Industrial H2 accelerator	DESNZ	Cost reduction	—
Japan	Expand green H2 supply using renewable energy, state-led	—	Hydrogen Society Construction Technology, Green Innovation Fund Project	METI, MOE	State-led supply	—
France	Clean H2 production for export to NE and SE Asia	$1.3B	Regional H2 Ecosystem, H2 Tech Demonstration, PEPR-H2	MEF, MET, MTER	Export	—
Australia	Develop technology; expand supply chains for clean H2	$1.7B (~'20)	Hydrogen Headstart, Regional H2 Hubs Program	DCCEEW	Supply chains	—

Source: Korea International Trade Association, Green Transition Team (2023). Policy research for strengthening hydrogen industry competitiveness: Policy comparison of major countries for eco-friendly hydrogen production. p. 11.

Policy support is transitioning from visions and targets to implementation, with nearly USD 100 billion in public funds announced or allocated to low-emissions hydrogen projects in the past year. Although two-thirds of these funds are still at the announcement stage, they reflect significant government commitment. Most of this funding comes from advanced economies, while EMDEs have limited economic incentives for domestic industry development. Despite being a small fraction of the investment needed to achieve net-zero goals, this funding is crucial for the early stages of the low-emissions hydrogen industry and for building experience across different regions.

Public funding for hydrogen supply is nearly 1.5 times higher than for demand, with USD 62 billion allocated to supply-side policies and USD 40 billion to demand-side policies in the past year. Developed markets primarily use public subsidies, while tax incentives are common in EMDEs. Direct grants, mostly from advanced economies, are crucial for reducing capital expenditure and de-risking investments. Competitive bidding for hydrogen production and use is widespread, contributing to market formation and cost reduction.

Governments are also developing certification schemes and clarifying rules for hydrogen under national frameworks. The United States is creating guidelines under the Inflation Reduction Act, while the European Commission is defining “low-carbon” hydrogen. The United Kingdom updated its Low-Carbon Hydrogen Standard, Kenya introduced sustainability criteria for green hydrogen, and Brazil established a GHG threshold for low-carbon hydrogen. Japan proposed GHG thresholds for various hydrogen-related fuels under the Hydrogen Society Promotion Act.

These efforts reflect a significant commitment to advancing low-emissions hydrogen, though challenges remain. The funding and policies are essential for demonstrating deployment, building experience across regions, and driving down costs, ultimately supporting the transition to a sustainable hydrogen economy.

Table 5. GHIAA Country Member List.

Country	Member Organization

Country	**Member Organization**
Korea	H2Korea
USA	HCHEA
EU	Hydrogen Europe
Canada	CHFCA
Netherlands	NWBA
Norway	NHF
Denmark	Hydrogen Denmark
Germany	DWV
Sweden	Hydrogen Sweden
Spain	A2H2
France	France Hydrogene
UK	UK Hydrogen and Fuel Cell Association
Singapore	HFCAS
China	IHFCA
Australia	AHC
Argentina	H2ar Consortium
Colombia	Association Colombia
Chile	H2Chile

Source: Global Hydrogen Industrial Association Alliance. https://ghiaa.net/eng/brand/partners.do

In addition, the importance of government-private sector cooperation is increasing to activate the hydrogen economy. In May 2022, the Global Hydrogen Industrial Association Alliance (GHIAA) was launched with the participation of hydrogen associations from 18 countries, including the United States and the EU. This alliance is expected to create new industries and provide opportunities for the resurgence of traditional industries by enabling the use of hydrogen across various sectors.

2.2. Challenges of Hydrogen Production in South Korea

By-product hydrogen, the domestic hydrogen supply source, has limitations in expanding production, and the technology for direct hydrogen production is lacking compared to competing countries. Therefore, policies to secure foundational technologies for hydrogen production are being actively pursued at the national level.

Domestic hydrogen production mainly occurs as a by-product of petrochemical processes, amounting to 1.71 million tons in 2018, which is only 1.5% of the global share. Korea's hydrogen production breakdown in 2018: Refining (75%), Naphtha cracking (13%), Natural gas reforming (6%), Chlor-alkali (3%).

Domestic hydrogen production technology is at 60% of the level of leading countries. Most of it is reintegrated as raw material for refining, with only 240,000 tons (14%) sold externally. Until 2018, support policies were led by the Ministry of Trade, Industry, and Energy, and since the announcement of the Hydrogen Economy Activation Roadmap (January 2019), government-wide investments in technology development for hydrogen production have been underway.

Current Status of Hydrogen Production in South Korea

According to the Hydrogen Economy Comprehensive Information Portal, the planned hydrogen production is 30,394 tons per year. In comparison, the government's announced hydrogen production target is 6.2 million tons per year by 2040. This stark contrast highlights that the current production levels are still significantly short of the ambitious goal. It underscores the substantial efforts and advancements needed to bridge this gap and achieve the target.

Table 6. Status of Domestic Hydrogen Production Centers as of 2024.

