



HYDROGEN AND FUEL CELLS IN JAPAN

JONATHAN ARIAS

Tokyo, October 2019



EU-Japan Centre for Industrial Cooperation

ABOUT THE AUTHOR



Jonathan Arias is a Mining Engineer (Energy and Combustibles) with an Executive Master in Renewable Energies and a Master in Occupational Health and Safety Management. He has fourteen years of international work experience in the energy field, with several publications, and more than a year working in Japan as an energy consultant. He is passionate about renewable energies, energy transition technologies, electric and fuel cell vehicles, and sustainability.

He also published a report about “Solar Energy, Energy Storage and Virtual Power Plants in Japan” that can be considered the first part of this document and is available in <https://lnkd.in/ff8Fc3S>.

He can be reached on [LinkedIn](#) and at jariasbecerro@gmail.com.

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List of Abbreviations

Abbreviation	Meaning
AGT	Ammonia-fired Gas Turbines
AHEAD	Advanced Hydrogen Energy Chain Association for Technology Development
AIST	National Institute of Advanced Industrial Science and Technology
ANRE	Agency of Natural Resources and Energy
APEC	Asia Pacific Economic Cooperation
APEREC	Asia Pacific Energy Research Centre
ARENA	Australian Renewable Energy Agency
BEV	Battery Electric Vehicle
CAPEX	Capital Expenditures
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization and Storage
CDV	Clean Diesel Vehicle
CGS	Cogeneration System
CHP	Combined Heat and Power
COP	Conference of Parties
DR	Demand Response
EOR	Enhanced Oil Recovery
EU	European Union
EUR	Euro (an exchange rate of 123 JPY per EUR has been used)
EV	Electric Vehicle. Also PEV (BEV + PHEV)
EVI	Electric Vehicles Initiative
FC	Fuel Cell
FCCJ	Fuel Cell Commercialization Conference of Japan
FCEV	Fuel-Cell Electric Vehicles (or FCV)
FCV	Fuel-Cell Vehicles (or FCEV)
FDMA	Fire and Disaster Management Agency
FIT	Feed-in Tariff
FRA	The Japan Fisheries Research and Education Agency
FREA	Fukushima Renewable Energy Institute
FY	Fiscal Year (April to March)
GAC	The Green Ammonia Consortium
GHG	Greenhouse Gasses

GDP	Gross Domestic Product
GTCC	Gas Turbine Combined Cycle
GW	Gigawatt
HESC	Hydrogen Energy Supply Chain
HEV	Hybrid Electric Vehicle
HRS	Hydrogen Refueling Stations
HySTRA	CO ₂ -free Hydrogen Energy Supply-chain Technology Research Association
HySUT	Association of Hydrogen Supply and Utilization Technology
IAE	Institute of Applied Energy
IEA	International Energy Agency
IEEJ	The Institute of Energy Economics, Japan
IFS	Institute of Fluid Science of the Tohoku University
INDC	Intended Nationally Determined Contribution
IRENA	International Renewable Energy Agency
JAMA	Japan Automobile Manufacturers Association
JHyM	Japan H ₂ Mobility
JPEC	Japan Petroleum Energy Center
J-POWER	Electric Power Development Co., Ltd.
JPY	Japanese Yen
JST	Japan Science and Technology Agency
KEPCO	Kansai Electric Power
KHI	Kawasaki Heavy Industries
kW	Kilowatt
kWh	Kilowatt Hour
LNG	Liquefied Natural Gas
MCH	Methylcyclohexane
METI	Ministry of Economy, Trade and Industry
MHPS	Mitsubishi Hitachi Power Systems
MLIT	Ministry of Land, Infrastructure, Transport and Tourism
MMBtu	Million British thermal unit
MOE	Ministry of the Environment
MOFA	Ministry of Foreign Affairs of Japan
MoU	Memorandum of Understanding
MPa	Megapascal
MW	Megawatt
MWh	Megawatt Hour
NEDO	New Energy and Industrial Technology Development Organization

NeV	Next Generation Vehicle Promotion Center
NESTI	National Energy and Environment Strategy for Technological Innovation
NILIM	National Institute for Land and Infrastructure Management
NIMS	National Institute for Materials Science
Nm ³	Normal Cubic Meter
NO _x	Nitrogen Oxide
NPMC	Non-Precious Metal Catalyst
P2G	Power-to-Gas
PEFC	Polymer Electrolyte Fuel Cell (or PEMFC)
PEMFC	Polymer Electrolyte Membrane Fuel Cell (or PEFC)
PEV	Plug-in Electric Vehicles (or EV)
PHEV	Plug-in Hybrid Electric Vehicles (or PHV)
PHV	Plug-in Hybrid Electric Vehicles (or PHEV)
PV	Photovoltaic
R&D	Research and Development
SIP	Strategic Innovation Promotion Program
SOFC	Solid-Oxide Fuel Cell
TEPCO	Tokyo Electric Power Company
TMG	Tokyo Metropolitan Government
Toshiba ESS	Toshiba Energy Systems & Solutions Corporation
UK	United Kingdom
US	United States
USD	United States Dollar
VPP	Virtual Power Plant
VRE	Variable Renewable Energy
V2H	Vehicle to Home
V2G	Vehicle to Grid
W	Watt
ZEH	Zero Energy House
ZEV	Zero-Emission Vehicles

1. EXECUTIVE SUMMARY

Since the Great East Japan Earthquake of March 2011, the Japanese government has been promoting a low-carbon society through energy efficiency measures and the development of a stable and reliable supply of renewable energy, reducing electricity costs and CO₂ emissions. After the adoption of the Paris Agreement, Japan announced its intention to reduce GHG emissions by 26% by 2030 compared to 2013 in July 2015. Furthermore, in May 2016, the Plan for Global Warming Countermeasures established a long-term goal of an 80% reduction by 2050.

The Japanese government is also promoting the use of the hydrogen as a clean and alternative energy vector. It is the key for reducing energy procurement and supply risks since it can be produced from various energy resources, and for decarbonizing the Japanese energy supply and demand structure, transport, heating (buildings), industry and power sectors.

The fast growth of variable renewable energy capacity provides an opportunity to complement solar and wind installations with the production of hydrogen using the surplus that would otherwise be wasted, keeping power systems flexible and helping to balance the grid. Hydrogen, in contrast to storage batteries, can be stored on a large scale and for the long term.

But its widespread adoption faces challenges, especially a high cost. Realize a hydrogen society in Japan implies the necessity of both expanding hydrogen demand and the construction of reliable supply chains to meet that demand at a low cost, and reaching the cost parity with traditional fossil fuels, which will depend also on the application of a carbon price for those emitting CO₂. The government has been supporting demonstration projects for building supply chains from overseas to produce green hydrogen from renewable sources or from fossil fuels plus the carbon capture and storage.

The government aims to establish also regional hydrogen supply chains using local unused resources, including renewable energy, waste plastics, sewage sludge, and by-product hydrogen, which will contribute to improving the regional energy self-sufficiency rates and creating new regional industries. The combination of low solar and wind costs, continuously in a downward trend, and more efficient and cheaper electrolysis technologies are gradually making the large-scale renewable electrolysis a viable option in the near future.

Power generation accounts for 40% of total national CO₂ emissions, so the use of hydrogen in this sector will greatly contribute to reducing them and will directly lead to massive hydrogen consumption, which will contribute to cost reduction. Power-to-gas is expected to be one of the countermeasures against problems related to grid stability and reliability due to the higher penetration of renewables in Japan.

In 2030, the government aims to reduce emissions by 39% in the residential sector and by 40% in the commercial sector compared to the emissions in 2013. Stationary fuel cell systems, which generate electricity and heat, are contributing to that goal, with around 300,000 units deployed across the country. Large-scale SOFC systems for commercial centres and other buildings are growing in importance.

The transportation sector contributed with 19% to entire CO₂ emissions in Japan in 2015, and the government's target is to reduce it by 25% by 2030 increasing the popularization of the next-generation vehicles and reaching a share in the new car sales between 50% and 70% by 2030. Fuel cell vehicles offer a low emission driving performance, overcome electric vehicles' weight, range and charging limitations, though their deployment is being slower because they are more difficult to produce, they are much expensive, and there are not enough refueling stations.

