



Hydrogen Roadmap Korea

Presenting a vision, roadmap and recommendations
for Korea's future hydrogen economy

This report was authored by the Study Task Force, consisting of senior executives of 17 companies (in alphabetical order): Air Liquide Korea Co., Ltd., Doosan, Energy & Marine Solution Co., Ltd., H₂ Korea, Hyundai Motor Company, Hyundai Motor Investment & Securities, Hyundai Oilbank, Kolon Industries, Inc., Korea Gas Corporation, Korea Investment and Securities Co., Ltd., Lotte Chemical, NH Investment & Securities Co., Samsung Securities Co., Ltd., Shell Korea Limited, Toyota Tsusho Korea Corporation, UBS Securities Pte. Ltd., World Wide Fund for Nature.

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A vision, roadmap and recommendation
to develop Korea's hydrogen economy

Executive summary

Hydrogen can play a key role in South Korea's energy transition because it offers three key benefits to the country's industries and citizens.

First, Korea could become an industry leader in the quickly growing hydrogen economy. It already features a robust platform for further development in FCEVs and fuel cell technologies. With a strong domestic market, these industries could flourish, becoming suppliers to large markets for hydrogen technology, such as those emerging in China, Japan and Europe. We envision Korea's hydrogen economy could create up to KRW 70 trillion in revenues, securing 600,000 jobs in 2050.

Second, hydrogen can decarbonize Korea's buildings, industry, transport and power system, especially in segments that would otherwise find it hard to decarbonize. Deploying hydrogen as suggested by this roadmap could close as much as 40% of the gap toward a "two-degree" scenario. Doing so would also significantly improve local emission levels, such as particulates and sulfur oxides.

Third, hydrogen can diversify the national energy mix away from its current heavy reliance on LNG and oil imports toward renewable and low carbon energy sources. It can serve as an energy carrier to enable the shipment of renewable energy into Korea, speeding up the transition toward renewables. Having a more diverse energy mix with new sources will increase energy security and in the long-term allow the country to tap into lower-cost sources of green energy.

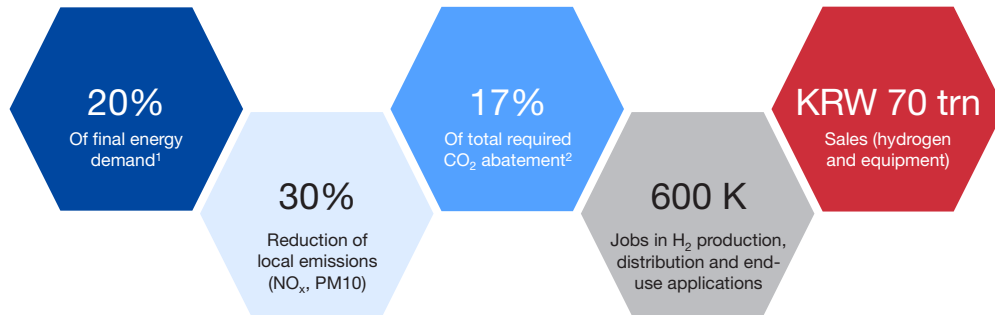
This report lays out the potential of hydrogen in Korea, describes a roadmap for deployment, and suggests recommendations to ignite the transition. Developed as a collaborative effort, it involved 16 leading companies across the energy value chain and multilateral organizations inside Korea.

The total potential of hydrogen in Korea amounts to 17 Mt (equivalent to 564 TWh) in 2050, accounting for more than 20% of total national energy demand. Hydrogen will "work" in power generation, transport, industry, buildings, and industrial feedstock. Its use will double by 2030, followed by a steep ramp-up during the post-2030 period when a virtuous cycle of investment, technological advancement, customer adoption and cumulative end-user equipment purchases will drive it upwards.

IMPACT OF A HYDROGEN ECOSYSTEM IN KOREA

2050 hydrogen vision

In annual figures



¹ Excluding feedstock usage of hydrogen

² Compared to the reference scenario

SOURCE: Hydrogen Coalition Members' Study; Hydrogen Korea Study team

All five segments show strong demand potential, but particularly high demand exists in transport, buildings and power generation, enabled by South Korea's leading positions in both stationary and mobile fuel cell applications. In transport, its advantages in energy density and fast refueling are most important for trucks, commercial vehicles and mid-size and large passenger cars. System cost and fuel cell stack cycle life improvements can further accelerate this uptake and enable fuel cells in transportation to break even for a wide range of applications in the next several years. By 2030 our vision sees that 800,000 FCEVs can travel Korea's roads, of which 100,000 can be trucks and buses.

The ramp up of hydrogen in buildings will likely result from the market success of hydrogen fuel-based micro combined heat and power (mCHP) units and the deployment of the hydrogen infrastructure. Korea is already a leader in mCHPs, and government policies, such as the obligation to use renewable energy for new buildings, can drive the uptake of "green" hydrogen applications. By 2030, buildings can have 20,000 mCHPs consuming as much as 150,000 tons of hydrogen per year.

In power generation, Korea is also leading in fuel cell deployment, with currently started projects already exceeding the government target for 2030. As the costs of hydrogen and fuel cells both drop, power generation from hydrogen will continue to grow. Turbines could enable the power generation sector to decarbonize faster still. By 2030, Korea could install as much as 3.5 GW in hydrogen fuel-cell power generation capacity.

Gaining access to green hydrogen will require renewable energy in hydrogen production, using electrolysis or hydrogen derived from LNG in steam methane reformers (SMRs) with carbon capture and storage (CCS). An alternative involves importing hydrogen generated by far-offshore wind farms or from carbon-free sources overseas, tapping into low-cost renewables and gas fields. The cheapest way to produce hydrogen today involves SMR, which produces less carbon emissions than in most fossil fuel applications without CCS. As

costs for renewables and electrolyzers come down, hydrogen from electrolysis will become more affordable. By 2040, the importation of hydrogen from electrolysis plants operating on renewable energy or via the domestic use of renewable energy in electrolysis will be competitive enough to replace LNG-based SMR as the main source of hydrogen in Korea.

To realize this roadmap, Korea's industry needs to step up activities along the value chain. Industries must also invest in scaling up manufacturing capacities and continuous R&D activities. Compared internationally, Korea is among the leading countries in terms of its hydrogen market and industry development for downstream applications, such as FCEVs. It lacks, however, capabilities in upstream technologies related to the production and distribution of hydrogen, as well as domestic infrastructure such as refueling stations. These shortfalls could hinder market uptake, and stakeholders actively need to address them. Building infrastructure to support this roadmap would require about KRW 8 trillion by 2030. While a significant amount, it equals only 1% of Korea's annual total investments.

To guide Korea's industry toward the successful introduction of hydrogen technologies, a holistic policy framework and support mechanisms are key. This framework must align with the understanding that development and deployment across the entire value chain needs to synchronize, as a delay in one step could become a bottleneck for the entire hydrogen economy. Such a long-term roadmap will allow the private sector to make the necessary investments, as Japan's roadmap to a hydrogen economy currently demonstrates.

Such a framework should include tangible milestones for policymakers, industry and investors, as well as a shared understanding of the opportunities and barriers involved. This roadmap proposes concrete milestones for the short-term (2022) and the mid-term (2030). They focus on priority applications such as fuel cell electric vehicles, mCHP fuel cells for building heating and power and fuel cells for power generation. Such apps have significant potential and can create systemic effects to spark and accelerate the required technology, infrastructure and market development. By 2022, we recommend the transport sector target 60,000 hydrogen-powered passenger cars (passenger cars and vans/LCVs) on the roads and build 300 hydrogen refueling stations. By the same time, the industry should install domestic production capacities for 3.7 million tons of hydrogen from SMR and electrolysis.

We are convinced that hydrogen has a major economic and environmental potential for Korea. We represent the most important actors along the hydrogen value chain, and support the collaboration and joint investments needed to make this vision a reality.

To realize these milestones, Korean policymakers, industry and investors need to work together. If they do, they will initiate virtuous cycles of deployment, scale-up and cost reduction. The effort required will generate a handsome return: a cleaner energy system, economic opportunities and more diverse and secure energy for Korea.

By 2050, hydrogen could fuel ...



~7 m
passenger cars¹



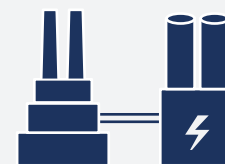
~1 m
trucks



200-300 k
drones



~60 TWh
of power generation



120 TWh
of building heat
and power

... in total amounting to ...



~17 Mt
of annual
hydrogen demand



~150 Mt
annual
CO₂ abatement



>600 k
jobs

¹ Including vans and light commercial vehicles

Contents

Our vision for Korea's hydrogen economy in 2050	11
Why hydrogen	13
Target picture 2050	14
Hydrogen demand and deployment	17
Power generation	19
Transportation	21
Industry energy	25
Building heating and power	26
Industry feedstock	27
Supporting the deployment with hydrogen supply	31
Technology improvements required	33
Hydrogen supply	35
Distribution of hydrogen	37
Supporting investments	38
Benchmarking industry and market development	41
Korea's relative competence	43
Benchmark points	46
Recommendations	49
Recommendation 1: Set concrete deployment milestones for key applications	52
Recommendation 2: Support deployment milestones via public-private partnerships	53
Recommendation 3: Develop Korea's transport system into the leading global hydrogen and fuel cell mobility market	54
Recommendation 4: Strengthen Korea's hydrogen and fuel cell industry	54
Recommendation 5: Build a long-term pathway for the decarbonization of Korea's gas network	54
Recommendation 6: Build a sustainable and competitive hydrogen supply industry	55
Abbreviations	56

Our vision for Korea's hydrogen economy in 2050



This report is the product of a collaborative effort among 17 leading companies across the energy value chain and multilateral organizations inside Korea. Its goal: develop a joint vision for the future of hydrogen as a green energy carrier for the country. Drawing on proprietary data and expertise from each participating company, this study seeks to develop an unbiased perspective on the role hydrogen can play in Korea's future energy system and what societal benefits this transition could bring.

Why

Of all the potential ways to power Korea's future, why choose hydrogen? After all, other "green" solutions are now available and ready for commercialization at scale. Nonetheless, we believe hydrogen will become a key pillar of the global energy transition and of Korea's as well. As a green energy carrier, hydrogen is already experiencing unprecedented momentum in Korea, which we believe will grow substantially.

Three key-advantages are driving hydrogen's rise. First, hydrogen technology is a growing international business opportunity. Second, it can play a central role in achieving established CO₂ targets, and third, it enables the diversification of the country's energy mix, thereby increasing energy security.

Korea can become a leader in hydrogen technology and build a new industry around fuel cell electric vehicles (FCEVs), hydrogen production equipment, distribution infrastructure and components. Establishing a domestic market will build on Korea's already-strong hydrogen industry (e.g., FCEVs), sparking innovation and accelerating the scale-up of hydrogen technology and positioning Korea at the forefront of technology leadership. Such a position could lead to further export opportunities, fueling increases in revenues as well as jobs.