Operating Organization	Region	Production and Shipping Volume
JNK Heater Co., Ltd.	Changwon, Gyeongnam	330 tons/year, 460 Nm3/h (1 ton/day)
DH2 Energy Co., Ltd.	Samcheok, Gangwon	430 tons/year, 600 Nm3/h (1.2 tons/day)
Korea Gas Technology Corporation	Pyeongtaek, Gyeonggi	2,350 tons/year, 3,300 Nm3/h (7.1 tons/day)
Daejeon Urban Corporation	Dong-gu, Daejeon	430 tons/year, 600 Nm3/h (1.2 tons/day)
Korea Gas Technology Corporation	Gijang, Busan	430 tons/year, 600 Nm3/h (1.2 tons/day)
Incheon Green Energy	Jung-gu, Incheon	430 tons/year, 600 Nm3/h (1.2 tons/day)
Korea Gas Technology Corporation	Wanju, Jeonbuk	720 tons/year, 600 Nm3/h ×4 (5.2 tons/day)
Korea Gas Corporation	Gwangsan, Gwangju	1,420 tons/year, 2,000 Nm3/h (4.3 tons/day)
Korea Gas Corporation	Changwon, Gyeongnam	3,560 tons/year, 5,000 Nm3/h (10.8 tons/day)
Korea Gas Corporation	Pyeongtaek, Gyeonggi	5,340 tons/year, 7,500 Nm3/h (16.2 tons/day)
Deokyang Energen	Yeosu, Jeonnam	2,560 tons/year, 3,600 Nm3/h (7.8 tons/day)
Linde Hydrogen Energy	Nam-gu, Ulsan	4,950 tons/year (15 tons/day)
Lotte Air Liquide Energy	Seosan, Chungnam	4,950 tons/year (15 tons/day)
—	Buan, Jeonbuk	331 tons/year, 466 Nm3/h (1 ton/day)
Korea Gas Technology Corporation	Pyeongchang, Gangwon	391 tons/year, 500 Nm3/h (1 ton/day)
Korea East-West Power	Donghae, Gangwon	391 tons/year, 500 Nm3/h (1 ton/day)
Korea Midland Power	Boryeong, Chungnam	391 tons/year, 500 Nm3/h (1 ton/day)
JNK Global Co., Ltd. / Air Rain Co., Ltd.	Cheongju, Chungbuk	990 tons/year (3 tons/day)

Source: Hydrogen Economy Comprehensive Information Portal.

Among major countries, Germany is investing USD 22 billion, the United States USD 32 billion, and the UK USD 6.5 billion in hydrogen national strategies, including R&D. In comparison, South Korea's investment of USD 2.6 billion is significantly lower. This difference underscores the need for South Korea to reassess its investment strategy in the hydrogen sector.

South Korea does not have an abundance of feedstock for hydrogen, nor does it possess superior import technologies. This reality makes it even more critical to strategically allocate resources to areas that can yield the highest returns. To gain a technological edge in the hydrogen market, it is crucial to make aggressive investments in areas that align well with the industrial structure of South Korea. This might include developing advanced hydrogen production methods, improving storage solutions, or enhancing transportation infrastructure.

Additionally, related companies must align their technology development with these trends to stay competitive. Businesses should focus on R&D efforts that support the national strategy and collaborate with international partners to acquire and develop cutting-edge technologies. By doing so, South Korea can build a robust hydrogen economy that not only meets domestic needs but also positions itself as a leader in the global market.

Table 7. R&D Investment Scale in South Korea by Ministry/Field (Cumulative 2016–2020).

Utilization (Transport, Power Generation)	Storage, Transportation	Production	Others (Safety, Environment, Infrastructure)	Cumulative Investment (2016–2020)
$1.4 billion	$0.3 billion	$0.6 billion	$0.3 billion	$2.6 billion

Source: Korea Institute of Science and Technology Evaluation and Planning Report and Government Press Release Summary.

To lead technologically on a global scale, not only is a substantial budget required, but it is also essential to consider specializing and focusing on areas such as hydrogen production, storage, transportation, and utilization. South Korea must identify and invest in niche areas where it can develop a competitive advantage. This could involve leveraging existing industrial strengths or fostering innovation in emerging technologies.

2.3. Comparison of South Korea Hydrogen Industry Holdings

Among the major industry categories, 'hydrogen utilization' has the highest number of businesses with 1,294 (45.3%). This is followed by hydrogen distribution (26.8%), hydrogen-related services (14.1%), and hydrogen production (13.9%). Among the sub-industry categories, 'mobility' has the highest number of businesses with 18.0%, followed by hydrogen refueling (16.1%), hydrogen process utilization (15.0%), and hydrogen production (13.9%).

Table 8. Status of the South Korea Hydrogen Industry.