The main issues for the dissemination of HRSs are the high construction and operation costs of and the strict regulations. METI is reviewing the regulation that affects to HRSs and working on the standardization of equipment to achieve lower costs.

The government awaits the results of several demonstration projects around 2020 to start the operation of hydrogen large-scale infrastructures. Demonstration projects must reveal the deficiencies of the different technologies and allow to focus on the most technical and cost-effective areas, taking into account their applicability in real operating conditions

This document can be considered the second part of the report "Solar Energy, Energy Storage and Virtual Power Plants in Japan", published by the same author in October 2018 and available in <https://lnkd.in/ff8Fc3S>.

In terms of content, this report begins by explaining the framework that caused the evolution of the energy market in Japan, mainly the Great East Japan Earthquake and the Paris Agreement, following by the main chapter that describes the current situation of the hydrogen and fuel cells markets in Japan.

That chapter explains the main three hydrogen applications: stationary fuel cells, mobility and power generation. Later, the characteristics and ongoing demonstration projects of the principal energy carriers are described, as well as how the growing hydrogen demand will be fulfilled through overseas and domestic supply chains.

Finally, the main research clusters of the country, organizations and associations, and main private companies involved in the market are introduced, identifying which are the potential opportunities for European companies, and including some recommendation for those willing to address the Japanese market.

2. INTRODUCTION: ENERGY SCENARIO AFTER THE GREAT EAST JAPAN EARTHQUAKE

Because of the earthquake in March 2011 and outage that followed, all 54 units were shut down in May 2012. Since then, 6 units declared decommissioning due to the accident, and 5 units declared decommissioning in March 2015. Due to this reason, Japanese imports of fossil fuels, coal, oil and especially liquefied natural gas (LNG), increased from around 81% in 2010 to around 89% in 2016 [1]. Nowadays, Japan is still the world's third-largest importer of coal behind China and India, and the largest importer of LNG. This impacted all 3E's, this is, energy security, economy and environmental conservation:

- The energy self-sufficiency ratio decreased from around 20% in 2010 to 6.4% in 2014, and it was still under 10% in FY 2017 [2].
- The electric power costs increased by about 38% for industries and about 25% for homes. Although the downward trend since 2014, those rates were still higher in FY 2017, about 21% for industries and 16% for homes [2].

CO₂ emissions increased by about 4% because of the higher electric generation by thermal power plants [3]. In FY 2017, GHG emissions dropped to below the level of FY 2010, before the Great East Japan Earthquake [2], confirming the downward trend from 2013, mainly because of the increased in the renewable energy generation and the restarting program of nuclear power plants.

The Government formulated the Strategic Energy Plan of Japan in April 2014, "Fourth Energy Basic Plan" [3], under the Basic Act on Energy Policy, which entered into force in June 2002. The plan presented the basic direction of Japan's energy policy, based on the fundamental principles of safety, energy security, and improvement of economic efficiency and environmental suitability. It was followed by the Long-term Energy Supply and Demand Outlook on July 2015 [4], which foresees the future energy mix towards 2030, with a 22-24% ratio for the renewable generation (Figure 1). The objectives of the government in 2030 are the following:

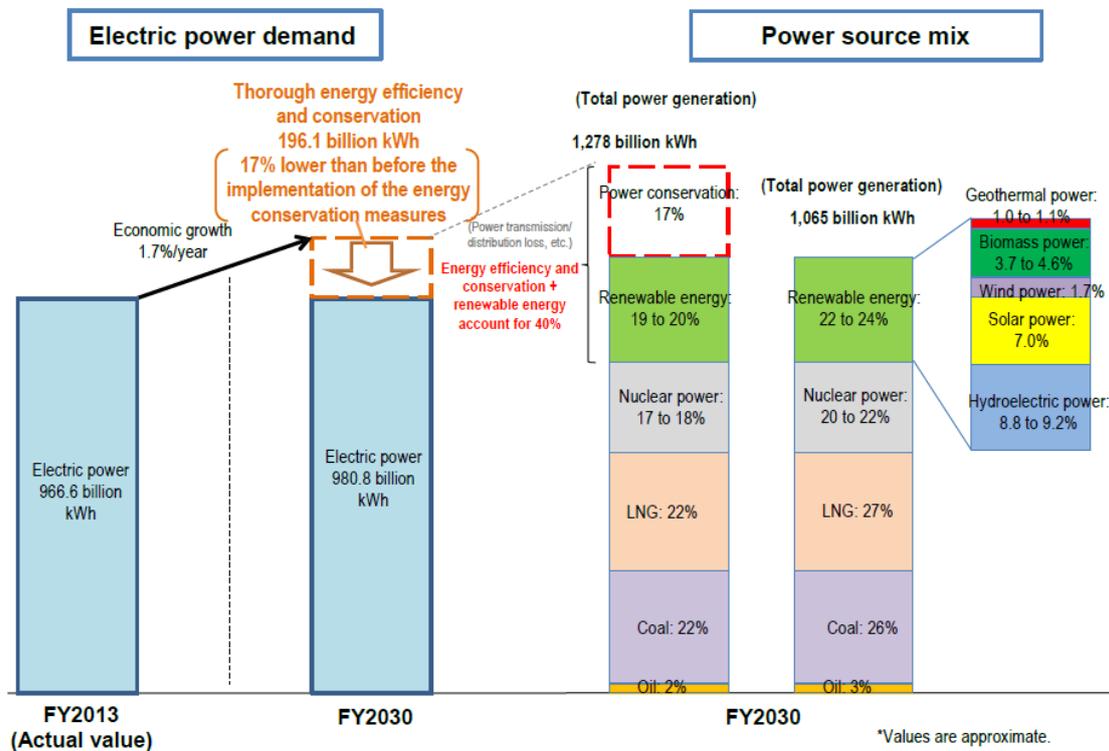
- Raise the self-sufficiency rate up to around 40% by 2030.
- Reduce the dependence on fossil fuels to 56% on the basis of power source composition.
- Substitute nuclear power by the expansion of renewable energy, especially geothermal, hydroelectric and biomass powers, which can be operated stably despite weather conditions, and by improving the efficiency of thermal power generation.

- Reduce the electric power demand by 17%, even with an expected economic growth of 1.7% real Gross Domestic Product (GDP) per year. In FY 2017, the Japanese economy grew 1.4%, but the primary energy consumption slightly decreases by 0.1% due to continuous energy conservation efforts [5].

The Japanese government is promoting an energy-efficient society, with an integrated implementation of the Act on Rationalizing Energy Use (Energy Conservation Act) and support measures. Energy conservation measures in the industrial, commercial, residential and transportation sectors are expected to improve the energy efficiency by 35% by FY 2030. Several measures such as Top Runner Programme and Zero Energy House (ZEH) are carrying out by the government. Together with the maximum renewable energy penetration, the government expects to cover about 40% of electricity demand in FY 2030.

Top Runner Programme aims to improve the energy efficiency in equipment and devices and has already contributed to greatly enhance the energy efficiency of consumer electronics and automobiles in Japan. It covers around 70% of household energy consumption and it is mandatory for companies (manufacturers and importers), encouraging competition and innovation among them without increasing market prices.

Figure 1: Targets for the Electric Power Supply-Demand Structure in Japan in 2030



Source: Ministry of Economy, Trade and Industry (METI) [4].

Keeping in mind the goals of increasing the energy self-sufficiency rate and creating a low carbon society, the deployment of renewable energy has continued to be important for the Japanese government. The installed capacity of renewables has grown by 2.5 times since the introduction of the feed-in tariff (FIT) scheme, being the solar photovoltaic (PV) energy the centre of this revolution. The government aims to develop and utilize renewable energy as the major power source by 2030. Efforts are being made to reduce costs and overcome system constraints. The development and deployment of high-performance low-price storage batteries are also being promoted.