Korea could also emerge as an early adopter of hydrogen technology, simultaneously realizing its energy transition and reducing CO₂ and local emissions at the same time. In fact, hydrogen is already an integral pillar in Korea's efforts to achieve its transition to cleaner power. It can help reduce CO₂ emissions from transport, building heating and industry. It can make it possible to integrate intermittent renewable energy sources into the country's power system, and open a route to imports of decarbonized energy. More specifically, it is an integral part of Korea's decarbonization path toward the targets set in the Paris agreement – the country's currently announced 2030 National Greenhouse gas reduction roadmap addresses about half of the required abatement. Hydrogen can help close the remaining gap towards the required reduction targets by 40% in 2050. It can also reduce and remove local emissions such as fine particulates and sulfur oxide (SO_x) while simultaneously reducing noise pollution. In fact, fuel cell electric vehicles have negative emissions as they clean the air inside the fuel cell system in the process of bringing air oxygen and hydrogen together, only emitting pure water. (Exhibit 1)

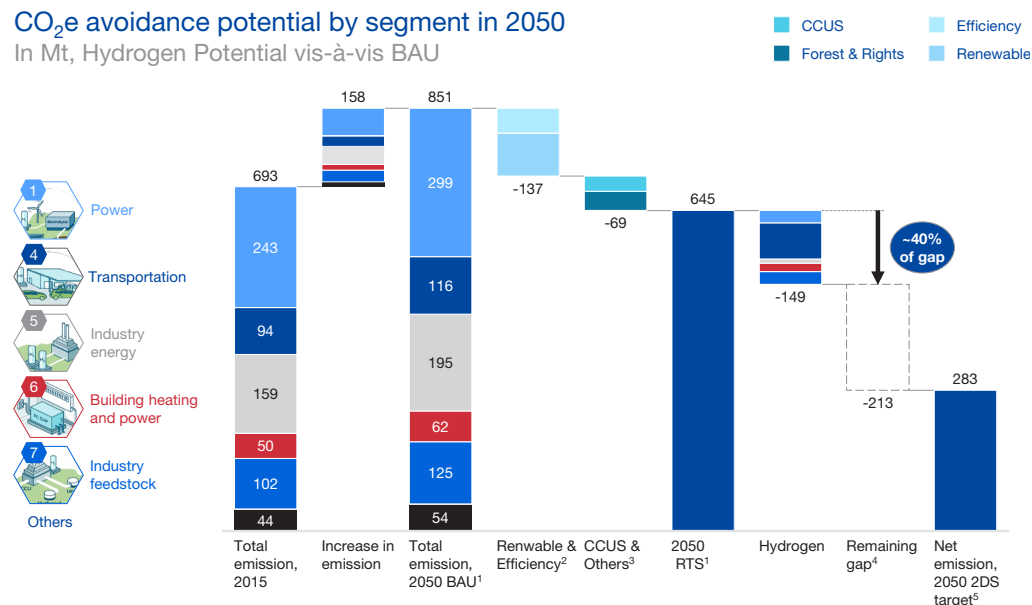
Adopting hydrogen could also enable Korea to diversify its energy mix, reducing the country's dependence on liquefied natural gas (LNG) and oil imports and increasing energy security in the process. Importing low-carbon hydrogen would accelerate the switch to renewable and low-carbon energy carriers in Korea.

KOREA'S CO₂ REDUCTION ROADMAP IN A HYDROGEN SCENARIO

EXHIBIT 1

CO₂e avoidance potential by segment in 2050

In Mt, Hydrogen Potential vis-à-vis BAU



¹ Assumed equal total emission as in 2030 resulting from population decrease and changing industry profile (towards service-based economy)

² Assumed equal reduction from efficiency in 2050 as in 2030 by hypothesizing reaching limits

³ in efficiency gain by 2030; reduction from renewable was achieved by scaling projected reduction from renewable in 2030 by the increase in the share of renewable power generation in 2050

⁴ Used 3x higher CCUS potential as in 2030 resulting from availability of CCU in the East sea post-2030; assumed reduction from others measures (forest, emission rights) equal as in 2030

⁵ Government has carbon reduction roadmap until 2030 but the areas with less clear plans were not considered and assumed that hydrogen could instead play a more concrete role

⁶ Used government target until 2030 and then scaled until 2050 by the annual decrease in total emission under government target plus the annual growth rate of total emission in 2015-2030 (since the annual decrease under government target is accounting for growth in emission in 2015-2030 under BAU)

SOURCE: Ministry of Environment; MOTIE; Hydrogen Coalition Members' Study; Hydrogen Korea Study team

Potential overseas sources for hydrogen include Australia (via solar power), or Canada (by harnessing excess hydro power). Another hydrogen sourcing option involves the expansion of wind power to include far-offshore wind parks in Korea's deep waters. By diversifying Korea's energy mix, hydrogen would allow the country to produce a larger share of its own power domestically in the long term and reduce dependency on LNG imports.

Target picture 2050

By 2050, hydrogen could address 16.9 Mt – around 21% – of Korea's annual final energy demand. Its use will range across all sectors, from transport, building heating and power, power generation and industrial energy use to new applications such as hydrogen's use as a feedstock. Based on an ambitious scenario of FCEV deployment, the domestic fleet of fuel-cell-powered EVs could reach 8 million vehicles, including privately owned passenger vehicles, taxis, buses and light- and heavy-duty commercial vehicles. Likewise, hydrogen could provide up to 27% of the heat required by residential and commercial buildings via micro combined heat and power (mCHP) units, amounting to more than 117 TWh of power annually. Stationary fuel cell systems and gas turbines burning hydrogen could contribute 61 TWh of power generation (10% of the total demand), and 13% of industrial energy demand could also rely on hydrogen, which amounts to 37.5 TWh.

This transition to a “hydrogen economy” could create a new domestic market and sustain the growth of the country’s advanced industries. Domestic revenues across the energy value chain, from hydrogen generation through distribution to end-user applications such as FCEVs, should reach KRW 70 trillion by 2050. On a global scale, hydrogen technology could potentially become a market with revenues amounting to KRW 2,500 trillion by 2050. An industry this large will trigger strong employment demand: viewing the domestic market only, we envision Korea’s hydrogen industry will employ roughly 600,000 white- and blue-collar workers in 2050. While the standalone domestic market could be sufficiently attractive, the export market would offer even more economic opportunities for Korean industries. For example, we believe that the Korean auto industry, including OEM and suppliers, can generate more than KRW 25 trillion in annual revenues by 2050, assuming its share in the global FCEV market is similar to the country’s global automotive market now.

Hydrogen demand and deployment



This report focuses on the impact hydrogen will have on five key segments of Korea's economy: power, transport, industry, buildings, and industrial feedstock. Together, these segments consume massive amounts of energy, and will thus require an equally substantial decarbonization effort. The fact that they account for the majority of Korea's final energy demand and have well-defined supply chains makes them ideal targets for analyzing and discussing the potential benefits of adopting hydrogen.

Each of these segments exhibits strong potential to adopt hydrogen as a cleaner source of energy, and have attracted intense levels of interest and research both domestically and globally. Research has concentrated on two areas: hydrogen's environmental benefits, and its economic potential. For example, hydrogen provides a way to decarbonize energy consumption beyond currently adopted renewable sources of energy, such as solar and wind power. It also offers cost advantages based on its high efficiency and flexibility – attributes that segments currently relying on sub-optimal traditional technologies should highly value. Korea's strong willingness and technological leadership in this space suggests the country can benefit significantly from the quick deployment and scale up of hydrogen application across its energy sectors.

Based on our analysis of Korea's hydrogen vision, demand should reach 1,690 Mt in 2050, compared to its current level of 240 Mt. Demand will grow slowly up to 2030, followed by a steep ramp-up during the post-2030 period, when a virtuous feedback cycle of investment, technological advancement, customer adoption and cumulative end-user equipment purchases will drive it upwards. All five segments show strong demand potential, but particularly high demand exists in transport and buildings, enabled by Korea's leading positions in both stationary and mobile fuel cell applications. Exhibit 2 illustrates Korea's envisioned demand across the five segments through 2050. The following sections will explain in more detail the potential for hydrogen in each segment and subsegment, how hydrogen demand could develop based on our vision and what the key underlying drivers for this demand could look like.

Power generation

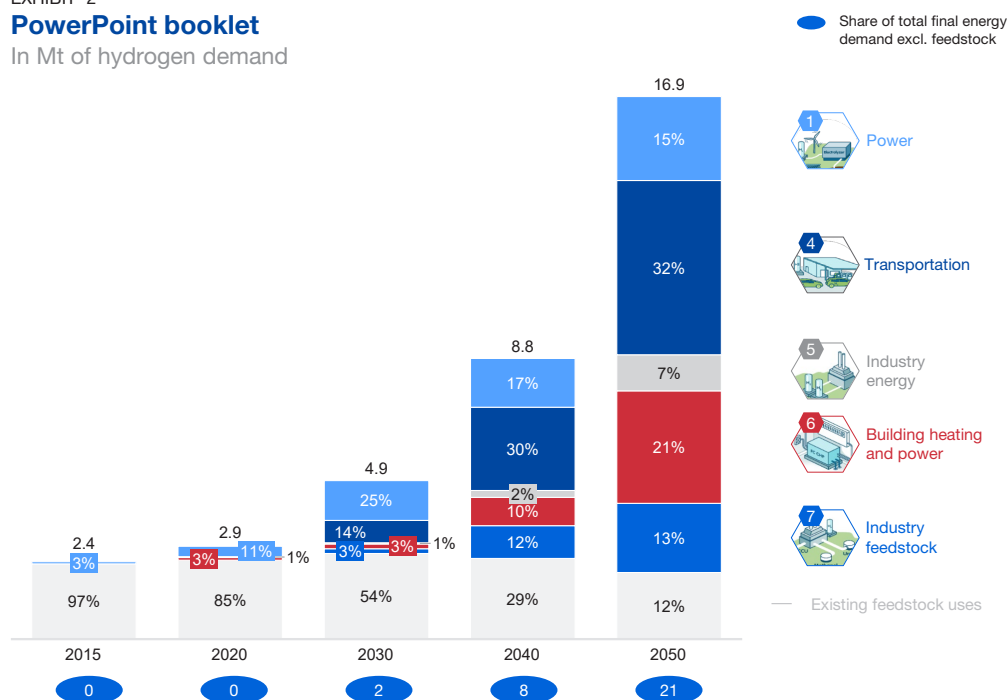
Korea's large power segment consumes massive amounts of energy each year. Analysts expect the segment to continue to grow at about 1% annually through 2050, in alignment with ongoing electrification trends such as increased electric vehicle (EV) demand and the rapidly expanding internet of things (IoT). The Korean power sector currently relies heavily on fossil fuels, which provide 60% of today's total energy. With the government's nuclear phase-out policy, the country urgently needs to introduce more renewable sources for decarbonization. At the same time, Korea faces the challenge of unfavorable conditions for the fast, large-scale deployment of solar and wind power generation due to its small landmass and its topography on-shore and off-shore. Such factors make renewable power an expensive method for decarbonizing the power sector, compared to other countries with more favorable conditions and higher solar radiation levels.

HYDROGEN DEMAND ACROSS 5 SEGMENTS

EXHIBIT 2

PowerPoint booklet

In Mt of hydrogen demand



SOURCE: Hydrogen Coalition Members' Study; Hydrogen Korea Study team

Such conditions leave green hydrogen as the only option to decarbonize the Korean power sector at scale, potentially via large imports of the fuel from neighboring countries, coupled with the adoption of fuel cell and hydrogen gas turbine power plants. With large-scale investments in technology and infrastructure and high utilization, hydrogen has the potential to become an economical alternative fuel, even when compared with existing power generation solutions.

The power segment has two main ways to adopt hydrogen: using either fuel cell power plants or hydrogen turbine combined-cycle power plants. Korea has already commercialized the former, and companies in Japan, Germany and the United States are developing the latter. Fuel cell power plants currently in operation are running on a range of fuels besides hydrogen, with total capacity of about 300 MW (in 2017). This solution's benefits include high efficiency compared to hydrogen turbines (i.e., roughly 90% total efficiency compared to about 60%) and they generate heat that nearby customers can use. However, the high cost of hydrogen limits the fuel cell power plant's current economics and further adoption. Hence, the future adoption of hydrogen in the power sector likely depends on the availability of lower-cost hydrogen.

Despite their benefits, fuel cell power plants still have disadvantages. For one thing, their construction costs remain high relative to other technologies. For example, an 80-megawatt (MW) power plant under construction in Korea costs about KRW 525 billion, which is enough to build a 450-MW gas power plant. Companies can only capture the plant's

true efficiency when there are end-users of heat in the vicinity. Such characteristics limit hydrogen's potential in power sector fuel cell plants without the inclusion of complementary methods.

Hydrogen turbines, a fledgling technology, can nonetheless help the power sector make a quantum leap toward the wide-spread adoption of hydrogen and decarbonization. Operating like traditional natural gas turbines but consuming hydrogen as fuel, energy companies can retrofit them on existing natural gas power plants by adding relevant auxiliary equipment and upgrading the pipeline. Retrofitting can make hydrogen turbines an economical option for the power sector.

Currently, only prototype-level hydrogen turbines are in operation. However, Japan's recent 1-MW hydrogen turbine, which started up in 2018, is on track for commercial operation, opening the possibility for larger capacity units. Experts believe that the industry could commercialize hydrogen gas turbines with capacities of about 100 MW capacity by 2030 and even larger units in the following years.

Reflecting this trajectory, Korea's vision statement projects that power sector hydrogen demand could reach 0.8 Mt in 2030 and 26 Mt in 2050, the latter being about 10% of Korea's total centrally generated power at that time. We believe fuel cell type plants will account for most of the demand in the early years, with approximately 0.8 Mt in 2030 and 1.4 Mt in 2050, while deployment of hydrogen turbines will only start ramping-up in 2030. In 2050 hydrogen turbines could reach 1.2 Mt in hydrogen demand and the power generation from hydrogen turbines and fuel cells could be almost equally split.