Description	Number of Businesses	Proportion (%)
Hydrogen Production	397	13.9
Hydrogen Distribution	766	26.8
Hydrogen Utilization	1,294	45.3
Hydrogen-Related Services	402	14.1
Subtotal	2,859	100
Hydrogen Production	397	13.9
Hydrogen Storage	221	7.7
Transportation	84	2.9
Hydrogen Refueling	461	16.1
Mobility	515	18.0
Fuel Cells	214	7.5
Hydrogen Utilization for Power Generation	136	4.8
Hydrogen Process Utilization	429	15.0
Hydrogen-Related Safety Products	53	1.9
Engineering Services	65	2.3

Description	Number of Businesses	Proportion (%)
R&D and Scientific Services	159	5.6
Hydrogen-Related Maintenance Services	19	0.7
Safety Management, Maintenance, and Consulting	86	3.0
Hydrogen-Related Educational Services	6	0.2
Hydrogen-Related Associations and Organizations	14	0.5
Subtotal	2,859	100

Source: Hydrogen Economy Comprehensive Information Portal.

2.4. Hydrogen Technologies and Key Licensors

Grey Hydrogen Production

South Korea primarily produces hydrogen as a by-product of petrochemical processes, making it crucial to examine grey hydrogen production technology. In 2018, domestic production was 1.71 million tons, only 1.5% of the global share, with most hydrogen reintegrated into refining.

Table 9. Grey Hydrogen Production Technologies and Costs.

Case	Plant Type	Feedstock	Technology Type	CO_2 Capture (%)	Hydrogen Production Capacity	Levelized Cost of Hydrogen
1	Reforming	Natural Gas	Steam Methane Reforming	0	483,000 kg/day	$1.06/kg
2				96.2		$1.54/kg
3			Autothermal Reforming	94.5	660,000 kg/day	$1.51/kg
4	Gasification	Illinois No. 6 Coal	Shell/Air Products-type oxygen-blown, entrained flow gasification	0		$2.58/kg
5				92.5		$2.92/kg
6		Illinois No. 6 Coal/ Torrefied Woody Biomass		92.6	133,000 kg/day	$3.44/kg

Source: NETL. Technologies for hydrogen production. p. 3.

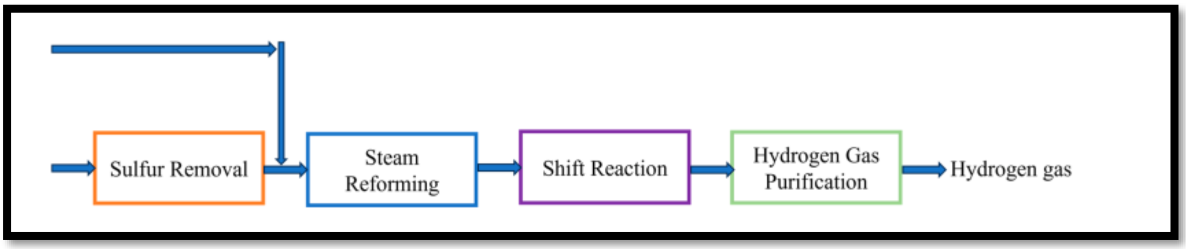
a) Steam Methane Reforming (SMR)

Methane is a colourless, odourless, and highly inflammable compound which is obtained from both renewable (organic matter and animals) and non-renewable sources (coal production and fossil fuels). Steam methane reforming, one of the three hydrocarbon reforming technologies, is the least expensive and most widely used method for producing hydrogen from natural gas. Partial oxidation and autothermal reforming are the other two methods used in this technology. Methane makes up a significant portion of natural gas and is one of the major contributors to global warming. Thus, generating hydrogen gas from methane provides a solution for slowing down its accumulation in the atmosphere. The process involves sulphur removal, steam reforming, shift reaction, and pressure swing absorption. The stages that characterise this process are the mixing of methane with steam under high temperature and pressure in the presence of a catalyst (Equation 1) and a shift reaction in which carbon dioxide produced in the process undergoes additional reaction with steam to produce more hydrogen gas (Equation 2).

$$CH4 + H2O \rightarrow CO + 3H2 \quad \ldots\ldots\ldots\ldots\ (1)$$

$$CO + H2O \rightarrow CO2 + H2 \quad \ldots\ldots\ldots\ldots\ (2)$$

Figure 1. *Simplified steam methane reforming process. Source: Clean Technologies (2023). A Comparative Analysis of Different Hydrogen Production Methods and Their Environmental Impact. Clean Technologies, p. 1349.*



This is a well-established technology with developed infrastructure and large-scale production capabilities. It is also cost-effective and makes use of natural gas infrastructure. However, this method is heavily dependent on fossil fuels, leading to the emission of carbon dioxide into the atmosphere, thus increasing carbon dioxide levels.

b) Auto Thermal Reforming (ATR)

Auto Thermal Reforming (ATR) is a process that combines partial oxidation and steam reforming to produce syngas, a mixture of hydrogen, carbon monoxide, and carbon dioxide. In ATR, methane reacts with oxygen and steam in a single reactor, where the exothermic partial oxidation reaction provides the necessary heat for the endothermic steam reforming reaction. This integration allows for efficient hydrogen production with a flexible H2:CO ratio, making ATR suitable for large-scale hydrogen production and applications requiring specific syngas compositions. ATR is particularly advantageous for its ability to achieve high carbon capture rates when combined with carbon capture technologies.

Table 10. Grey Hydrogen Production Technologies and Efficiency.