However, in order to achieve the S (Safety always comes first) and 3E's targets in 2030, a nuclear power generation ratio between 20 and 22% was established by the government (Figure 1). One of the biggest issues of the Japanese energy market is that it depends on foreign fossil-fuel supply, becoming easy to be affected by international situations. This, securing a stable supply, is one of the reasons because nuclear power generation is indispensable nowadays in Japan. Other reasons are that its use reduces the CO₂ emissions and electric power costs, even taking into account the costs of the accident risk response. And it is an important baseload power supply that contributes to the stability of the supply and demand structure of energy. Therefore, the restarting of the nuclear power plants that have conformed to new regulatory requirements evaluated by the Nuclear Regulation Authority is promoted [6]. The licensing status of the Japanese nuclear facilities can be checked on the website of the Japan Nuclear Safety Institute¹. There are nine plants in operation and another seven that already received the approval.

The 2015 Outlook was prepared with Paris' climate change objectives in mind. After its adoption, Japan announced its Intended Nationally Determined Contribution (INDC) in July 2015 to reduce the GHG emissions by 26% by FY 2030 compared to FY 2013 (a 25.4% reduction compared to FY 2005). Furthermore, in May 2016, the Plan for Global Warming Countermeasures was decided by the Cabinet of Japan, establishing a long-term goal of an 80% reduction by FY 2050, and clarifying policies and measures to be implemented [7].

To support these promises, the government is working together with industry and academia to promote energy technology innovation under the Energy and Environment Technological Innovation Plan, focusing on 2030 targets, and the National Energy and Environment Strategy for Technological Innovation towards 2050 (NESTI 2050), in which hydrogen was listed as one of the innovative energy-storage technologies.

In April 2016, the Cabinet Office also announced the Energy and Environment Innovation Strategy. The main innovative technologies are related to the efficient power generation, the reduction of the cost of renewable energies, storage energy battery technologies beyond lithium, and efficient energy carriers such as hydrogen. In July 2016, The Long-term Global Warming Countermeasures Platform, consisting of members from the government, industry and academia, was established to discuss measures for reducing GHG emissions on a long-term basis [8].

¹ Japan Nuclear Safety Institute: <http://www.genanshin.jp/english/facility/map/>.

Apart from the implementation of energy conservation measures and the maximum introduction of renewable energy, the government promotes the use of the hydrogen as a clean and alternative energy vector. It is the key for reducing energy procurement and supply risks since it can be produced from various energy resources, and for decarbonizing the Japanese energy supply and demand structure. Hydrogen will play an important role in applications such as stationary and portable power, energy storage, and mobility, allowing also a higher penetration of variable renewable energy sources. The government aims to build a hydrogen-based society, and in order to achieve it, it released the Strategic Roadmap for Hydrogen and Fuel Cells in June 2014², revised in March 2016³ and March 2019⁴, and the Basic Hydrogen Strategy in December 2017 [9].

The government is also promoting new businesses based on smart community-related technologies such as the demand response (DR), virtual power plants (VPPs) and blockchain technology as a way to increase the energy efficiency through distributed generation, storage and trade of energy [6].

The Fifth Basic Energy Plan was released in July 2018 [10]. The Government kept the same targets for FY 2030, describing the nuclear and coal-based thermal power stations as “important baseload power sources” that contributes, in the case of the nuclear generation, to the stability of the long-term energy supply and demand structure.

Critical opinions arrived from the Ministry of the Environment (MOE) and the Ministry of Foreign Affairs of Japan (MOFA) against the METI’s proposal of making expansive use of coal, keeping an unrealistic target for nuclear power, which will require extending the life of many old reactors and building some new ones⁵, and give insufficient consideration to renewable power. It seems contradictory to argue the use of nuclear energy to help create a decarbonized energy market and continue to promote the use of coal.

Coal-fired power plants are likely to face higher costs in order to take environmental countermeasures in the future, while the cost of renewables continues to decrease. The adoption of the Paris Agreement clearly showed the direction for decarbonisation, and coal-fired power generation is the energy source that produces the largest amount of CO₂ emissions. Most of the countries in the world are phasing out the use of coal in power generation as an important step to fight against global warming. More than 20 countries launched the Powering Past Coal Alliance in 2017, that is committed to phasing out coal power by 2030, and utilities in 26 out of 28 EU member states signed an agreement to not build any more coal-fired power plants from 2020 onwards [11].

Many financial and other institutions in the US and Europe ended their investments and loans to coal-fired power projects. Nippon Life Insurance Co., the largest insurer in Japan, will no longer extend loans for or invest in coal power plants at home and overseas due to environmental

² METI, 24 June 2014: https://www.meti.go.jp/english/press/2014/0624_04.html.

³ METI, 22 March 2016: https://www.meti.go.jp/english/press/2016/0322_05.html.

⁴ METI, 12 March 2019: https://www.meti.go.jp/english/press/2019/0312_002.html.

⁵ The Asahi Shimbun, May 18, 2018: <http://www.asahi.com/ajw/articles/AJ201805180028.html>.

concerns, except if they include CO₂ capture and storage technology, an expensive option used only in a few locations worldwide.

Japanese banks are among the largest financiers of coal-related projects globally, but that seems to be changing, in addition to tightening lending criteria for coal power in the last months. Sumitomo Mitsui Trust Bank Ltd. would stop providing financing for new coal power plants "as a basic rule", and Mitsubishi UFJ Financial Group Inc. and Mizuho Financial Group would also revise lending to coal-power plants, leaving an open possibility for highly efficient projects⁶.

However, adding high-efficiency generating capacity fueled by coal would produce electricity at a higher cost than that produced from natural gas. Therefore, planned investments in coal-fired generating capacity across several Japanese prefectures have been cancelled. In this context, the ammonia-coal co-firing technology may be the key to the nearest future of the Japanese coal-fired power plants⁷, with several successful demonstration projects in Japan in the last years (Chapter 3.3.1).

2.1. ABOUT HYDROGEN

Hydrogen is the most abundant and lightest of the elements but does not exist as a gas on Earth. It is odourless and non-toxic, and has the highest energy content of common fuels by weight, nearly three times that of gasoline.

It has the advantage of being produced from several energy sources, such as fossil fuels through a chemical process called reforming, the most common and least expensive method but resulting in CO₂ emissions, and through electrolysis of water using electricity from renewable resources, a clean but expensive method. According to the International Renewable Energy Agency (IRENA), over 95% of current hydrogen is produced from reforming of natural gas, liquefied petroleum gas and coal gasification. Its largest use is in industry and refining as a by-product from industrial plants.

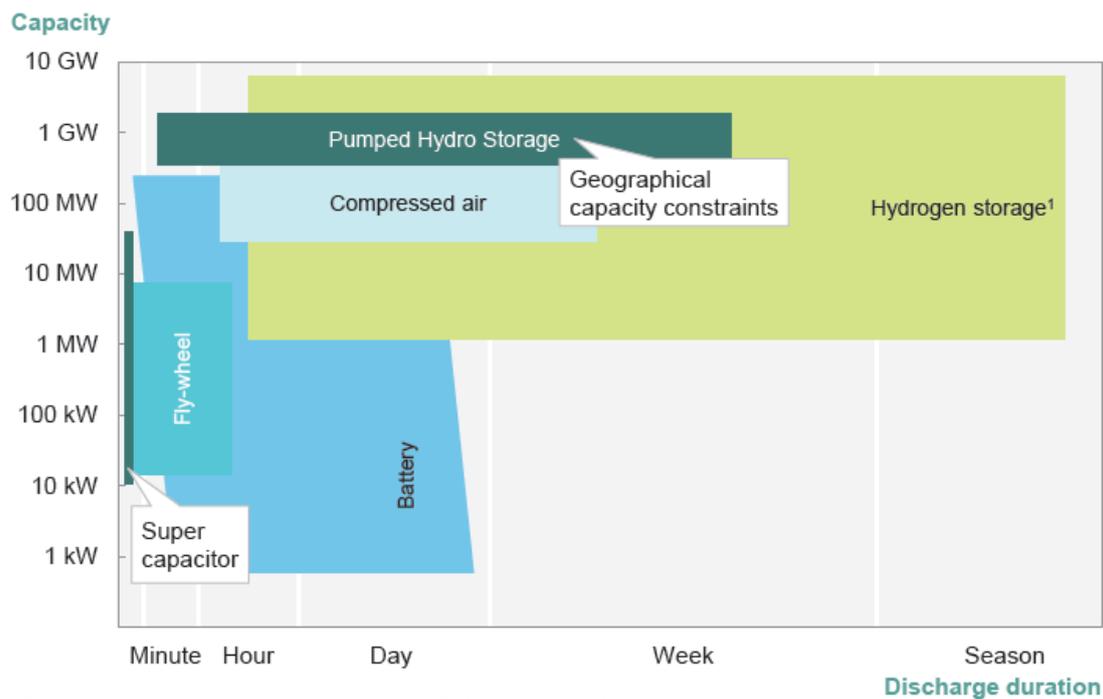
The fast growth of variable renewable energy (VRE) capacity provides an opportunity to complement solar and wind installations with the production of hydrogen using the surplus that would otherwise be wasted, keeping power systems flexible and helping to balance the grid. Hydrogen can be stored on a large scale and for a long term, similar to natural gas, in caverns, tanks or pipelines, ensuring a reliable power supply when the renewable generation is not enough or prices are favourable to convert it back to power. Hydrogen and electricity are in fact