For this vision to become real, stakeholders must make continuous investments in R&D to lower the capex costs and the production cost of hydrogen. At the same time, the government could also subsidize the cost of power generation from hydrogen, treating it similarly to solar and wind power-based electricity.

Transportation

The transport sector has an urgent need for decarbonization as it accounts for a large share of greenhouse gas emission. This sector generates particulate matter (over 20% of PM 2.5 in 2015 according to NAPES) considered to be the main culprit behind air pollution and associated diseases. Fortunately, it's also a hotbed of new technologies designed to tackle precisely those problems (e.g., battery electric vehicles and fuel cell vehicles).

Hydrogen provides some clear advantages in the transport segment. It is ideal for long-range, heavy payload vehicles with high energy consumption and high utilization such as trucks, buses and commercial vehicles, and light weight applications, such as unmanned aerial vehicles (UAVs). It also makes sense in segments such as cargo ships and trains, where the cost of using hydrogen fuel-cell powertrains should be even cheaper than competing technologies such as battery-electric solutions. (Exhibit 3)

COMPARING MEANS OF TRANSPORTS' ENERGY CONSUMPTION

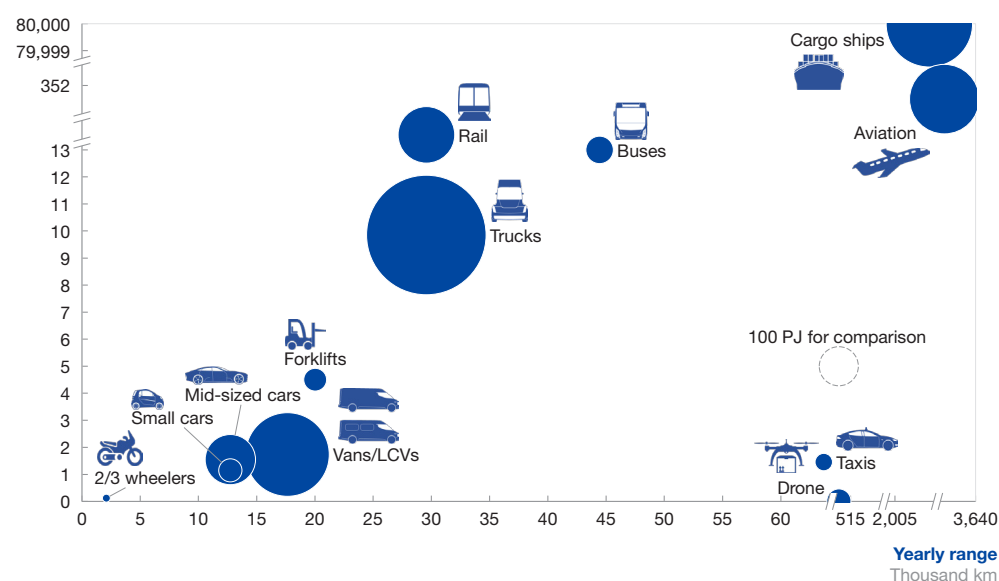
EXHIBIT 3

Comparison of annual vehicle energy consumption

By transportation type

Weight

Thousand tons



SOURCE: Hydrogen Coalition Members' Study; Hydrogen Korea Study team

The competitiveness of hydrogen in these segments results from the high energy density of hydrogen tanks, which are rechargeable like those for conventional fossil fuel-based vehicles. These benefits stand out in comparison to the hydrogen fuel cell's main competing clean technology, the battery electric powertrain. (Exhibit 4)

For many heavy-duty truck and bus applications, fuel cell powertrains could soon be cost competitive with any other zero-emission alternative. For example, for long-haul trucks driving 500 miles and more, hydrogen's high energy density means the fuel cell powertrain can be 2.5 times lighter compared to battery electric trucks. This allows for more payload and longer driving range. In contrast, batteries often cannot carry enough energy to propel heavy vehicles over long distances. With increasing range, a fuel cell powertrain also becomes cost competitive: the cost for on-board hydrogen storage should fall below KRW 10,000 per net kilowatt-hour. At this point, the system costs for a long-haul truck could fall to KRW 22 million – a cost level no other green energy storage option could match.

EVs also take a long time to recharge: even fast chargers take 30 minutes versus about 5 minutes to fill a hydrogen fuel tank fully. That means battery power is not technologically feasible for some large and long-range segments. Hydrogen also offers a more realistic choice in crowded cities with limited space for EV charging posts (typically, a single hydrogen refueling station can replace 15 EV charging posts). These advantages make hydrogen a more attractive option for commercial fleets that require high vehicle utilization

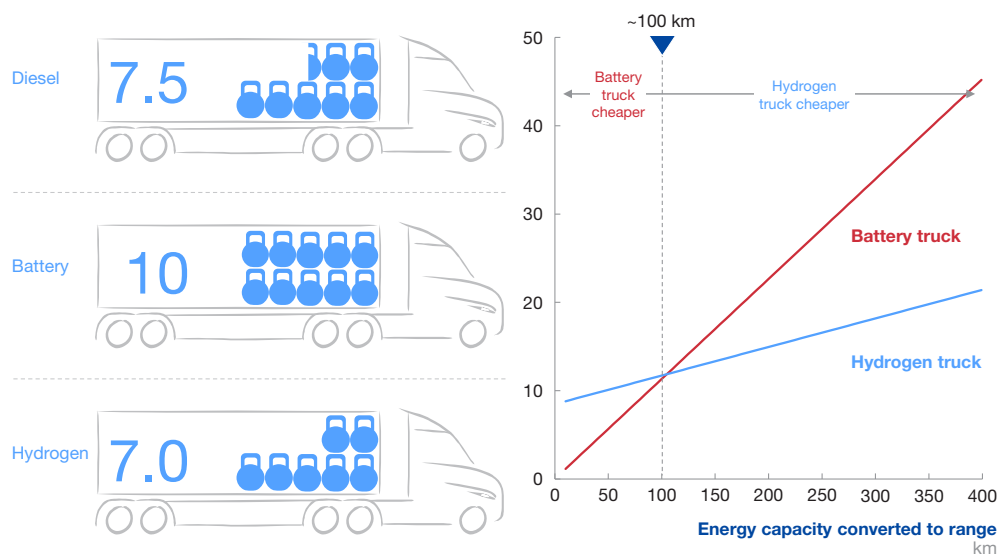
levels. For example, having a commercial electric bus sitting idle at charging stations for 4 to 6 hours every day would reduce CAPEX utilization by up to 25%.

THE ADVANTAGES OF HYDROGEN FUEL CELLS FOR TRUCKS

EXHIBIT 4

Powertrain weight comparison¹
In tons for a 40 tons semi truck

System costs of battery vs. hydrogen
In million KRW



¹ Assumptions: Component weight for diesel powertrain, in kg: ICE system 1,000; fuel system 1,050; transmission 200; exhaust 200; Component weight for BEV powertrain, in kg: transmission 50; E-motors 100; power electric 300; battery 4500; Component weight for FCEV powertrain, in kg: transmission 50; E-motors 100; power electric 300; battery 600; fuel cell 150; H₂ tank 800. Reference truck: 40 t semi truck with 18 t GVW truck tractor 4x2; FCEV truck with 120 kWh battery; BEV truck with 900kWh battery; FCEV and BEV battery with 5kg/kWh; FCEV and BEV with two electric motors; FCEV truck with 300 kW fuel cell weighing 150kg (2 kW/ kg)

SOURCE: DOE, Tesla Semi, Nikola One, and McKinsey

Hydrogen offers passenger vehicles similar benefits, especially in mid-size to large vehicle categories. And with continuously developing technology and subsequent cost reduction, hydrogen can also become an attractive option for smaller-size vehicles as well.

While the technical safety of fuel cell powertrains fulfils current requirements, stack cycle life still requires improvements, particularly to achieve the longer lifetime requirements for commercial vehicles. (Exhibit 5)

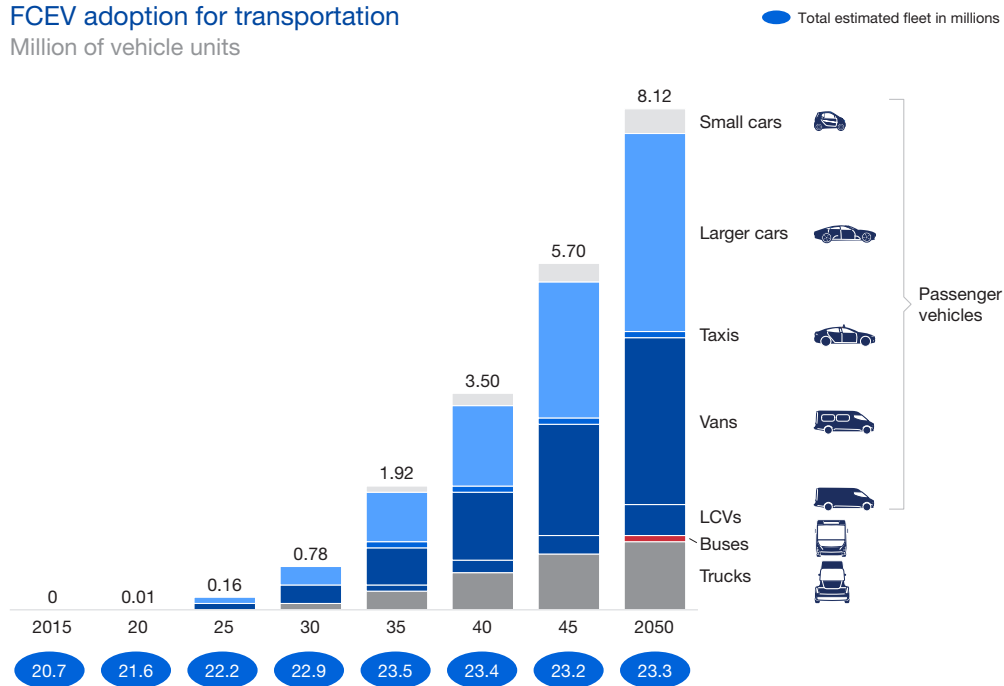
Other means of transport can also benefit from adopting hydrogen. For example, hydrogen is effectively the only green option for powering new airborne transport, such as drones. Hydrogen can improve the flight time of a fuel cell-powered drone for commercial applications by the factor of from 4 to 12 compared with battery-electric technologies. It can boost the payload by a factor of up to 4 due to its high energy density compared with batteries. Such UAVs or vertical takeoff and landing (VTOL) taxis may sound futuristic, but blue-chip companies and startups alike are making big bets on them. For instance, more than 80 companies are developing VTOL aircraft, including Boeing, Airbus, Uber, and startups like Volocopter. The first applications should launch soon: Uber Elevate aims to start in 2023 in Dallas, Los Angeles and another international city.

FUEL CELL ELECTRIC VEHICLE DEPLOYMENT

EXHIBIT 5

FCEV adoption for transportation

Million of vehicle units



SOURCE: Hydrogen Coalition Members' Study; Hydrogen Korea Study team

Also, UAVs for commercial applications will see a fast uptake soon. Last-mile deliveries could grow to more than 240 billion parcels by 2035, over three times as many as in 2017, when deliveries totaled 75 billion. At the same time, cities in Korea are taking actions to reduce local emissions and improve air quality. Hence, last mile delivery must 'go green', which also benefits hydrogen fuel cell systems, and investments are flowing in hydrogen's direction. In Korea alone, the market for UAVs should grow to KRW 4.4 trillion by 2026 and attract KRW 350 billion in public investment. Based on the projections of industry experts and an analysis of global and national trends in Korea, we estimate the market for fuel cell UAVs will see increased momentum in 2025, and by 2030, a fleet of about 68 thousand will be in the air, reaching 233 thousand in 2050. This uptake assumes that from 2025 half of the newly sold commercial UAVs will rely on hydrogen fuel cell systems.

Rail and cargo shipping are other transport areas with the potential to use hydrogen. Germany has already commercialized hydrogen-fueled locomotives, replacing old diesel-fueled engines that emit large amounts of greenhouse gases and particulate matter. While Korea already has far more electric locomotive than diesels (4,220 to 493 according to KORAIL), hydrogen fuel cell powertrains offer the potential to decarbonize the remaining diesel locomotives with a clean energy source and without the need to construct overhead wiring and changing tracks, bridges and tunnels.