Technology	Method of Production	Technology Maturity	Feedstock	Efficiency (%)	Temperature (°C)
Fossil fuel-based	NH_3 reforming	Near team	NH_3	28.3	800–900
	Aqueous reforming	Medium term	Carbohydrate	35–55	220–270
	Plasma reforming	Long term	Hydrocarbon	9–85	900–1300
	Pyrolysis	Near term	-	51	1000–1400
	POX	Commercial	-	60–75	800–1000
	ATR	Near term	-		700–1000
	SMR	Commercial	-	74–85	

Source: Clean Technologies (2023). A Comparative Analysis of Different Hydrogen Production Methods and Their Environmental Impact. Clean Technologies, p. 1369.

c) Pressure Swing Adsorption (PSA)

Pressure Swing Adsorption (PSA) is a technology used to separate specific gases from a mixture under pressure based on their molecular characteristics and affinity for an adsorbent material. In hydrogen production, PSA is typically used to purify hydrogen by removing impurities such as carbon dioxide, carbon monoxide, and methane. The process involves passing the gas mixture through adsorbent beds that selectively adsorb the impurities at high pressure. When the adsorbent becomes saturated, the pressure is reduced, releasing the adsorbed impurities and regenerating the adsorbent for the next cycle. PSA is known for its efficiency and ability to produce high-purity hydrogen.

Linde plc

Figure 2. *Photo of Linde PSA equipment. Source: Linde Engineering. https://www.linde-engineering.com/products-and-services/process-plants/adsorption-and-membrane-plants*

Among the various hydrogen production processes, Pressure Swing Adsorption (PSA) is particularly significant in South Korea due to its use of by-product hydrogen. This method is highly demanded in the country as it efficiently purifies hydrogen from various industrial by-products, making it a cost-effective and practical solution for hydrogen production.

Linde is a key player in the PSA process and has a strong presence in South Korea. The company has designed and delivered over 900 PSA plants globally, including many in South Korea. Linde's PSA technology is known for its high performance and reliability, providing a cost-effective means of separating and purifying hydrogen. This widespread adoption of Linde's PSA technology in South Korea underscores its importance in the country's hydrogen economy, particularly in utilizing by-product hydrogen from industrial processes.

However, it is important to note that Korean hydrogen production technology is currently at 60% of the level of leading countries. This gap highlights the need for continued investment and development in hydrogen production technologies to enhance efficiency and competitiveness in the global market. Korean EPC companies often contract with licensors like Linde to design PSA modules overseas, leveraging their advanced technology and expertise.

Hydrogen Storage

Hydrogen storage technology is crucial for countries that lack the raw materials needed for hydrogen production or have insufficient hydrogen production technology. These countries need to secure hydrogen to meet their future demands. South Korea, for instance, faces a potential shortfall in hydrogen supply compared to future demand due to its lack of raw materials.

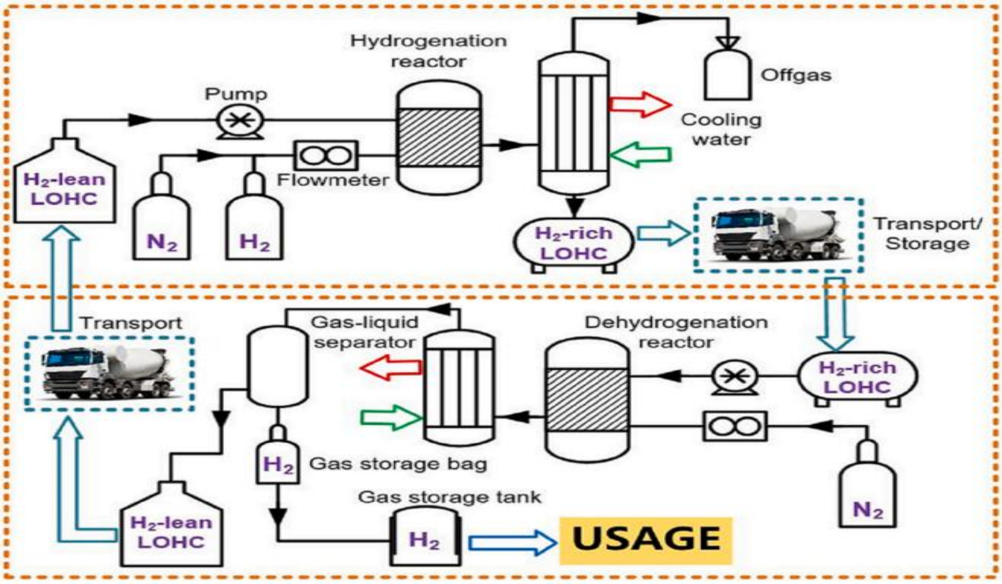
To address this, the Ministry of Trade, Industry and Energy announced plans to import 1.96 million metric tons of green hydrogen from overseas by 2030. This strategy aims to ensure a stable hydrogen supply to meet the country's future energy needs.

a) Liquefied Hydrogen Storage

Liquefied hydrogen is crucial for South Korea for several reasons. Liquefied hydrogen has 1/800th the volume of gaseous hydrogen, making it much easier to store and transport in large quantities. This is particularly beneficial for long-distance transportation and large-scale storage. Liquefied hydrogen can be transported at low pressure, enhancing safety, and it allows for fast refueling with minimal waiting time. This makes it ideal for commercial vehicles like buses and trucks, promoting the transition to hydrogen-powered transportation.