⁶ The Business Times, July 23, 2018: <https://www.businesstimes-com-sg.cdn.ampproject.org/c/s/www.businesstimes.com.sg/energy-commodities/japans-nippon-life-to-stop-financing-coal-fired-power?amp>.

⁷ Ammonia Energy, 18 July 2019: <https://www.ammoniaenergy.org/the-evolving-context-of-ammonia-coal-co-firing/>.

complementary energy carriers: hydrogen can be converted to electricity, and electricity can be converted to hydrogen. Storage batteries are only suitable for short-term storage since the electric power stored in batteries continuously declines over time due to natural discharge (Figure 2). In Japan, Kyushu Electric Power Co. already asked the photovoltaic producers to reduce their output due to the demand-and-supply unbalance, which is a utility's right by law [6].

Figure 2: Overview of Carbon-free Energy Storage Technologies



Source: Hydrogen Council [12].

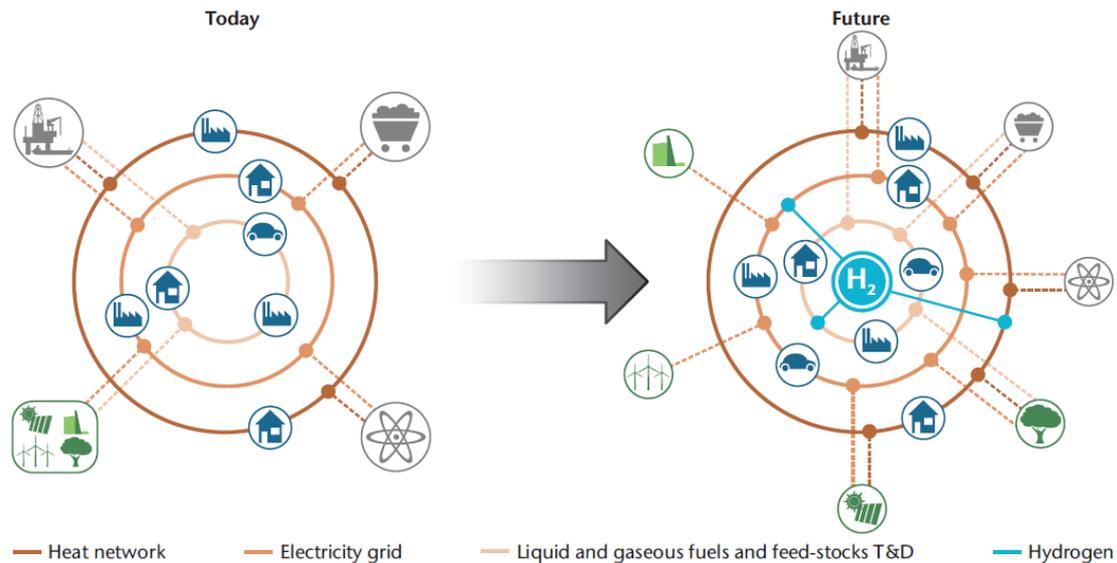
When it is compressed, it can be easily stored for long periods, transported over long distances, and used in many ways across the entire energy sector, supporting decarbonisation in transport, heating (buildings), industry and power sectors. It can take advantage of existing energy infrastructure. Up to a certain share, hydrogen can be injected into natural gas grids reducing the emissions of existing gas infrastructure, such as gas turbines for the power sector.

Hydrogen can be converted to electricity by a fuel cell through a chemical reaction with oxygen in the air, and with water and heat as the only byproducts. Fuel cells are scalable.

Hydrogen fuel cell electric vehicles, or just fuel cell vehicles (FCVs), offer a low emission driving performance and can complement electric vehicles, overcoming their weight, range and charging limitations.

Therefore, hydrogen can link different energy sectors and energy transmission and distribution networks, and thus increase the operational flexibility of future low-carbon energy systems.

Figure 3: Energy System



Source: International Energy Agency (IEA) [13].

According to its “Vision 2050”, the Hydrogen Council foresees that hydrogen market could reach USD 2.5 trillion and create 30 million employment globally by 2050. Hydrogen could contribute to 18% of energy demand and 20% of CO₂ reduction, 6 billion tonnes of CO₂ per year. Hydrogen power generation will reach 1,500 TWh per year, and excess renewable energy of 500 TWh will be stored and utilized annually through hydrogen.

But its widespread adoption faces challenges, especially a still too high cost. At the moment, hydrogen is mainly produced from natural gas (“grey” hydrogen) for industrial uses, which generates significant carbon emissions. If the carbon emissions are captured and stored, or reused, then it is called “blue” hydrogen. “Green” hydrogen is the cleanest one since it is generated by renewable energy sources without producing carbon emissions.

The main driver for grey hydrogen and blue hydrogen is the price of natural gas, which varies around the world. Grey hydrogen is cheaper than the other two, estimated around EUR 1.50 per kilogram⁸. But its CO₂ emissions carry an additional cost that will gradually increase in the future. As an example, CO₂ cost in the European Union’s emissions trading system is about EUR 20-30 per ton, and it will increase to between EUR 30 and 40 per ton over the next ten

⁸ IEA, 23 April 2019: https://www.iea.org/newsroom/news/2019/april/the-clean-hydrogen-future-has-already-begun.html?utm_campaign=IEA%20newsletters&utm_source=SendGrid&utm_medium=Email

years, which could add around EUR 0.50 per kilogram to the cost of grey hydrogen in Europe, for a total cost of around EUR 2 per kilogram.

The second-most important driver for blue hydrogen is the cost of CO₂ capture, utilization and storage (CCUS), between EUR 50 and 70 per ton. Future innovations and scalability will push down the cost of CCUS, while the price of CO₂ emission will increase in the coming years, closing the cost gap between grey and blue hydrogen.

Finally, the current cost of green hydrogen is between EUR 3.5 and 5 per kilogram. One of the main reasons is the cost of electrolysis. Its total global capacity is limited and costly at the moment, but it is growing, and according to IEA, if all the current projects come online by 2020, cumulative capacity will rise from 55 MW in 2017 to over 150 MW. A significant price reduction of around 70% is also expected over the next decade according to McKinsey, also as a consequence of the sharp reduction of the price of renewable energy generation during the last years.