Some shipwrights are already developing hydrogen-powered ships, with small size prototypes currently in operation in environmentally protected areas. Large-scale

applications will take longer due to the huge infrastructure and retrofit requirements. However, given the tightening marine pollution regulations – for example, fuel sulfur must drop from 3.5% to 0.5% by 2020, followed by aggressive greenhouse gas reduction requirements – hydrogen represents one of the few fueling alternatives.

Following such a trajectory, Korea's vision for hydrogen demand in the transport segment projects that it could reach up to 0.7 Mt in 2030 and 5.4 Mt in 2050. That translates to about 8 million on-road FCEVs running in the country. The segments spearheading this push will include trucks, with the largest share of 0.2 Mt of demand in 2030 and 2.6 Mt in 2050, followed by vans and light commercial vehicles with 0.1 Mt in 2030 and 1.4 Mt in 2050. Buses will use 0.02 Mt of hydrogen in 2030 and 0.2 Mt in 2050. This ramp up could be realized initially by a large-scale public purchase (e.g., replacing city buses and FCEV taxi fleets), followed by commercial fleet owners (e.g., trucks). Infrastructure and markets such as hydrogen refueling stations and after-service markets will follow, lifting uptake of hydrogen in other vehicle segments. The total demand from new means of transport (i.e., UAVs) is aspired to reach 0.05 Mt by 2030 and 0.2 Mt by 2050.

Fuel cell powertrains for FCEVs, which are currently still more expensive than combustion powertrains, could be less than 10% more expensive than ICEs by 2030. The biggest cost improvements should come from economies of scale, optimized manufacturing processes and improved specifications. In the longer term, technology improvements such as the reduction of platinum use and improved fuel cell membrane electrode assemblies (MEAs) may further reduce costs.

Industry energy

Industry accounts for a large portion of air pollution in Korea. Aside from power consumption (addressed in the power section, above), industry demand for heat is another large segment where hydrogen could offer substantial environmental benefits. Aside from emitting over 5% of greenhouse gases, according to a National Air Pollutants Emission Service report in 2015, the industry sector is also the largest source of sulfur oxide (SO_x) emissions. It accounts for over 50% of these emissions in Korea, according to the NAPES in 2015. Consequently, switching industry heating to hydrogen could significantly reduce the environmental damage caused by industry, making this segment one of the most sustainable in the world.

Beyond refining and steelmaking (discussed in the industry feedstock section, below), the cement industry holds the highest long-run potential for adopting hydrogen as an energy source for heating, since it is the third largest industry in terms of carbon emissions in Korea after the aforementioned two. It consumes a huge amount of heat energy to achieve high grade heat (exceeding 1,000 degrees Celsius) to operate pre-heaters and kilns. Currently, the most widely used fuel is coal. Nevertheless, recent cost increases and lower margins have forced cement makers to adopt other types of fuel such as waste oil, waste tires and even renewable sources. At the same time, the industry is under significant pressure to decarbonize.

For example, in Spring 2018, a major debate took place over the government's potential decision to make the cement industry pay for emission rights that it previously enjoyed

without cost. If realized, the cement industry would pay more than KRW 200 million – an amount equal to all the profits of the seven major cement makers in Korea. We believe trends such as fuel diversification and the push for decarbonization will eventually leave the industry no choice other than clean fuel. And hydrogen is an ideal choice due to its high combustion temperatures and potential for massively importation at low cost.

Other industries such as manufacturing also use heat energy, which users can replace either with direct hydrogen combustion or through on-site combined heat and power (CHP) that could also provide electricity for local use.

Following such a trajectory, Korea's hydrogen vision for industry could reach up to 0.04 Mt in 2030 and 1.1 Mt in 2050. Despite the potential for a quick ramp-up after 2030, the overall hydrogen consumption potential could be relatively low considering that by 2050 Korea could move away from a manufacturing industry-based economy to one focused on service industries. Considering the cost sensitivities of industry players, adoption will require a strong government push to make sure responsible industry players pay the indirect environmental costs, and to ensure incentives (such as tax cuts) are available for those who voluntarily implements decarbonization measures through adoption of hydrogen.

Building heating and power

Hydrogen offers the only large-scale way to decarbonize building energy use, which currently relies on natural gas and grid electricity. Building electricity consumption that comes from the grid can be massively decarbonized using the methods explained in the power section above. Building heating still primarily relies on fossil-fuel based energy, with over half coming from natural gas and other fossil fuel-based energy in Korea. Rooftop solar power generation offers limited potential due to the small effectively usable surface area in densely populated areas coupled with limited radiation and comparatively high air pollution in major cities in Korea, thus lowering the potential utilization of solar panels.

Building hydrogen applications such as mCHPs can provide both heat and power at high efficiency, potentially lowering the energy bills of building users, assuming reduced hydrogen prices in the future. (Exhibit 6)

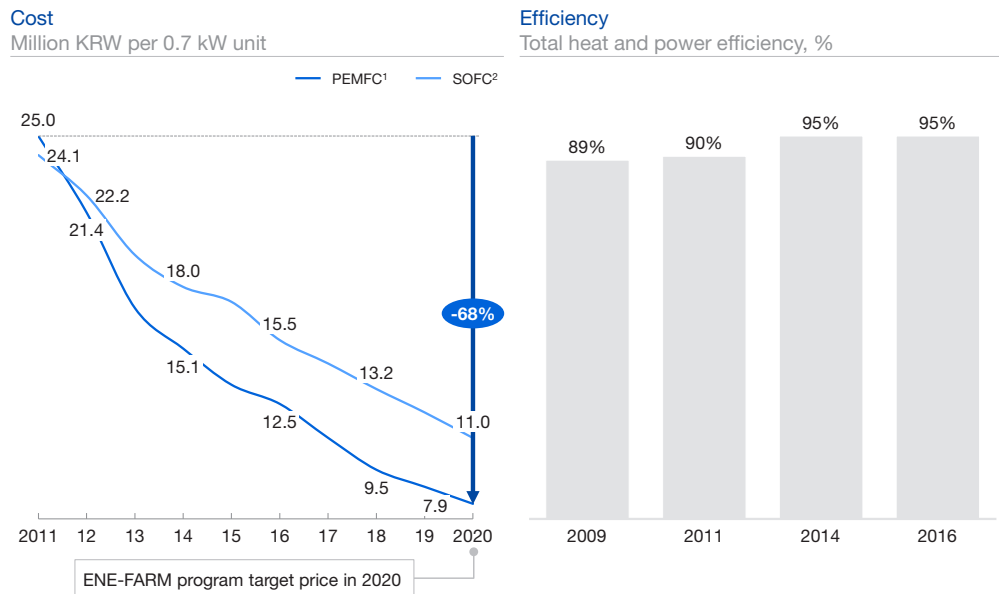
Building heating applications can adopt hydrogen in three main ways. First, by employing hydrogen-fueled power generation described in the power sector above. Second, by switching to hydrogen by blending it with the existing gas pipeline. Third, by constructing new pipeline networks that can carry 100% pure hydrogen for either direct burning or use in mCHPs that generate both heat and power.

Building-related hydrogen demand will reach 0.15 Mt in 2030 and 3.5 Mt in 2050. The ramp up of hydrogen in buildings will depend on the sales of hydrogen fuel-based mCHPs and the deployment of infrastructure. The government's push for regulating the mandatory use of renewable energy for new buildings can drive the uptake of renewable energy, including hydrogen mCHPs. Because regulators view hydrogen as a renewable energy source, buildings can adopt mCHPs and thus satisfy the regulation.

MICRO COMBINED HEAT AND POWER UNITS' IMPROVEMENT

EXHIBIT 6

Historical trends in Japanese mCHP



Industry feedstock

Industry feedstock consumes large amounts of fossil fuel-based materials as inputs to produce other useful materials, giving it a large decarbonization potential when companies replace these input ingredients with hydrogen. Much research has focused on how companies can alter existing industrial processes to embrace hydrogen to reduce emissions. For example, steel-making innovations featuring hydrogen, such as direct reduced iron (DRI), are already in use in some geographies. Also, utilizing captured carbon in a mix with hydrogen can create synthetic methane that can serve as a useful feedstock in chemical processes.

In some applications, the use of hydrogen in industrial feedstock is already happening. Refiners, manufacturers such as semiconductor and display makers, and metal processing companies had been using hydrogen in their processes. In these cases, the adoption of hydrogen probably will not grow substantially, since it is proportionally linked with output. Nonetheless, these two sub-segments already consume 2.4 Mt of hydrogen annually. Other new applications also exist, including steel making and chemical production (i.e., when mixed with captured carbon).

Envisioned hydrogen demand from industry feedstock is 2.8 Mt in 2030 and 4.2 Mt in 2050. Refining should continue as the dominant hydrogen end-user in feedstock, accounting for 2.3 Mt in 2030 and 1.7 Mt in 2050. Decreasing hydrogen demand from refining will result

from a decline in refining production, based on the assumption that Korea will consume less fuel oil in the future as alternatives enter the mix. The second largest user of hydrogen should be steel making, accounting for minimal in 2030 and 1.1 Mt in 2050. This rapid ramp up should result from the completion of technological solutions in Korea after 2030 and the envisioned decrease in the cost of hydrogen.

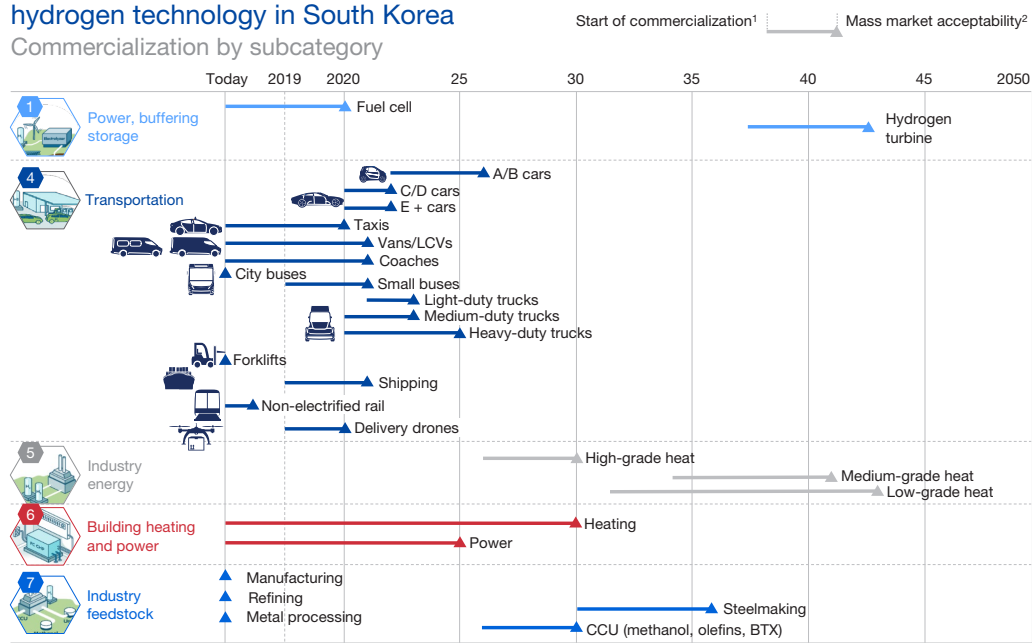
Chemical production based on carbon capture and utilization (CCU) approaches (such as for BTX and Olefin) has high potential for hydrogen use but will be shaped by the domestic availability of captured carbons. Korea is a small country, which limits its potential to store captured carbon on-land. Sub-sea storage is an option but such stored captured carbon is not available for use in general. Hence the availability of captured carbon in Korea puts a limit on the hydrogen demand from CCU based chemical production. (Exhibit 7 & 8)

HYDROGEN TECHNOLOGY START OF COMMERCIALIZATION

EXHIBIT 7

Start of commercialization and mass market acceptance of hydrogen technology in South Korea