For South Korea's strategy to import hydrogen from overseas, liquefied hydrogen is essential. Its reduced volume and ease of transport make it the most viable option for importing large quantities of hydrogen efficiently and cost-effectively. These factors make liquefied hydrogen an essential component of South Korea's sustainable energy transition and hydrogen economy development.

Figure 3. *Integrated system for hydrogen storage and release. Source: Chenyang Chu, Kai Wu, Bingbing Luo, Qi Cao, Huiyan Zhang. Carbon Resources Conversion, p. 343.*



Liquefied hydrogen storage involves cooling hydrogen gas to extremely low temperatures (around −253°C or −423°F) to convert it into a liquid state. This process significantly reduces the volume of hydrogen, making it easier to store and transport. Liquefied hydrogen is stored in specially designed, insulated tanks to maintain its low temperature and prevent it from evaporating. This method is commonly used in various industries, including aerospace, energy, and transportation, due to its efficiency in handling large quantities of hydrogen.

b) Major Countries Developing Technologies for Stable Hydrogen Storage

Table 11. Global Key Licensors for Hydrogen Storage Technologies.

Country	Company	Technology	Features
USA	Air Products & Chemicals	N-heterocycles / Liquefaction	Cools H2 to −253°C; liquid H2 has 862× storage density of gaseous H2 and 2.8× energy content of high-pressure gas; >4 plants with 6–35 tons/day capacity installed
Germany	Linde	Hydrogen Liquefaction Plant	Cools H2 to −253°C; commercialized liquefaction technology (entering global refueling market); ~150 hydrogen refueling stations deployed in Europe, USA, and Japan
France	Air Liquide	Hydrogen Liquefaction Plant	Cools H2 to −253°C; operates world's largest H2 storage facility (Baytown, Texas cavern); plans to supply LH2 to FEF private refueling stations throughout California
Australia	CSIRO	Ammonia Decomposition Gas H2 Purification	Membrane-based technology for purifying hydrogen from ammonia decomposition gas
Japan	Iwatani	Hydrogen Liquefaction Plant	Cools H2 to −253°C; supplies 60% of Japan's hydrogen production; 50% supplied as LH2
Japan	Chiyoda	LOHC Storage and Transportation	Stores H2 in liquid organic compounds (MCH carrier); planned demonstration of H2 transport between Brunei (hydrogenation) and Japan (dehydrogenation) by ship

Source: IEA (2024). Global Hydrogen Review.

In contrast to major hydrogen-producing countries, South Korea faces a significant challenge due to the lack of prominent licensors in the hydrogen sector. This shortage of leading licensors hinders the country's ability to compete on a global scale and develop a robust hydrogen economy. The absence of well-established licensors means that South Korea must rely heavily on external partnerships and imported technologies, which can limit its growth and innovation potential in the hydrogen market.

Hydrogen Utilization: Electric Power Generation

The necessity of hydrogen utilization in power generation is driven by its potential to significantly reduce carbon emissions and enhance energy sustainability. Hydrogen can be used in gas turbines and fuel cells to generate electricity with minimal greenhouse gas emissions, making it a key component in the transition to cleaner energy sources.

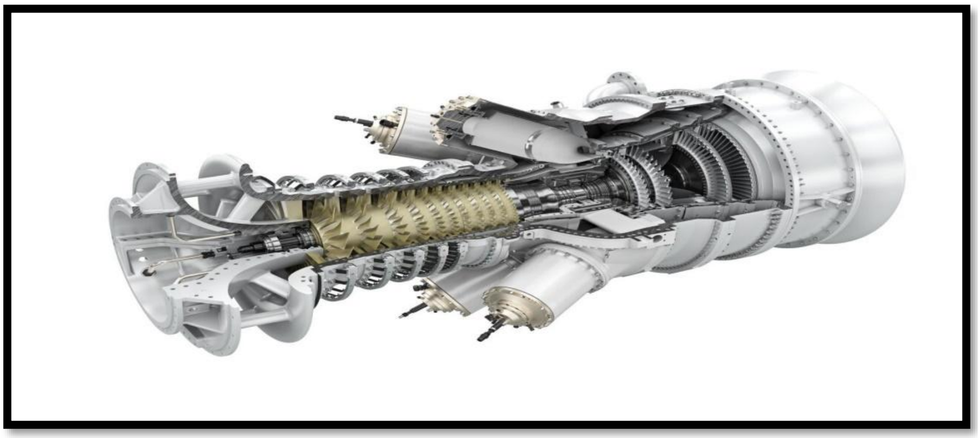
Hydrogen-powered gas turbines can operate on a mix of hydrogen and natural gas, gradually increasing the hydrogen ratio as technology advances. This flexibility allows for a smoother transition from fossil fuels to renewable energy sources. Additionally, hydrogen fuel cells offer high efficiency and reliability for power generation, especially in distributed energy systems and backup power applications. Fuel cells convert the chemical energy of hydrogen directly into electricity through an electrochemical process, producing only water and heat as by-products.

a) Hydrogen in Gas Turbines

Gas turbines, which emit about 45% less greenhouse gases compared to coal, are emerging as a crucial technology for achieving carbon neutrality. In particular, the hydrogen turbine sector, which uses hydrogen as a carbon-free fuel, is gaining new attention as an essential technology for achieving carbon neutrality and is expected to grow rapidly.