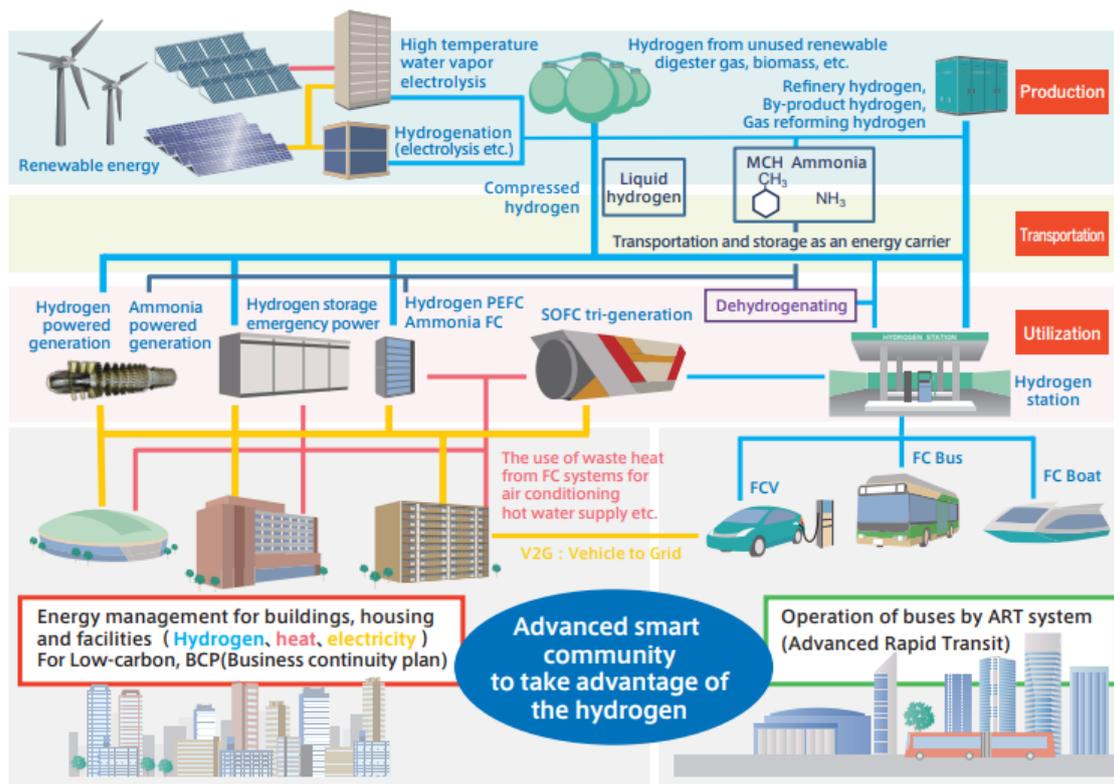
A study released in July 2018 [14] concluded that hydrogen produced from wind energy is already cost-competitive with small- and medium-scale hydrogen supply produced from fossil fuels both in Germany and Texas, but not with large-scale industrial sales, which will also become competitive in the coming years. It pointed out the importance of the operating flexibility in near real-time to either sell electricity at the current market price or convert it to hydrogen.

Besides, green hydrogen can be shipped around the world from places with cheap renewable energy sources. In this sense, Japan is carrying out several important pilot projects with countries including Australia, Saudi Arabia and Brunei (Chapter 3.3) to determine the best way to transport green or blue hydrogen over large distances by ship.

3. HYDROGEN MARKET IN JAPAN

Japan is a poor country in energy resources. Hydrogen will allow Japan to achieve the “3E+S” goals by reducing the supply and procurement risks, and carbon emissions in power generation, transportation, heating and industrial processes. The research, development and demonstration of hydrogen technologies with industry-academia-government collaboration under the leadership of government will contribute significantly to solve energy and environment problems in Japan. Eventually, it will also bring the world’s leadership in hydrogen utilization and the related industries. Japanese hydrogen and fuel cell technologies are the world’s most advanced. Japan will keep expanding its technologies domestically and overseas promoting a worldwide collaboration that leads to cheaper costs and the realization of a hydrogen-based society.

Figure 4: Basic Scheme of Hydrogen Society



Source: Cross-Ministerial SIP [15].

With the Tokyo 2020 Olympic Games as the first point of reference, it is estimated that the market will reach JPY 590.3 billion (around EUR 4.8 billion), though the projections will vary

depending on the success of the government's support and regulations. According to NEDO's estimation, the hydrogen market will reach JPY 1 trillion (about EUR 8 billion) by 2030 and JPY 8 trillion (around EUR 65 billion) by 2050.

Japan has more than 40-year history of hydrogen and fuel cell technology research and development (R&D) under projects such as the Sunshine Project and the Moonlight Project launched in the 1970s, the Japan Hydrogen and Fuel Cell Demonstration (JHFC) Project and a large-scale demonstration project for stationary fuel cells, accumulating world-leading technologies, knowledge, and knowhow in its industrial and academic sectors [9].

The idea of intercontinental transport of liquefied hydrogen is also not new. The World Energy Network (WE-NET), an international cooperation in R&D of clean energy systems with particular emphasis on hydrogen, started in 1993 with the aim to construct a worldwide energy network for effective supply, transport and use of renewable energy using hydrogen. The program was launched by the National Institute of Advanced Industrial Science and Technology (AIST) with the New Energy and Industrial Technology Development Organization (NEDO) as project coordinator of a joint industry-government-academia effort, and it was divided into three phases extending over a 28-year period from 1993 to 2020⁹.

In December 2013, METI established the Council for a Strategy for Hydrogen and Fuel Cells, consisting of experts from industry, academia, and government, to study ideal approaches for the future utilization of hydrogen energy. In April 2014, the government approved the Fourth Strategic Energy Plan¹⁰, which described measures and goals to promote the use of hydrogen toward the realization of a hydrogen society, and called for the formulation of a roadmap. In June 2014, the Council formulated the Strategic Roadmap for Hydrogen and Fuel Cells¹¹, which described the pathway to follow until 2040 for realizing a hydrogen-based society through the following three-step program, also shown in Figure 5:

- Phase 1: dramatic expansion of hydrogen use, by expanding the use of stationary fuel cells and FCVs, capturing the global market.
- Phase 2: full-fledged introduction of hydrogen power generation and establishment of a large-scale system for supplying hydrogen (by the second half of the 2020s). Further expansion of the demand for hydrogen, while widening the scope of hydrogen sources to include unused energy imported from other countries. Establish a new secondary energy structure in which hydrogen will be added to existing traditional resources.

A basic approach is to combine cheap, unused energy from overseas with CCS (carbon capture and storage) technology, or procure massive amounts of hydrogen from cheap, renewable energy electricity in parallel to the establishment of international supply chains through the development of storage and transportation infrastructure.

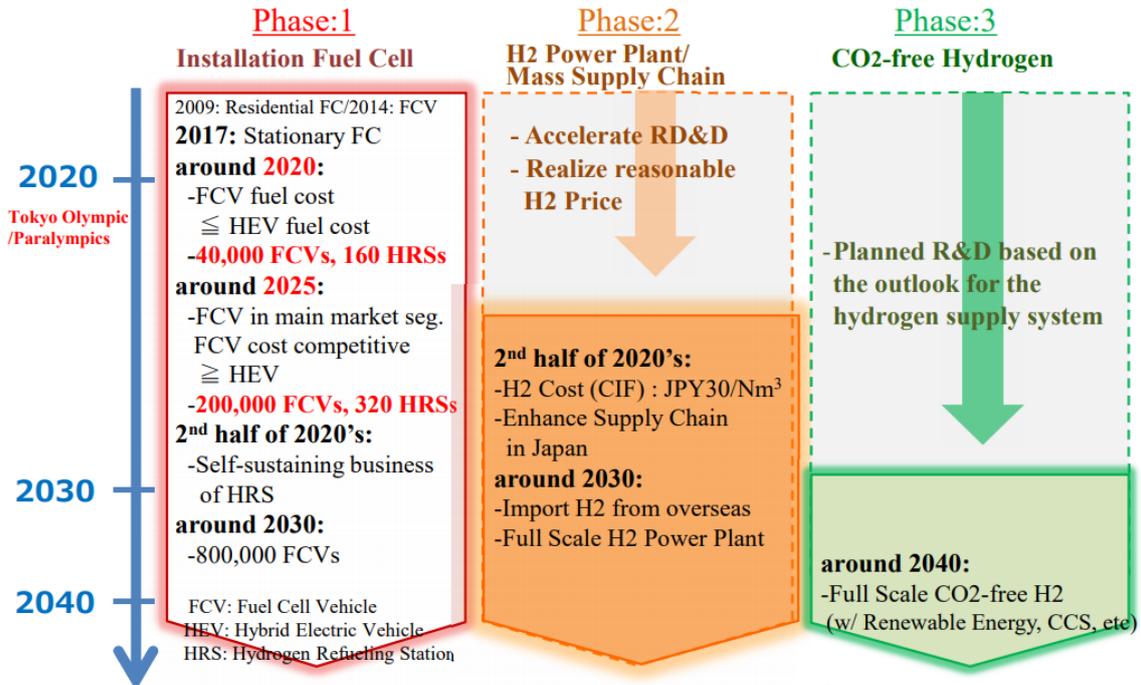
⁹ WE-NET: https://www.ena.or.jp/WE-NET/contents_e.html.