Commercialization by subcategory

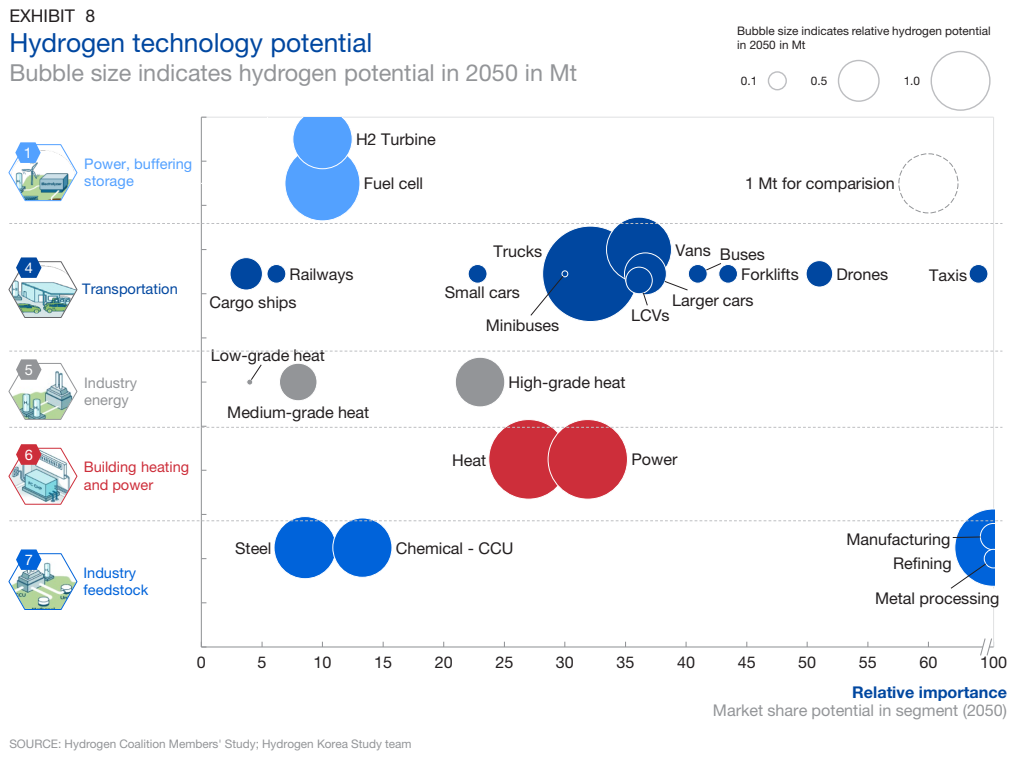


¹ Defined as adoption rate of ≥0.1% within the segment

² Defined as adoption rate of ≥1% within the segment

SOURCE: Hydrogen Coalition Members' Study; Hydrogen Korea Study team

HYDROGEN TECHNOLOGY ADOPTION RATES AND TOTAL POTENTIAL
ACROSS SECTORS



Supporting the deployment with hydrogen supply



The vision outlined in this roadmap will require stakeholders to make a significant “step-up” along the entire value chain. Specifically, they need to tackle three main barriers for the deployment of supply in line with the envisioned demand for Korea. The first involves the costs of green hydrogen production and the lack of renewable energy for such hydrogen supply. The second concerns the lack of distribution infrastructure for hydrogen, and the third is the cost of hydrogen powered end-use applications such as FCEVs.

Four main channels can supply hydrogen in Korea: hydrogen as by-product, electrolysis, steam methane reforming (SMR), and imports from other countries such as Australia or Canada.

By-product hydrogen is most favorable in terms of cost because little additional investment is involved in capturing the product. Electrolysis is currently not cost efficient due to the low energy-to-hydrogen efficiency and high electricity costs. Electrolysis via renewable energy such as solar or wind is even more costly due to the capital expenditures involved and the high volatility of the energy source. However, this method is desirable since it would produce “green hydrogen,” without greenhouse gas emissions.

SMR is currently the second most cost-efficient and scalable production method, but is not particularly environmentally desirable because it uses natural gas as feedstock and emits more CO₂ per calorific value than using LNG directly. However, it is still a valuable technology to facilitate the transition to a hydrogen economy, as it emits less pollutants than gasoline or coal and would promote the deployment of hydrogen infrastructure and the adoption of hydrogen applications. Finally, importing hydrogen from countries such as Australia is not yet a viable option due to the technological difficulty involved and the cost of transportation.

A steady and accessible supply is key to the adoption of hydrogen economy. With appropriate investments in technology and infrastructure, the above methods will become more economically viable and environmentally desirable over different phases of transition into the hydrogen economy.

Technology improvements required

The cost of green hydrogen from electrolysis on renewable energy will decline from current levels of USD 14.90 per kg H₂ to about USD 2.72 per kg H₂ by 2030, and USD 1.36 in 2050, if producers can achieve the following two improvements: First, if renewable energy from solar and wind continue to fall in levelized cost of energy (LCOE) from about USD 148.93 (solar) and 92.72 (wind weighted average) per kWh today, to about USD 47.29 and 56.32 per kWh in 2030, respectively, and an estimated USD 25.27 and 44.94 per kWh in 2050. And second, if electrolyzer efficiencies rise from 60% now to 85% in 2030 and 2050. (Exhibit 9)

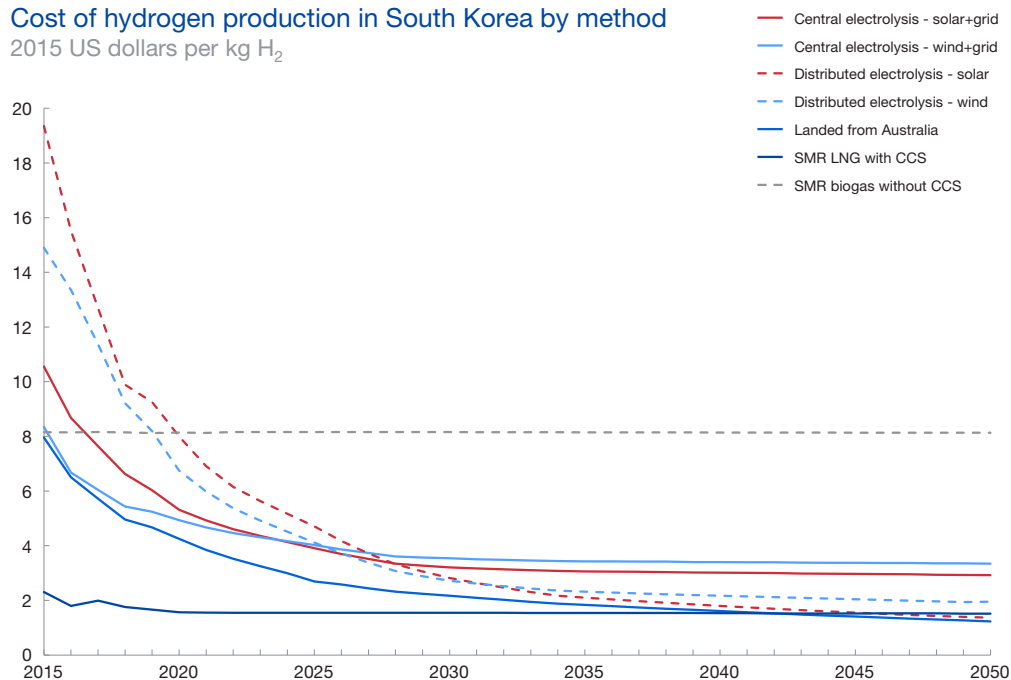
While the rapidly decreasing LCOE from renewable sources will make electrolysis economically viable, using only renewable power sources also comes with more volatility. The complementary use of grid power or battery storage can make electrolysis on renewable energy more productive and less volatile, despite an increase in the levelized cost of hydrogen (LCOH) due to the high costs associated with current grid power or battery

COST OF HYDROGEN FROM DIFFERENT PRODUCTION METHODS

EXHIBIT 9

Cost of hydrogen production in South Korea by method

2015 US dollars per kg H₂



SOURCE: McKinsey Energy Insights' Global Energy Perspective, Enerdata; Hydrogen Coalition Members' Study; Hydrogen Korea Study team

prices. Exhibit 9, above, depicts this situation in the case of centralized electrolysis (CE). In 2030, if a 50MW solar power CE plant runs at a 90% utility rate with grid power assistance, the amount of produced hydrogen will increase from 1,719 to 9,869 tons per year while the cost per kilogram of hydrogen produced will also increase from USD 2.79 to 3.21. Using batteries to store excess renewable energy for use in electrolysis would always be more expensive than relying on assistance from the grid; the same utilization increase via batteries would result in USD 5.95 per kg of H₂.

The addition of carbon capturing and sequestration (CCS) can make SMR more environment friendly. Without CCS, each kilogram of hydrogen produced through SMR would cause the emission of 9.80 kg of CO₂. With CCS, which costs roughly USD 0.26 per kg of hydrogen, emissions can be reduced to 1.20 kg of CO₂ per kg of hydrogen. Companies can further use the captured carbon in CCU, or would need to store it (CO₂ storage costs of USD 5.43 per ton CO₂).

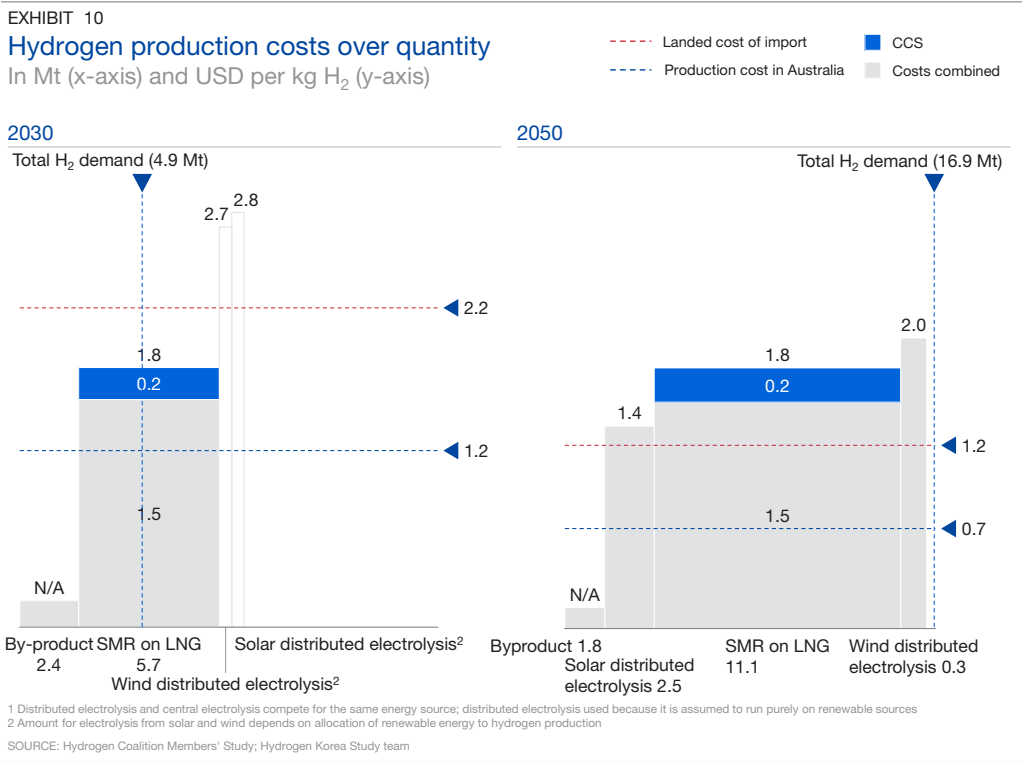
Importing hydrogen from a country like Australia could become economically viable if the industry can achieve lower production costs there, along with lower transportation costs. The LCOH from centralized electrolysis in Australia should decrease at a steeper rate than in Korea, due to its comparatively cheaper and more abundant solar power.

Shipping liquefied hydrogen is not yet a viable option economically, but costs will decrease with liquefaction and storage technology development. Liquefaction and storage (USD 0.40

per kg H₂ in 2050) will still be the biggest cost factor of total liquified shipping transportation (USD 0.56 per kg H₂).

Technological developments should also help overcome the hurdle of distribution infrastructure for hydrogen. Hydrogen refueling systems can achieve cost efficiency in the short term by optimizing supply sources and station models, benefiting from lower overhead costs for station manufacture and maintenance, and scaling up certain production methods. Since current hydrogen use as a feedstock already exceeds the amount of by-product hydrogen available, the ideal production method for hydrogen refueling station (HRS) supply in the short term, as depicted in Exhibit 10, would be SMR with CCS either on-site or centralized and delivered due to cost efficiency. Electrolysis would not yet be cost efficient in the short term unless supplied with cheaper grid power or free renewable energy that is otherwise wasted due to transmission limits.