A hydrogen turbine is a device that uses a gas turbine to generate electricity by expanding high-temperature, high-pressure gas produced during the combustion of a mixed fuel of existing LNG and hydrogen (hydrogen co-firing). Hydrogen turbines can be used by modifying or newly manufacturing only a part of the existing LNG combined cycle gas turbines, which currently account for about 26% of domestic power production. They can also flexibly mix LNG and hydrogen for power generation in line with the expansion speed of renewable energy.

Figure 4. *SGT-400 gas turbine to demonstrate 100% hydrogen combustion. Source: Siemens Energy website.*



This technology is already in the commercialization stage as it can address the intermittency problem pointed out as a drawback of renewable energy, reduce social and economic costs incurred in the process of achieving carbon neutrality, and reduce carbon and nitrogen oxide emissions. This means that hydrogen turbine power generation can overcome the limitations of renewable energy sources such as solar and wind power, which cannot stably produce electricity.

Considering the job losses and regional economic downturns due to the closure of existing coal power plants, and the complaints arising from the construction of new power plants, hydrogen turbine technology, which reduces carbon emissions by modifying or replacing gas turbines in existing LNG power plants, is expected to mitigate social and economic shocks during the energy transition process.

Table 12. Korean and Major 3 GT (Gas Turbine) Latest Status.

Category	Doosan	Siemens	Mitsubishi	GE
Model Name	DGT6-300H S2	SGT6-9000HL	M501JAC	7HA.03
Output (MW)	330 / 550	388 / 577	425 / 614	430 / 640
Efficiency (%)	43 / 63	42 / 63	44 / 64	43.3 / 63.9
Inlet Gas Temp. (°C)	1,650	1,550	1,650	1,600
Combustion Type	Single-stage	Single-stage	Single-stage	Single-stage
NOx (ppm)	30	25	25	25
CO (ppm)	10	10	10	9
H2 Co-firing (%)	30 (exp. 2025)	30 (exp. 2025)	50 (exp. 2025)	50 (exp. 2025)

Source: Energy News Korea. https://www.energy-news.co.kr/news/articleView.html?idxno=80265

A gas turbine is the heart of combined cycle or cogeneration power plants. It consists of over 40,000 parts, with more than 450 blades inside the turbine. A gas turbine that has completed its initial test encompasses the highest level of technology, including superalloy materials and precision casting techniques that withstand temperatures of 1,500–1,700 degrees Celsius, axial compressors, low-emission combustors, and system integration that combines key components like compressors, combustors, and turbines. Once installed, a power generation gas turbine has a lifespan of 20–30 years. Moreover, securing the core technology is challenging, making it a highly competitive market with high entry barriers. The gas turbine market has been dominated by three major companies—General Electric (GE), Siemens, and Mitsubishi Power (MPW)—which together hold over 80% of the global market share.

Most experts predict that the dominance of these three major companies will continue in the global gas turbine market until 2028, with their market share expected to exceed 82%. Recently, Mitsubishi has been reported to be conducting a national project to verify a gas turbine with an inlet temperature of 1,700 degrees Celsius by directly connecting it to the grid. To date, all 150 gas turbines introduced into the domestic power market are foreign products. Recently, GE supplied its latest gas turbine models to the Shin Sejong Cogeneration Plant, while Siemens supplied its latest models to the Yeoju, Cheongju, and Eumseong Cogeneration Plants.

b) Siemens Energy AG

An excellent example of the advancements in hydrogen turbine technology is the Zero Emission Hydrogen Turbine Center (ZEHTC) in Finspång, Sweden, developed by Siemens Energy. This center demonstrates the practical application and benefits of hydrogen turbines, showcasing how they can integrate with renewable energy sources and energy storage solutions to create a flexible and sustainable energy system.