¹⁰ METI, 11 April 2014: https://www.meti.go.jp/english/press/2014/0411_02.html.

¹¹ METI, 24 June 2014: https://www.meti.go.jp/english/press/2014/0624_04.html.

- Phase 3: establishment of a CO₂-free hydrogen supply system by around 2040, combining the technology for manufacturing hydrogen with CCS, or making use of hydrogen derived from renewable energy resources.

Figure 5: Strategic Roadmap for Hydrogen and Fuel Cells (June 2014)



Source: METI.

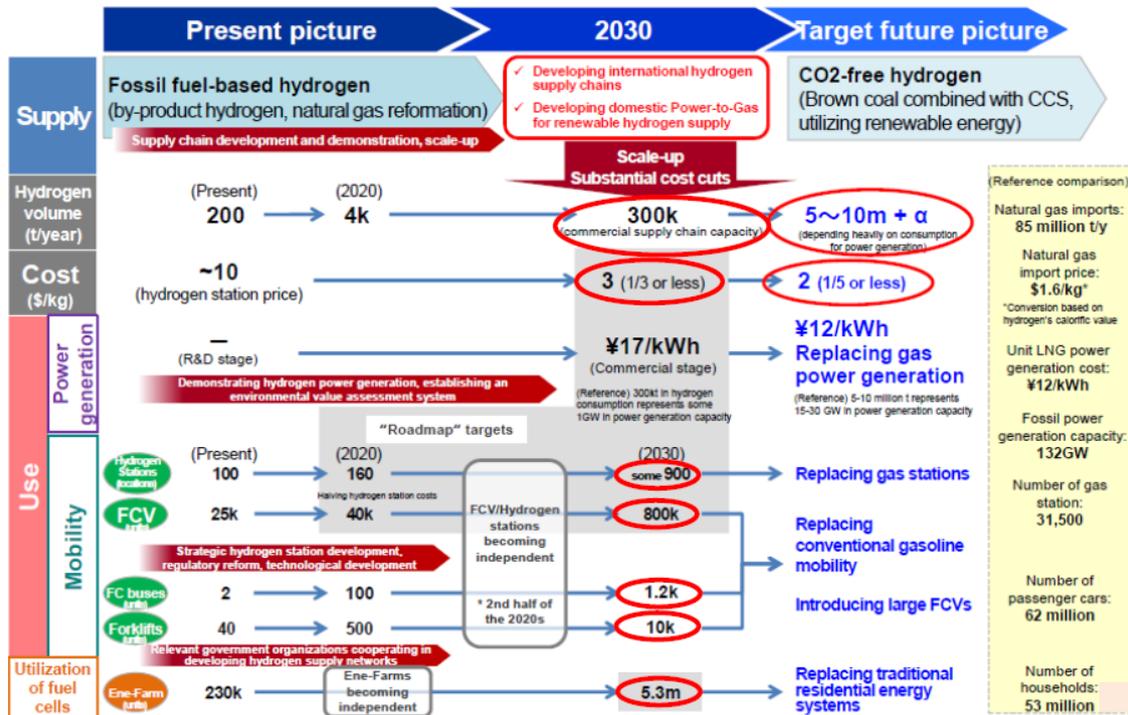
Then, the Roadmap was revised in March 2016 to include new goals and specific explanations of efforts to be made¹². METI also establish a Working Group on CO₂-Free Hydrogen under the Council aiming at the future expansion of CO₂-free hydrogen utilization. The Working Group compiled the results into a report on March 2017¹³, describing current challenges and the direction of future efforts.

In April 2017, the Ministerial Council on Renewable Energy, Hydrogen and Related Issues held its first meeting, promoting initiatives that will ensure Japan becomes the first country in the world to realize a hydrogen-based society. Then, the plan was specified in the Investments for the Future Strategy 2017 (Cabinet Decision on June 9, 2017). Based on the above background, the government released the Basic Hydrogen Strategy in December 2017 [9], which includes an action plan through 2030 and a future vision for the year 2050, and seeks also to reduce the cost of carbon-free hydrogen to that of conventional fuels (Figure 6).

¹² METI, 22 March 2016: https://www.meti.go.jp/english/press/2016/0322_05.html.

¹³ METI, 7 March 2017: https://www.meti.go.jp/english/press/2017/0307_003.html.

Figure 6: Basic Hydrogen Strategy (December 2017)



Source: METI.

One of the main barriers for the dissemination of hydrogen use and the realization of a hydrogen-based society is its high procurement and supply costs. The current retail price of hydrogen in Japan is about JPY 100 per Nm³ (around EUR 0.81), producing around 200 tons of hydrogen annually in April 2018¹⁴. The strategy specifies the necessity to establish a commercial-scale hydrogen supply chain to procure 4,000 tons of hydrogen per year by 2020, and 300,000 tons of hydrogen annually by 2030 (amounting to 1 GW in power generation capacity), expanding its demand in the mobility and power generation sectors.

Therefore, the main objective of this strategy is to reduce the hydrogen supply cost to JPY 30 per Nm³ (about JPY 334 per kilogram, EUR 0.24 per Nm³ or EUR 2.7 per kilogram¹⁵) by 2030, less than one-third of its current cost and similar than the traditional fuel sources, this is, gasoline in transport and natural gas in power generation, reducing the price. Japan seeks to cut the hydrogen power generation cost to JPY 17 per kWh by that time.

Beyond that, the target is to procure between 5 and 10 million tons of hydrogen annually (amounting to between 15 and 30 GW in power generation capacity), heavily depending on the

¹⁴ METI, 26 December 2017: https://www.meti.go.jp/english/press/2017/1226_003.html.

¹⁵ One Nm³ of hydrogen gas is equal to 0.08988 kilograms or 1.269 liters. One Nm³ of hydrogen has approximately the same energy value than a third of a liter of gasoline. This is, burning 1 kilogram of hydrogen releases the same amount of energy as burning 2.75 kilograms of petrol. The exchange rate used in this document was 1 € equal to 123 yen.

consumption for power generation and with the intention of replacing the gas power generation. The Institute of Applied Energy estimates that the hydrogen demand in Japan in 2050 will be 53 Mtoe (0.22 trillion Nm³), resulting in a 13% share of the total primary energy supply [16].

The cost gap with traditional energy sources after incorporating environmental cost adjustments will be lowered, reaching a price of JPY 20 per Nm³ (about EUR 0.16 per Nm³ or EUR 1.8 per kilogram) by expanding international hydrogen supply chains on the supply side and the industrial use on the demand side. In this scenery, the production cost from brown coal gasification will be reduced to JPY 12 per Nm³.

This will require scaling-up and improving efficiency of brown coal gasifier, and scaling-up and improving thermal insulation properties to increase the efficiency of liquefaction from 13.6 kWh/kg to 6 kWh/kg, and the capacity of the liquefied hydrogen tank until 50,000 m³. The development of low-cost CO₂ capture technologies such as physical absorption is also on the table to reduce the cost of CO₂ separation, from around JPY 4,200 per ton of CO₂ in Japan to around JPY 2,000 per ton of CO₂.

After the Basic Hydrogen Strategy, the Fifth Strategic Energy Plan was also released in July 2018 [10], and the Tokyo Statement in October 2018. Because of these documents, and to ensure the achievement of the goals toward a hydrogen-based society, the council reviewed the existing roadmap in March 2019¹⁶. It defines new targets on the specification of basic technologies and the breakdown of costs, the necessary measures for achieving these goals, and that the government will convene a working group consisting of experts to review the status of implementation in each area stipulated by the roadmap (Figure 7 and Annex A).