COMPARISON OF HYDROGEN PRODUCTION COSTS WITH PRICE FOR IMPORTED HYDROGEN

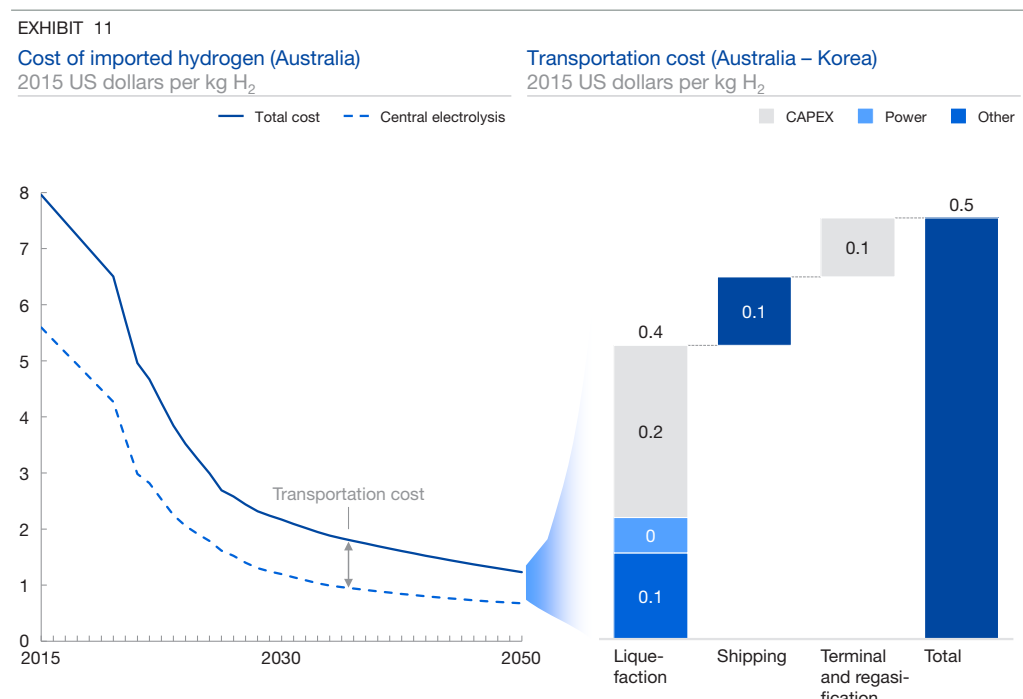


Hydrogen supply

With the cost and production capacity improvements discussed above, several hydrogen production methods will become available and relatively more desirable over phases of transition to the hydrogen economy. Exhibit 10, above, shows production costs on the y-axis and maximum possible production quantity on the x-axis, for different hydrogen production methods. Water electrolysis is shown as distributed electrolysis, to signify only green hydrogen from electrolysis on renewable sources. Imports don't show a width in the

graph because possible production totally exceeds Korea's total demand of hydrogen and can come from various sources. We do not account for distribution costs in the comparison because hydrogen distribution costs from the production site to the end-user would differ by method among pipeline, tube trailer, ammonia, and liquefaction, and because the desirable method of distribution would differ per combination of transportation size, distance, location of consumption and application of hydrogen use. However, to place imports on the same starting line, we included transportation costs up to and including landing in Korea for comparison, as shown in Exhibit 11.

HYDROGEN IMPORT COSTS



Hydrogen imports from renewable energy electrolysis would enable Korea to increase its share of renewable energy and reduce carbon emissions relative to total energy consumption. Imports could come from Australia, where solar energy and cheap land for placing solar PVs are both abundant, or from Canada, making use of otherwise unused hydropower. They could also originate in far offshore wind farms where electricity transmission lines would be prohibitively expensive. Alternative import sources could involve SMR hydrogen from countries with access to low-priced gas, if suitable storage for sequestered carbon in their gas fields can ensure CCS, resulting in low-carbon energy. Hydrogen prices from these sources would require fewer competitive advantages compared to domestic sources over time, if liquefaction and shipping costs rapidly decrease, as depicted in Exhibit 11.

While by-product hydrogen will remain the cheapest production method, in the near future SMR on LNG with CCS will be the next in line followed by imports from Australia

and electrolysis on solar and wind power. Because LCOH from SMR mostly depends on feedstock methane prices and electrolysis on power prices, changes in these factors may change prices and rankings accordingly.

Since the landed cost of imports will likely remain higher than cost of domestic SMR production in 2030, initial investments for hydrogen supply should focus on domestic production facilities rather than any foreign direct investments for imports. Doing so will secure hydrogen supply for the near future, enabling the end-user hydrogen uptake to develop as described. Meanwhile, companies should make investments to prepare for hydrogen imports, starting with building production facilities abroad, to establish a preemptive relationship with the exporter.

In 2030, domestic by-product and SMR hydrogen should meet total expected H₂ demand. In addition, we perceive Korea may have little more renewable energy than the government's goals to make 20% of total national energy consumption come from renewables. Since renewable energy exhibits high volatility, possibly resulting in peak generation levels that exceed transmission limits, some hydrogen could come from renewable energy that producers would otherwise waste, achieving a lower LCOH than SMR, depending on the sales price of that power. Also, if grid power is provided at a lower price, resulting in a lower LCOH than from SMR, producers could adopt hydrogen production from electrolysis earlier, although the result would not be emission-free (such as hydrogen from 100% renewable energy-based electrolysis).

In 2050, hydrogen from electrolysis via solar energy (at USD 1.36), SMR with CCS (at USD 1.75), and electrolysis via wind power (at USD 1.95 each per kg of H₂) will all cost more than imports from Australia (at USD 1.23 per kg). While Korea's total hydrogen demand will exceed domestic production and imports seem economically viable, which implies the need for imports, relying only on imports may not be a desirable option for supply security reasons. That realization thus opens room for domestic production from electrolysis via renewable energy and SMR.

The maximum production capacity for electrolysis (using only renewable power sources) depicted in Exhibit 11 assumes renewable energy will exceed government targets under the "3020" initiative and that producers will directly feed it into electrolyzers instead of the grid. Specifically, we assumed new additions to solar and wind energy capacity, based on constant investments in renewable energy after achieving government targets in 2030, would be directly allocated for water electrolysis. In addition to this growth in average capacity, volatility waste and grid power support can also increase the volume of hydrogen from electrolysis, as mentioned above.

The hydrogen production costs of below USD 2 per kg leave room for distribution costs, (expected to stay below USD 0.5 per kg in average) and profit margins, ultimately also without any subsidies. Hydrogen is expected to be already competitive with gasoline, when retail prices come below USD 3.4 per kg.

C. Distribution of hydrogen

To distribute the hydrogen, stakeholder can choose among a combination of on-site production, pipeline, pressured tube trailer, ammonia, and liquefied transportation according to needs and environmental factors. Among transportation methods, pipelines are currently cheapest and safest, especially in cases of high demand.

On-site production is desirable where there is steady demand, and is possible with both electrolysis or SMR. Electrolysis depends on the availability of renewable energy, and SMR is only constrained by the natural gas pipeline network. Where such on-site production is not viable or scalable, distribution would be made to individual end-users or hydrogen refueling stations through pipelines or land transportation.

Korea will need to construct a new nationwide network to supply hydrogen through pipelines to residential/commercial buildings, power plants, and factories. Mixing hydrogen into gas pipelines is in general feasible with up to 5% (in some specific cases even up to 20%), depending on the pipeline system. However, considering the existing long-range pipeline network in Korea with no changes to the infrastructure, the limit is as small as 0.1%, according to experts. This limit is due to the damaging effect of a higher hydrogen content. As an alternative, the Korean government and industry are already working on building a pure hydrogen network that covers core consumption regions and their catchment areas. It would be reasonable to start this effort in areas where the reconstruction and renovation of apartment complexes and large commercial developments takes place, which often occur in large cities in Korea.

Supporting investments

Achieving the hydrogen vision will require subsequent investments in hydrogen production, infrastructure, and the manufacturing of end-user applications. Hydrogen production includes capex investments in activities such as building SMR plants and electrolyzers (both centralized and distributed types). Infrastructure includes the storage, transportation and distribution of hydrogen to end-customers (for example, hydrogen pipelines should supply the fuel to buildings for their use).

The industry should also make appropriate investments in the manufacturing and construction of end-user applications to ensure the envisioned demand happens as the investments in infrastructure and production takes place. End-applications include fuel cells for power generation, H₂ turbines, FCEVs, the retrofit of factories, and hydrogen-fueled mCHPs and boilers.

Stakeholders are already making sizable, ongoing investments for selected applications such as FCEVs and fuel-cells for power generation. Continued investments (including R&D) will help all segments in reducing the cost of hydrogen adoption, which will in turn help Korea achieve its envisioned demand targets.

Total investment in hydrogen production and infrastructure for the outlined '2050 hydrogen scenario' amounts to KRW 35 to 55 trillion for hydrogen production facilities and KRW 45 to 60 trillion for storage, transportation and distribution, including refueling stations.

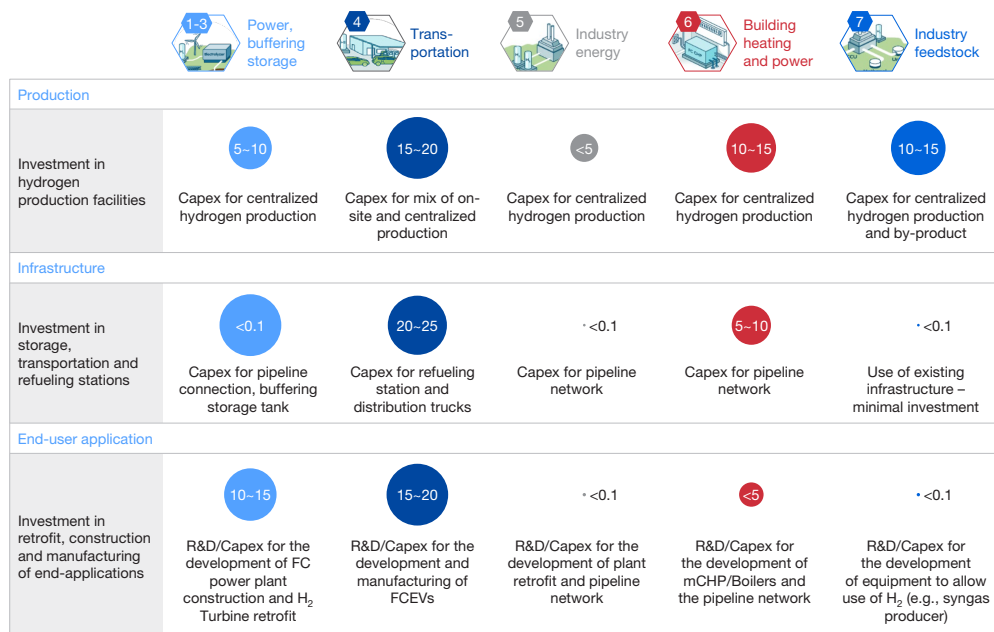
R&D spending is as important as investments in facilities that produce and construct end-user applications, since it drives quality and consumer choice. The capability to make premium end-user applications will not only drive domestic demand but also international demand and subsequent exports, which could further heighten the economic benefits from hydrogen. (Exhibit 12)

CUMULATIVE INVESTMENT

EXHIBIT 12

Cumulative investment across 5 segments in 2050

Bubble indicates the size of investment in Tn KRW



SOURCE: Hydrogen Coalition Members' Study; Hydrogen Korea Study team

It is important that the above three layers of investment – in production, infrastructure and end-user applications – take place hand-in-hand across the value chain to ensure that the lack of one does not become a bottleneck for hydrogen uptake. For example, little to no hydrogen uptake might occur if large investments only take place in hydrogen production while less spending targets end-user applications. In this case, while the industry could produce a lot of hydrogen, there would be no method to transport it, or FCEVs to use it. Consequently, all three investments should keep up with each other to unleash the full demand vision of hydrogen across all sectors.