Figure 5. *Siemens Energy plant in Finspång, location of ZEHTC. Source: Siemens Energy website.*

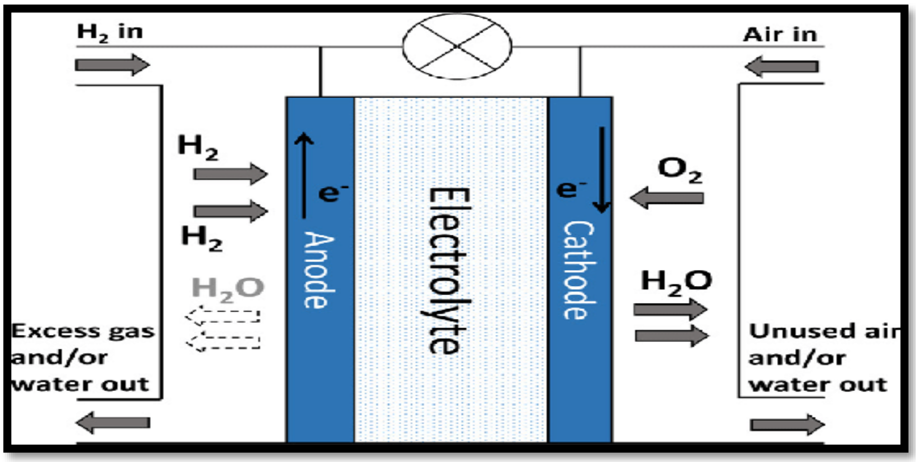
One of the key objectives of the ZEHTC is to enable the operation of gas turbines on up to 100% hydrogen by 2030. This initiative is part of Siemens Energy's broader goal to decarbonize the energy sector and reduce CO2 emissions. The center provides valuable insights into the use of hydrogen in gas turbines, contributing to the development of technologies that support a zero-emission energy future.

c) Hydrogen Fuel Cells

Hydrogen fuel cells offer several compelling advantages. They boast high energy conversion efficiency, ensuring most of the hydrogen is converted into usable power. Their operation is environmentally friendly, producing zero harmful emissions, which helps maintain a cleaner environment. Additionally, hydrogen fuel cells operate quietly and without vibrations, making them suitable for noise-sensitive areas. Their scalability and modularity allow them to be used in various applications, from small devices to large power systems. Moreover, with no moving parts, they require minimal maintenance, enhancing their reliability and lifespan.

A hydrogen fuel cell is an electrochemical device that converts the chemical energy stored in hydrogen and oxygen into electrical energy. The process involves combining hydrogen and oxygen in the presence of a catalyst to produce electricity, water, and heat.

Figure 6. *Simplified hydrogen fuel cell operation. Source: Meiling Yue (2021). Hydrogen energy systems: A critical review of technologies, applications, trends and challenges.*



- Anode Reaction: At the anode, hydrogen molecules are split into protons (H+) and electrons (e⁻). The reaction can be represented as: H2 → 2H+ + 2e⁻
- Cathode Reaction: At the cathode, oxygen molecules are reduced, and they react with protons and electrons to form water. The reaction is: O2 + 4H+ + 4e⁻ → 2H2O
- Overall Reaction: The overall reaction in a hydrogen fuel cell is the combination of the anode and cathode reactions: 2H2 + O2 → 2H2O + electrical energy

d) PowerCell Sweden AB

PowerCell Sweden AB has secured a significant order for marine fuel cell systems, valued at approximately SEK 165 million (around USD 16 million). This order, placed by a leading Italian marine OEM manufacturer, includes 56 units of the Marine System 225. Deliveries are scheduled to begin in mid-2025 and be completed by the end of the year. This marks one of the largest orders for marine fuel cell systems globally.

Most of these units will be installed on commercial cruise ships, providing over 6.3 MW of auxiliary power to internal electricity systems. Additionally, a 3.2 MW marine power solution will be built for an internal testbed, and another 3.2 MW solution will be installed on an additional vessel. According to PowerCell, this order represents a significant milestone in the decarbonization of the marine industry, featuring one of the largest marine hydrogen fuel cell systems to date.

Figure 7. *Marine fuel cell system 225. Source: PowerCell Group website.*

3. Case Analysis

3.1. Case 1: Liquefied Hydrogen Plant — SK E&S and the PSA Process

Figure 8. *The liquefaction facilities within SK E&S, Incheon. Source: SK E&S website.*

SK E&S, a subsidiary of SK Group, has constructed the world's largest liquefied hydrogen plant in Incheon, South Korea. This state-of-the-art facility boasts an annual production capacity of 30,000 tons of liquefied hydrogen, sufficient to fuel approximately 5,000 hydrogen-powered buses for a year. Strategically located within the SK Incheon Petrochemical complex, the plant ensures efficient transportation and supply of hydrogen to the Seoul metropolitan area and beyond.

The liquefaction process at the plant involves cooling gaseous hydrogen to −253°C, reducing its volume to 1/800th of its original size, which significantly enhances storage and transportation efficiency. A key aspect of the plant's operation is the use of the Pressure Swing Adsorption (PSA) process, developed under an overseas license. This process purifies hydrogen by removing impurities such as carbon dioxide, carbon monoxide, and methane, resulting in high-purity hydrogen (99.99%). The purified hydrogen is then liquefied for storage and distribution.

SK E&S's liquefied hydrogen plant is a crucial component of South Korea's broader hydrogen economy strategy. The company aims to build around 40 hydrogen refueling stations nationwide, with about 20 stations expected to be operational by the end of 2024. This infrastructure will support the transition to hydrogen-powered public transportation, contributing to the reduction of greenhouse gas emissions.