The updated Roadmap notes that, in order to achieve the grid parity, it is needed a hydrogen cost lower than the price of natural gas, which is unpredictable, setting a target for the imported hydrogen of JPY 13.3 per Nm³ (about EUR 0.11 per Nm³ or EUR 1.2 per kg) to match the current price of LNG on an energy-equivalent basis, equivalent to USD 10 per MMBtu, and without considering the environmental value. If the environmental value is added to the LNG, the target price would increase up to JPY 16.8 per Nm³ (Figure 8 and Figure 9).

In the industrial sector, there is no hydrogen target in Japan, though it can benefit from the development of burners, boilers and turbines that use a mix of hydrogen and fossil fuels. Hydrogen that is currently used for industrial processes such as steelmaking and oil refining is produced from fossil fuels and could be replaced with CO₂-free hydrogen in the future to reduce carbon emissions.

¹⁶ METI, 12 March 2019: https://www.meti.go.jp/english/press/2019/0312_002.html.

Figure 7: Action Plan in the Strategic Roadmap for Hydrogen and Fuel Cells (March 2019)

● In order to achieve goals set in the Basic Hydrogen Strategy,

① **Set of new targets to achieve (Specs for basic technologies and cost breakdown goals), establish approach to achieving target**

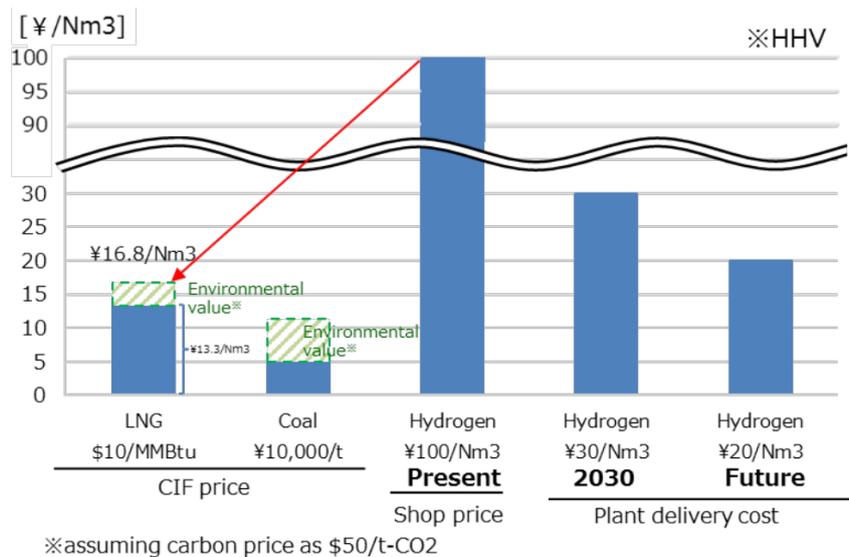
② **Establish expert committee to evaluate and conduct follow-up for each field.**

Goals in the Basic Hydrogen Strategy		Set of targets to achieve		Approach to achieving target
Use	Mobility	FCV 200k by 2025 800k by 2030	2025 <ul style="list-style-type: none"> Price difference between FCV and HV (¥3m → ¥0.7m) Cost of main FCV system (FC ¥20k/kW → ¥5k/kW, Hydrogen Storage ¥0.7m → ¥0.3m) 	<ul style="list-style-type: none"> Regulatory reform and developing technology
		HRS 320 by 2025 900 by 2030	2025 <ul style="list-style-type: none"> Construction and operating costs (Construction cost ¥350m → ¥200m, Operating cost ¥34m → ¥15m) Costs of components for HRS (Compressor ¥90m → ¥50m, Accumulator ¥50m → ¥10m) 	<ul style="list-style-type: none"> Consideration for creating nation wide network of HRS Extending hours of operation
		Bus 1,200 by 2030	Early 2020s <ul style="list-style-type: none"> Vehicle cost of FC bus (¥105m → ¥52.5m) 	<ul style="list-style-type: none"> Increasing HRS for FC bus
Supply	Power	Commercialize by 2030	2020 <ul style="list-style-type: none"> Efficiency of hydrogen power generation (26%→27%) ※1MW scale 	<ul style="list-style-type: none"> Developing of high efficiency combustor etc.
	FC	Early realization of grid parity	2025 <ul style="list-style-type: none"> Realization of grid parity in commercial and industrial use 	<ul style="list-style-type: none"> Developing FC cell/stack technology
	Fossil Fuel +CCS	Hydrogen Cost ¥30/Nm3 by 2030 ¥20/Nm3 in future	Early 2020s <ul style="list-style-type: none"> Production: Production cost from brown coal gasification (¥several hundred/Nm3→¥12/Nm3) Storage/Transport : Scale-up of Liquefied hydrogen tank (thousands m³→50,000m³) Higher efficiency of Liquefaction (13.6kWh/kg→6kWh/kg) 	<ul style="list-style-type: none"> Scaling-up and improving efficiency of brown coal gasifier Scaling-up and improving thermal insulation properties
	Green H2	System cost of water electrolysis ¥50,000/kW in future	2030 <ul style="list-style-type: none"> Cost of electrolyzer (¥200,000m/kW→¥50,000/kW) Efficiency of water electrolysis (5kWh/Nm3→4.3kWh/Nm3) 	<ul style="list-style-type: none"> Designated regions for public deployment demonstration tests utilizing the outcomes of the demonstration test in Namie, Fukushima Development of electrolyzer with higher efficiency and durability

※In addition, promote development of guidelines and technology development for expansion of hydrogen use in the field of FC trucks, ships and trains.

Source: METI¹⁷.

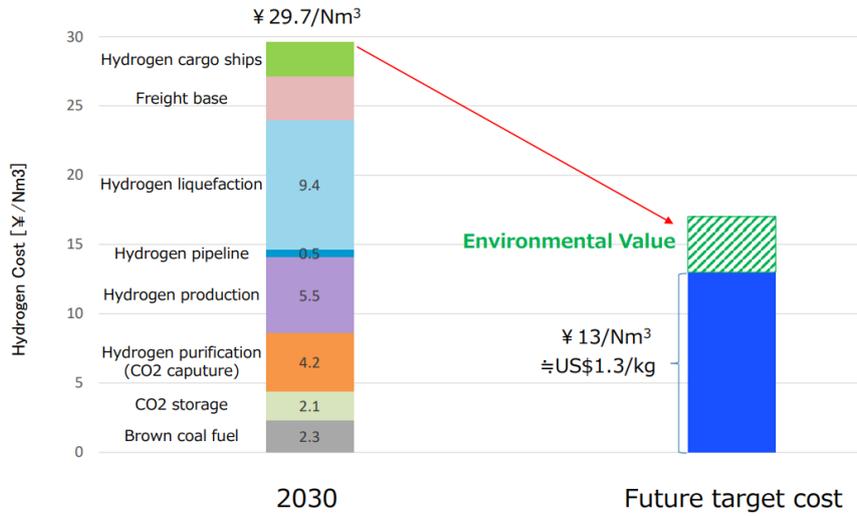
Figure 8: Hydrogen Cost Targets



Source: METI [17].

¹⁷ METI, 12 March 2019: https://www.meti.go.jp/english/press/2019/pdf/0312_002a.pdf.

Figure 9: Hydrogen Cost Perspective of the Supply Project



Source: METI [17].