Benchmarking industry and market development



Korea's relative competence

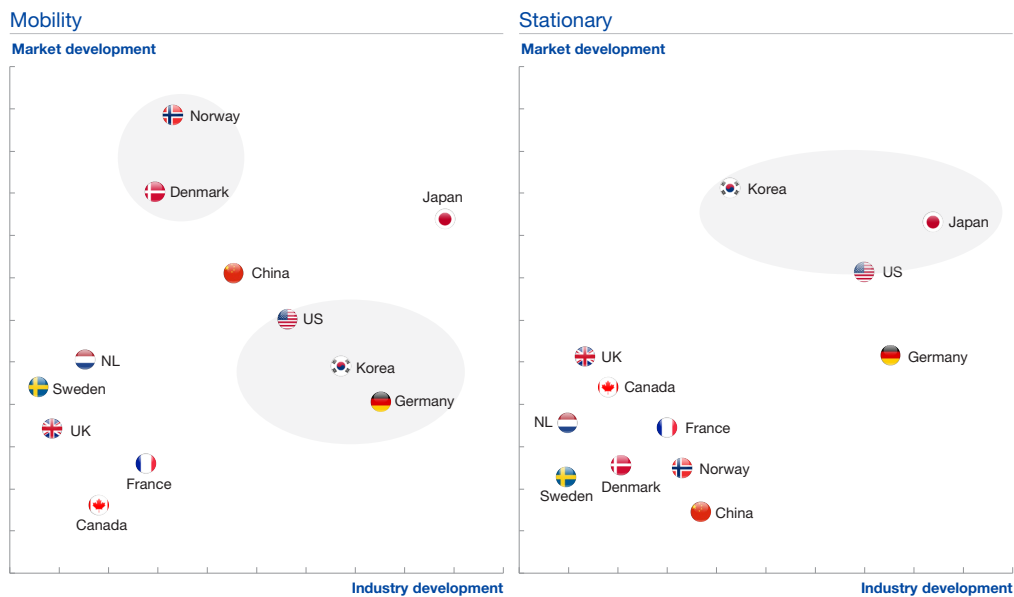
To assess Korea's relative position in the scale of hydrogen advancement and to highlight the areas for further improvements, we compared the leading hydrogen countries along two dimensions: First, stationary and mobile applications and second, market and industry development. Based on several indicators, we calculated scores for the countries along both dimensions. Overall, Korea stands among leading countries in terms of its hydrogen market and industry development. The analysis also highlights Korea's lack of readiness in upstream applications such as production and the need for a further deep-dive in this area, which we will discuss in this section. (Exhibit 13)

BENCHMARK OF MOBILITY APPLICATIONS AND STATIONARY APPLICATIONS

EXHIBIT 13

Applications

Benchmark of leading countries



¹ Index of 36 indicators in current uptake of hydrogen applications, market potential, industry strength, infrastructure (current and planned) and regulatory environment

SOURCE: Hydrogen Coalition Members' Study; Hydrogen Korea Study team

For mobile hydrogen applications such as FCEVs, Korea is one of the leading technology countries, ranking behind only Japan. In terms of market development, Korea globally ranks sixth, primarily due to relatively lower end-user application uptake. In particular, the country's lack of hydrogen mobility infrastructure hinders uptake: for example, only 12 HRS exist in the country today.

We do expect the status of hydrogen mobility infrastructure for the mobility applications to improve. The Korean government has set an ambitious target of 310 HRS in operation by 2022. Further, the establishment of a special purpose company (SPC) that includes industry leaders and the government is an important enabler for infrastructure improvement. The SPC aims to raise KRW 100 billion initial capital in 2018, ensuring adequate support for developing the infrastructure required to support higher FCEV uptake

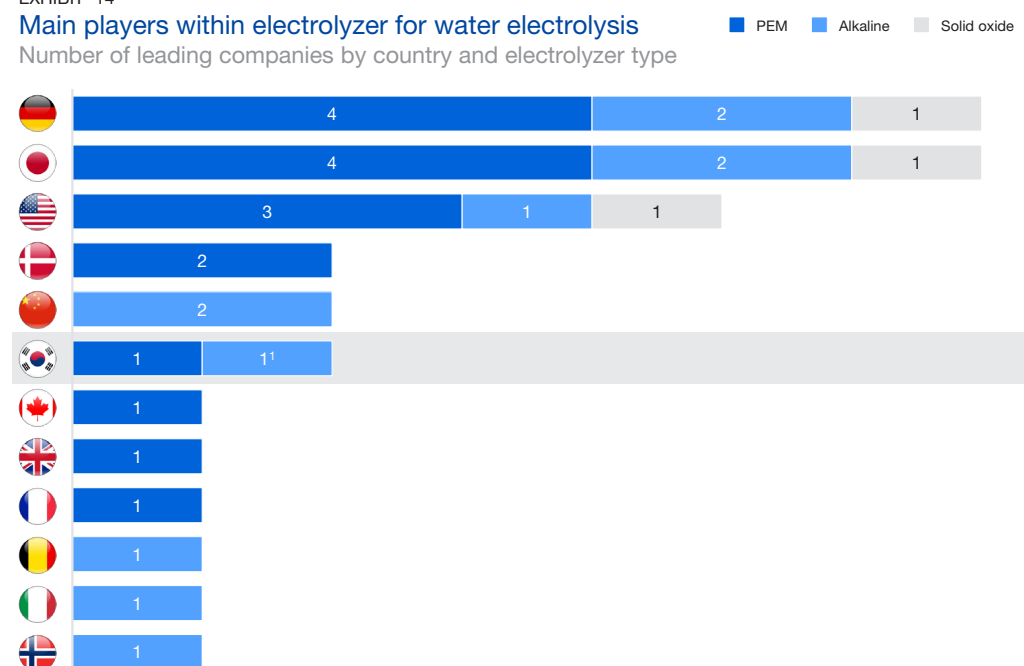
For stationary applications, Korea ranks among the four leading countries, with the others being Germany, Japan and the US. Korea has an advanced position in market development, primarily due to its installed capacity of large-scale commercial fuel cell applications (supported by large subsidies) and the presence of two globally leading commercial-scale stationary fuel cell manufacturers. For residential scale stationary fuel cell manufacturers, Germany's and Japan's domestic industries feature more offerings with significantly greater numbers of companies. For instance, Japan has more than three major manufacturers for the ENE-FARM program, Germany has about 16 strong companies, but Korea has no leading players. (Exhibit 14)

BENCHMARK OF COUNTRIES WITH MAIN PLAYERS WITH ELECTROLYZER TECHNOLOGIES

EXHIBIT 14

Main players within electrolyzer for water electrolysis

Number of leading companies by country and electrolyzer type



¹ EM Solution Co. and Eichenmtech registered as leading companies in South Korea

SOURCE: Expert interviews, IEA, U.S Department of Energy; Hydrogen Coalition Members' Study; Hydrogen Korea Study team

Hydrogen production and storage technologies are not yet a core competence of Korea's industry, primarily because the Korean government and industry have historically focused primarily on end-use applications. However, there has been a recent small-scale ramp-up of hydrogen production and storage technologies in Korea. The technological development programs have primarily received funding from KETEP, with a total FY2018 budget of KRW 25 billion. Still, the lack of a comprehensive policy framework causes a standstill of gas liquefaction and storage development, as for example for liquified hydrogen. A holistic policy framework and funding mechanism could unlock this potential. In brief, Korea has a strong industry position on the downstream side and significant potential to catch-up with leading countries on upstream hydrogen technologies. (Exhibit 15)

STRENGTH OF KOREAS HYDROGEN TECHNOLOGY INDUSTRY

EXHIBIT 15

Korea's industry's strength and development potentials in hydrogen technology

Based on industry survey and expert interviews



SOURCE: Coalition members' feedback, 38 indicators from benchmarking, Expert interviews; Hydrogen Coalition Members' Study; Hydrogen Korea Study team

Within electrolysis, industry is pursuing three main clusters of electrolyzer technologies: PEM, alkaline and solid oxide. The latter has not yet reached the same degree of technological maturity as the two former and requires about seven times higher temperatures, which represents a major practical limitation due to long start up and break-in times. PEM and alkaline electrolyzers are both deployed at large commercial scales and a 10 MW single unit electrolyzer is under construction for both technologies. While PEM and alkaline currently exhibit similar efficiencies, PEM can operate with higher current density and hydrogen output pressure, which makes it better suited for deployments with space limitations, such as HRS.

Both alkaline and PEM are technologically dominated by European and North American players. Korea currently has negligible electrolyzer capacity available (around 3 MW annual capacity). To put this in perspective, a leading European company is constructing an electrolyzer manufacturing plant with annual capacity 360 MW (equivalent to 448 electrolyzers), expected to be operational by 2020. Market pull and R&D investments are needed for the domestic Korean market to accelerate its domestic electrolyzer offerings.

Japan, on the contrary, is accelerating its development of production, storage and transport technology capabilities. For instance, a public-private partnership is currently deploying a 10-MW world-leading scale single electrolysis unit, expected to go live in 2020. The electrolysis plant utilizes domestic chlor-alkali technologies. Furthermore, a pilot for an international development supply chain between Japan and Australia is underway and will run from 2018 to 2021. This project is developing and testing technologies in all parts of

the supply chain. The Australia-Japan test pilot utilizes domestic storage technologies and the organic chemical hydride method for large scale transport. Japan is also researching alternative hydrogen storage technologies, most notably the Green Ammonia Consortium, which is combining know-how from government, academia and industrial heavyweights.

Benchmark points

Japan, on the contrary, is accelerating its development of production, storage and transport technology capabilities. For instance, a public-private partnership is currently deploying a 10-MW world-leading scale single electrolysis unit, expected to go live in 2020. The electrolysis plant utilizes domestic chlor-alkali technologies. Furthermore, a pilot for an international development supply chain between Japan and Australia is underway and will run from 2018 to 2021. This project is developing and testing technologies in all parts of the supply chain. The Australia-Japan test pilot utilizes domestic storage technologies and the organic chemical hydride method for large scale transport. Japan is also researching alternative hydrogen storage technologies, most notably the Green Ammonia Consortium, which is combining know-how from government, academia and industrial heavyweights.

Throughout the above comparative analysis, we reviewed Korea's relative position in different hydrogen applications and across the hydrogen supply chain. Our analysis highlighted the fact that the Korean government and industry have put more emphasis on end-user applications and less across the entire value chain. Such a bias seems to result from the absence of a master plan that considers different enablers and requirements to develop a successful transition to a hydrogen footing in a concerted manner. This is particularly conspicuous when compared to other leading Asian countries such as Japan and China that are already committed to following a clear hydrogen strategy, stressing the importance of government leadership and coordinated action in successfully transitioning to a hydrogen economy. For example, China is very active in terms of amending regulations to spark hydrogen industry and market development, while Japan has successfully taken actions on the issues of hydrogen production, storage and imported technologies.

To develop such a plan, the Korean government should strive to develop detailed, realistic and stable milestones using concrete deployment and cost metrics. It should also work to facilitate a regulatory framework to convince private sector companies to make investments under clear long-term views. Japan, for instance, has set a goal of fostering the development of domestic electrolyzer technologies to control the cost of power-to-gas more cost- efficiently than those of the current European and North American leaders. As the example suggests, continually revising cost metrics such as key performance indicators for development progress has ensured that those involved clearly understand the direction of technological development and can make business plans based on a clear long-term view.

Leading countries in the support of hydrogen are developing public-private partnerships and large funding schemes based on national roadmaps. For instance, NEDO of Japan operates a "Leading R&D Projects on Hydrogen Utilization" program that combines public and private know-how with the goal of achieving "highly efficient low-cost hydrogen production technology from renewable energy." The country is also working on hydrogen storage technology that can "facilitate long-distance transportation of hydrogen and

long-term storage.” As for funding schemes, METI of Japan earmarked a budget of USD 300 million in FY2018 budget to provide financial assistance for the demonstration of hydrogen technologies and utilization.

For those capabilities difficult to domestically develop with national plans due to a lack of players or overly large capability gaps, stakeholders should consider inorganic growth options. China provides a good example of this approach. Weichai Power, for instance, has recently acquired a 19.9% stake in fuel cell stack manufacturer Ballard Power systems (Canada) and became its largest shareholder. At the same time, Nedstack (the Netherlands) and DongFeng Trucks have signed a joint venture agreement where the former supplies PEM fuel cells for the latter’s commercial vehicles and heavy-duty trucks.

Recommendations



The hydrogen vision outlined in this report offers many economic, environmental and societal benefits to Korea. Making it a reality will require a major transition in how Korea produces, transports, and consumes energy, implying major changes across sectors. This transition will not happen by itself, as it will require joint, synchronized efforts by policymakers, industry players and investors.

The following recommendations aim to launch this roadmap, putting Korea on a path to realize its benefits and start virtuous cycles that can reduce costs and accelerate deployment. They prioritize the most attractive hydrogen applications for Korea and tackle the key barriers to their adoption.

Prioritizing the CO₂ mitigation opportunities among the hydrogen applications involves considering the timing by when each application can be produced at scale and the offering's relative performance compared to other de-carbonization levers. Attributes for the relative performance include the technical maturity, customer performance, and the cost (economic viability) of each hydrogen application.

From such an analysis, trucks and fleet applications emerge as a priority (see Exhibit 16) due to 3 reasons. First, the magnitude of their overall hydrogen consumption, and hence CO₂ emission reduction potential, is large. Second, fuel cells offer significant benefits over alternative decarbonized technologies (as described in the transport section), implying that the chance of success, i.e. widespread adoption of fuel cells, in this segment is high. Third, the timeframe for commercialization is in the mid-2020s, and hence closer than for other segments, such as for industry applications of hydrogen.