Despite being a domestic end-user, the use of processes like PSA under overseas licenses means that only vendors approved by the licensor can supply the necessary equipment modules. Consequently, even if hydrogen production facilities are expanded in South Korea, there will be a reliance on foreign products. This reliance may result in limited trickle-down benefits for domestic companies, as the key components and technologies will still need to be sourced from approved international vendors.

This dependency on international vendors could lead to higher costs and longer lead times for the construction and maintenance of hydrogen production facilities. It might also affect the overall efficiency and scalability of the hydrogen economy in South Korea, as domestic companies may face challenges in building a robust and self-sufficient supply chain for hydrogen production and distribution.

3.2. Case 2: Hydrogen Gas Turbine — Hydrogen Co-Firing Rate

HYFLEXPOWER Consortium

The HYFLEXPOWER project in France has successfully demonstrated the operation of a gas turbine powered solely by 100% hydrogen. This project, funded by the EU and launched in 2020, involved modifications at the Smurfit Kappa paper mill in Saillat-sur-Vienne to enable the CHP facility to operate on green hydrogen. Siemens Energy's SGT-400 gas turbine was adapted to run entirely on hydrogen, marking a significant milestone in the use of hydrogen as a fuel for industrial applications.

Figure 9. *SGT-400 gas turbine driven CHP plant. Source: Siemens Energy website.*

Hanwha Impact

In contrast, the demonstration of hydrogen turbines in South Korea has so far been limited to co-firing operations, where hydrogen is mixed with natural gas. Hanwha Impact has successfully tested an 80-megawatt hydrogen gas turbine at their Daesan plant in Seosan, South Chungcheong.

Figure 10. *Hanwha Impact's hydrogen gas turbine plant in Seosan, South Chungcheong. Source: Hanwha website.*

This turbine achieved a record hydrogen blend rate of 59.5%, demonstrating the potential for integrating hydrogen into existing natural gas infrastructure. However, the relatively high cost of hydrogen co-firing compared to international benchmarks has been a challenge, limiting the ability to increase the hydrogen blend rate further.

Despite these challenges, the progress made by Hanwha Impact highlights the potential for hydrogen to play a significant role in South Korea's energy transition. Continued efforts to reduce costs and improve the efficiency of hydrogen co-firing will be crucial for the broader adoption of hydrogen as a clean energy source.

3.3. Case 3: Hydrogen Fuel Cell — Marine Industry

PowerCell Group

PowerCell Group has developed and commercialized advanced fuel cell systems, such as the PowerCellution Marine System 200, which are already being used in various applications, including marine projects. This system is designed to provide clean and efficient power for ships, significantly reducing emissions and contributing to the decarbonization of the maritime industry. PowerCell's fuel cell technology is known for its high efficiency, reliability, and scalability, making it a preferred choice for various industrial applications.

Figure 11. *World's largest hydrogen fuel cell project in the marine industry.*

HD Hyundai

In contrast, Korean company HD Hyundai is still in the process of integrating and developing similar technologies through its recent acquisitions. While HD Hyundai has made strategic moves, such as acquiring Convion and investing in Elcogen AS, it is still building its technological capabilities and market presence in the hydrogen sector. These efforts are still in the early stages compared to PowerCell's established and commercialized products. It will take time for HD Hyundai to achieve the same level of technological maturity and market penetration that PowerCell Group currently enjoys.

4. Conclusions

Upon assessing the current status of the domestic hydrogen market, it is evident that there is a significant lack of production technology. Therefore, entering the market through overseas licensors presents a viable opportunity to dominate the domestic hydrogen market.

Forming strategic alliances with licensors in the hydrogen market offers several significant benefits. Firstly, these partnerships provide access to advanced hydrogen production technologies, which are crucial for staying competitive in a rapidly evolving market. Licensors often possess proprietary technologies and expertise that can enhance the efficiency and scalability of hydrogen production processes, such as Auto Thermal Reforming (ATR) and Steam Methane Reforming (SMR). By leveraging these technologies, companies can improve their production capabilities and reduce operational costs.

Secondly, strategic alliances with licensors can facilitate faster market entry and expansion. Collaborating with established licensors allows companies to quickly adopt and integrate proven technologies, reducing the time and resources required for research and development. This accelerated entry into the hydrogen market can provide a competitive edge, enabling companies to capitalize on emerging opportunities and respond swiftly to market demands.

Lastly, these partnerships can help mitigate risks associated with technology adoption and implementation. Licensors typically offer technical support, training, and ongoing assistance, ensuring that companies can effectively utilize the licensed technologies. This support can minimize operational disruptions and enhance the overall reliability and performance of hydrogen production facilities. Additionally, strategic alliances can foster innovation through collaborative research and development efforts, leading to the continuous improvement of hydrogen technologies and processes.

In conclusion, forming strategic alliances with licensors is a pivotal strategy for companies aiming to dominate the domestic hydrogen market. By leveraging advanced technologies, accelerating market entry, and mitigating risks, these partnerships can significantly enhance a company's competitive edge. Coupled with robust government support, this approach ensures sustainable growth and innovation, ultimately positioning companies as leaders in the hydrogen economy.

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