MASS MARKET ACCESSIBILITY OF END-USE APPLICATIONS

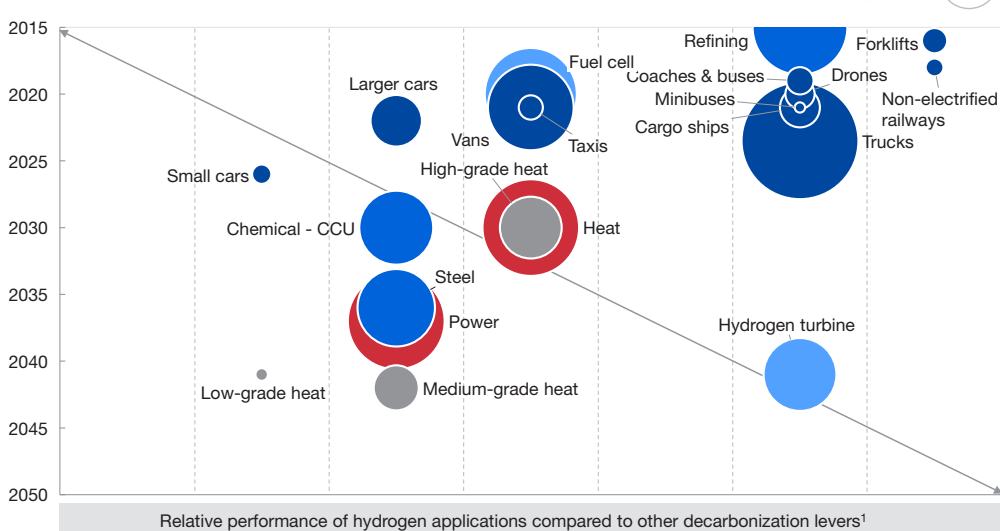
EXHIBIT 16

Comparison of relative attractiveness for hydrogen applications

By application subcategory

Mass market acceptability

Year of sales share > 1%



¹ Advantages of hydrogen compared to other decarbonization levers is assessed using three metrics for the given application: Cost performance; Timing of availability; Performance. Cumulative score used for ranking ranges from 0 to 6

SOURCE: Hydrogen Coalition Members' Study; Hydrogen Korea Study team

From the above analysis, the following 6 recommendations were derived:

Recommendation 1:

Set concrete deployment milestones for key applications

Korea should establish short-term deployment milestones through 2022 to spark the initial deployment of prioritized applications, and develop mid-term milestones for 2030. Doing so will ensure stakeholders take a long-term view regarding the development of their sector.

Concretely, we propose the following short-term milestones for 2022:

Hydrogen production	Install domestic production capacities of 3 million tons H ₂ from SMR and electrolysis. 300 tons of this production capacity should be solar and wind based (corresponds to 10 distributed electrolysis plants)
Hydrogen infrastructure	Build 300 hydrogen refueling stations (HRS) to cover all major cities and highways in Korea, enabling full mobility across the country
Transport	Deploy FCEVs across vehicle segments - Put 20,000 FCEVs on the road (~0.2%) - Operate 500 hydrogen buses - Operate 5,000 hydrogen trucks - Switch 5,000 taxis to hydrogen - Put 5 hydrogen trains in service
Heating	Demonstrate pure hydrogen heating at a large-scale - With 20,000 households with mCHPs - With utilization of heat emissions from fuel cell power plants
Technology	Provide KRW 200 billion in public R&D funding for a 4-year period from 2019 to 2022, accessible for academia and the private sector when matched 50:50 by industry - With KRW 100 billion for mobile and stationary fuel cell technology development - With KRW 100 billion for hydrogen production technology Note: Recommended size of R&D funding targets to match funding provided by leading countries to their domestic industries, such as Japan (source: <i>The International Partnership for Hydrogen and Fuel Cells in the Economy</i>) Set out specific technology targets, building on existing targets (e.g., as defined by the US DoE) and prioritizing the applications and properties most relevant to Korea (e.g., prioritize technologies required for import of hydrogen)
Investments	Stimulate KRW 6,000 billion in investment in 2019 to 2022 through e.g., government-backed loans or interest-free loans, which is required to achieve the above-mentioned targets along the value chain - Min. KRW 1,500 billion for hydrogen production facilities - Min. KRW 1,500 billion for hydrogen infrastructure - Min. KRW 3,000 billion for R&D, laboratory and production facilities
Incentive schemes	Transport - Provide adequate incentives to stimulate demand by end-consumers for FCEVs to the above-mentioned levels - Establish non-monetary benefits to spark the adoption of FCEVs, such as the use of bus lanes, free parking in urban centers, and subsidized free refueling - Harmonize regulations for FCEVs, e.g., access to tunnels, bridges, ships Power - Continued, but degressive support for fuel cells for power generation at utility scale - Establish large-scale demonstration project for H₂ turbine - Establish targets for number of mCHPs and energy produced from hydrogen in TWh Continue and extend the Renewable Portfolio Standards (RPS) and the Renewable energy certificates (REC) scheme, to encourage green hydrogen and hydrogen fuel cells. Additional option is to set-aside subsidies to directly support power generation from renewables (including fuel cells that operate on green hydrogen), e.g., through feed-in tariffs.

For 2030 we propose the following milestones:

Hydrogen production	Establish terminal capabilities for 4.5 million tons of hydrogen for far-offshore wind or imports from renewable sources (about half of domestic demand)
Hydrogen infrastructure	Extend HRS network to increase customer convenience, competitive with today's network of gasoline stations.
Transport	Increase deployment of FCEVs across vehicle segments to generate strong market pull and globally leading countries' ambitions - Put half a million FCEVs on the road (about 5% of total car park) - Create a fully decarbonized fleet of city buses (about 20,000 buses) - Put 100,000 hydrogen trucks on the road (about 3% of total) - Put 50,000 hydrogen taxis on the road (roughly 20%) - Replace all diesel-powered trains with hydrogen fuel cell trains
Heating	Target 200,000 households to use hydrogen-powered mCHPs
Industry	Establish large-scale demonstrations for steel production from DRI using hydrogen
Technology	Establish KRW 300 billion in public R&D funding, accessible for academia and the private sector when matched 50:50 by industry
Investments	Stimulate KRW 17,500 billion in investment in 2022 to 2030 through e.g., government-backed loans or interest-free loans, which is required to achieve the above-mentioned targets along the value chain - Min. KRW 3,500 billion for hydrogen production facilities - Min. KRW 5,500 billion for hydrogen infrastructure - Min. KRW 5,000 billion for R&D, laboratory and production facilities
Incentive schemes	Transport - Continue adequate incentives to increase demand by end-consumers for FCEVs to the above-mentioned levels - Retain non-monetary benefits to spark the adoption of FCEVs, such as the use of bus lanes, free parking in urban centers, and subsidized free refueling Power - Continue support for use of mCHPs in building - Post 2022 continue degressive support for fuel cells for power generation at utility scale - Support H₂ turbine projects Continue extended Renewable Portfolio Standards (RPS) and the Renewable energy certificates (REC) scheme. Review directly support for power generation from renewables.

Recommendation 2:

Support deployment milestones via public-private partnerships

Public and key players in the private sector should jointly commit to a hydrogen partnership, a roadmap and milestones. This partnership should:

- Provide funding for research, development and demonstration (RD&D) of KRW 450 billion and enough infrastructure funding to overcome market barriers (split into 2022 and 2030 goals)
- Create policy instruments that ensure deployment happens in a synchronized manner, reduce risk for all stakeholders and attract investments
- Link all subsidies, whether of RD&D, infrastructure or for end use applications, to improvements towards cost and technical targets. One way to achieve this is to use degressive cost targets, based on the actual uptake of subsidies. Prioritize those targets most relevant to scale-up, e.g., ensure that HRS costs come down over time, hydrogen becomes cheaper at the HRS pump etc.

- Gain clear commitments from industry for investments in RD&D, product development and infrastructure
- Ensure coverage of the whole value chain, from hydrogen generation through distribution to end-use applications
- Establish mechanisms to steer, align and coordinate the stakeholders and to enforce commitments

Beyond the activities directly linked to the roadmap, Korea needs to integrate hydrogen as a clean energy vector in any future energy transition roadmap and implementation plan, and as a long-term pillar of Korea's energy transition toward a more decarbonized, safer, and economically attractive energy system.

Recommendation 3:

Develop Korea's transport system into the leading global hydrogen and fuel cell mobility market

Given Korea's dense population, its nature as a peninsula, the strong market position of domestic manufacturers and their lead in hydrogen and fuel cell technology, the country could readily become a leading hydrogen mobility market. To achieve this goal, Korea should:

- Build 300 HRS by 2022 to cover all major cities and highways in the nation and enable full country-wide mobility, and then work to increase network's density in the long term
- Convert its fleet of buses and taxis to decarbonized powertrains by 2030, with a clear split of powertrains and intermediate milestones for 2022 and 2026
- Encourage the uptake of hydrogen for trucks and fleet applications by offering integrated solutions and financial and non-financial incentives

Recommendation 4:

Strengthen Korea's hydrogen and fuel cell industry

Korea is already strong in selected areas of the hydrogen value chain, but lacks capabilities, players and technology in others (see chapter 4 for details). To reinforce these areas, Korea should:

- Acquire and/or partner with competitive players to gain missing capabilities. Focus on inorganic ways to close the gap in terms of technology capabilities, especially in hydrogen production
- Form industry alliances. Share know-how domestically and internationally, encourage the creation of R&D consortiums across the value chain and for Korea

Recommendation 5:

Build a long-term pathway for the decarbonization of Korea's gas network

In the development towards this hydrogen vision, Korea should benefit from its experience from an extensive natural gas infrastructure and leading manufacturers of industrial equipment. Korea should:

- Build a long-term roadmap for a hydrogen pipeline and distribution network
- Study the ideal deployment paths for pure hydrogen networks and demonstrate the practical feasibility of reconstruction opportunities in cities
- Develop transportation technology and invest in infrastructure for tube trailers of pressured or liquefied hydrogen for where pipelines are not favorable

Recommendation 6:

Build a sustainable and competitive hydrogen supply industry

In order to make domestic electrolysis on renewable energies and imports of such “green” hydrogen economically viable, Korea should:

- Develop electrolysis technology at a utility scale, through policy support and subsidies until the production method gains cost competitiveness
- Develop a hydrogen import supply chain, together with international partners that can supply low-cost, carbon-free hydrogen from far-offshore wind farms and other countries
- Build technological capabilities in hydrogen overseas transportation (e.g., terminals, equipment and shipping) via liquefied hydrogen or ammonia

Abbreviations

BTX	Benzene Toluene Xylene
CAPEX	Capital expenditures
CCS	Carbon capture and sequestration
CCU	Carbon capture and utilization
CE	Central electrolysis, hydrogen production method using electrolyzer at sites without direct demand; assuming 50MW capacity in this report
CO₂	Carbon dioxide
CSIRO	Commonwealth Scientific and Industrial Research Organization
DE	Distributed electrolysis, hydrogen production method using electrolyzer at sites with direct demand; assuming 1MW capacity in this report
DRI	Direct reduced iron
EUR	Euros
FCEV	Fuel cell electric vehicle
FY	Financial year
GW	Giga(10 ⁹)watt
H₂	Hydrogen
HRS	Hydrogen refueling station
ICE	Internal combustion engine
KETEP	Korean Energy Technology Evaluation and Planning
KIER	Korea Institute of Energy Research
KRW	Korean Won
LCOE	Levelized cost of energy

LCOH	Levelized cost of hydrogen
LNG	Liquefied natural gas
mCHP	Micro combined heat and power
MEA	Membrane electrode assemblies
METI	Ministry of Economy Trade and Industry, Japan
MW	Mega(10^6)watt
NAPES	National Air Pollutants Emission Service
NEDO	New Energy and Industrial Technology Development Organization, Japan
NO_x	Nitrogen oxides
PEM	Proton-exchange membrane
PJ	Peta(10^{15})joules
PM₁₀	Particulate matter under 10 μ m size
R&D	Research and development
RD&D	Research, development, and demonstration
SMR	Steam methane reforming
SO_x	Sulfur oxides
SPC	Special purpose company
TWh	Tera(10^{12})watt hour
UAV	Unmanned aerial vehicle
USD	US Dollars
VTOL	Vertical takeoff and landing