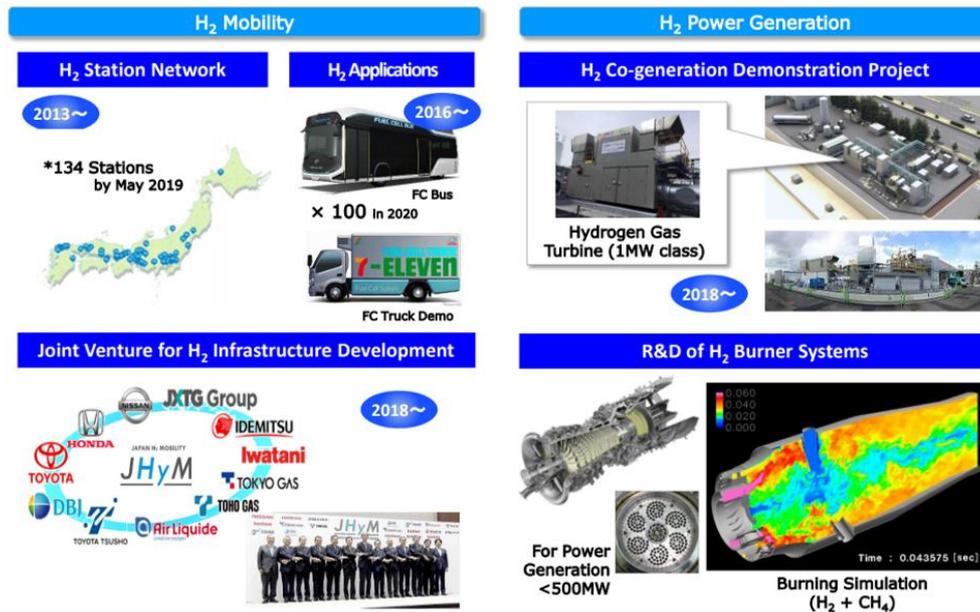
The government awaits the results of several demonstration projects around 2020 to start the operation of hydrogen large-scale infrastructures. Demonstration projects must reveal the deficiencies of the different technologies and allow to focus on the most technical and cost-effective areas, taking into account their applicability in real operating conditions. NEDO is the main player in the development of new technologies (Figure 10 and Figure 11).

Figure 10: Ongoing projects of METI and NEDO (Supply Side)



Source: METI [17].

Figure 11: Ongoing projects of METI and NEDO (Demand Side)



Source: METI [17].

In June 2019, METI and NEDO evaluated the hydrogen and fuel cells R&D projects conducted by NEDO in order to revitalize technology development across industry, academia and government. Based on the issues identified, the Hydrogen and Fuel Cell Strategy Council established the Hydrogen and Fuel Cell Technology Development Strategy in September 2019, which identified ten technological development items in three areas that should be prioritized to achieve the targets set in the Strategic Roadmap for Hydrogen and Fuel Cells¹⁸. They are the following:

- Fuel Cell Technology
 - Automotive fuel cells.
 - Stationary fuel cells.
 - Auxiliary machinery and tank related systems.
- Supply Chain
 - Large-scale hydrogen production.
 - Transportation and storage technology.
 - Hydrogen power generation.
 - Hydrogen stations.
- Water electrolysis and others
 - Water electrolysis technology.
 - Other industrial applications.
 - Discontinuous innovation technology.

¹⁸ METI, 18 September 2019: <https://www.meti.go.jp/press/2019/09/20190918002/20190918002.html> (only in Japanese).

Japan will use the 2020 Olympics and Paralympics as a platform to show the potential of hydrogen and fuel cells, as well as cutting-edge technologies. During this event, FCVs will be used as official vehicles, which will be powered by CO₂-free hydrogen produced in Fukushima (Chapter 3.5.2). Olympic Village will be completely powered by hydrogen fuel cells. Japan aims to involve resource-rich countries by sharing the outcome of several supply chain demonstration projects.

Table 1 shows the hydrogen-related subsidies from METI in the last three fiscal years, with a great growth of the budget for the projects that will create and secure the hydrogen supply chain from overseas resources. Additionally, MOE is supporting the development of regional supply chain with local renewable resources (Chapter 3.4.5), and the “SIP Energy Carriers” program, under the Cabinet Office, has had a budget of around JPY 3 billion per year from FY 2014 to FY 2018 (Chapter 3.4.1). Prefectures and local governments also provide subsidies to the dissemination of residential fuel cells and FCVs.

Table 1: Budget of METI for Hydrogen and Fuel Cells Technologies

Phase	Concept	Budget in JPY Billion		
		FY2016	FY2017	FY2018
Phase 1 (Installation Fuel Cell)	Stationary FCs (Accelerate the introduction and cost reduction of Ene-farm)	9.5	9.36	8.9
	HRSs (Support HRS installation and create FCV demand)	6.2	4.5	5.7
	FCVs	15 (also included other policy items)		
	R&D on FCs (Better performance and lower costs of FCs, and demonstrate stationary FCs for business use)	3.7	3.1	2.9
	R&D on HRSs (Develop technologies for lowering costs and for a safety use of HRS, and collect data for reviewing regulations).	4.15	4.1	2.4
Phase 2 (H ₂ Power Plant / Mass Supply Chain) and Phase 3 (CO ₂ -free Hydrogen)	H₂ Supply Chain (Demonstrate the production of H ₂ from untapped overseas resources, transport it in the form of liquefied H ₂ or organic hydride and use it to generate power. Implement tests on P2G, etc).	2.8	4.7	9.4
	R&D for producing, transporting and storing H₂ derived from renewable energy (Develop technologies on high efficiency water electrolysis units, tanks for storing liquefied H ₂ , etc).	1.55	1.0	0.9
	Construction of a H₂ energy network (Incl. other policy items) (Build a network that effectively connects multiple hydrogen applications in the region)	4.5	-	-

Source: Author, with data from METI and other sources.

On the other hand, and on a global level, Japan calls for global collaboration to lower costs and ensure stable supplies. The Hydrogen Council was launched in January 2017 at the World

Economic Forum and comprises leading energy, transport and industry companies that have teamed up to position hydrogen as one of the key solutions of the energy transition. It has 53 members across 11 different countries.

In October 2018, the first Hydrogen Energy Ministerial Meeting was held in Tokyo by METI and NEDO and with over 300 stakeholders from around the world to talk about the realization of a hydrogen society and future directions of related policies¹⁹. Accordingly, they shared the view that hydrogen can be a key contributor to the energy transition, and the importance of collaboration, information sharing and international joint research among member countries to achieve a hydrogen society, and works towards the harmonization of regulation, codes and standards. Under this mutual recognition, The Tokyo Statement, the chairman's summary of the meeting, was released.

Based on the recommendations from that meeting, a new international hydrogen partnership was announced in May 2019 under the leadership of Canada, the United States, Japan, the Netherlands and the European Commission at the 10th Clean Energy Ministerial²⁰. IEA will coordinate efforts under this Hydrogen Initiative to collaborate on policies, programs and projects to accelerate the commercial deployment of hydrogen and fuel cell technologies across all sectors of the economy. Leading industry stakeholders and collaborative forums such as the Hydrogen Council will contribute to work undertaken through the initiative.

Based also on the results of that meeting, the G20 Ministerial Meeting on Energy Transitions and Global Environment for Sustainable Growth, which was held in Japan in June 2019 under the chairmanship of Japan, held discussions on the importance of the role played by hydrogen to achieve energy transition and de-carbonization. On the sidelines of this meeting, METI, the European Commission Directorate-General for Energy (ENER) and the Department of Energy of the United States (DOE) signed a joint statement to strengthen the cooperation on hydrogen and fuel cell technologies, accelerate and expand the use of hydrogen globally²¹.

The second Hydrogen Energy Ministerial Meeting was held in September 2019. They reaffirmed the view that hydrogen can be a key contributor to clean, safe and affordable energy for the future, and the value of collaborating further to accelerate the progress in hydrogen technologies. They recognized that the next ten years will be critical to enable wider deployment of hydrogen by scaling-up production and use of hydrogen, as well as by bringing down the cost. They set up a non-mandatory goal to produce 10 million hydrogen-powered mobility systems, including vehicles, buses, trucks, trains and ships, and install 10,000 hydrogen refueling stations worldwide within 10 years²².

¹⁹ METI, 23 October 2018: https://www.meti.go.jp/english/press/2018/1023_007.html.

²⁰ Clean Energy Ministerial, 29 May 2019: <http://www.cleanenergyministerial.org/news-clean-energy-ministerial/countries-launch-new-international-effort-hydrogen-help-achieve>.

²¹ METI, 15 June 2019: <https://www.meti.go.jp/press/2019/06/20190615001/20190615001-1.pdf>.

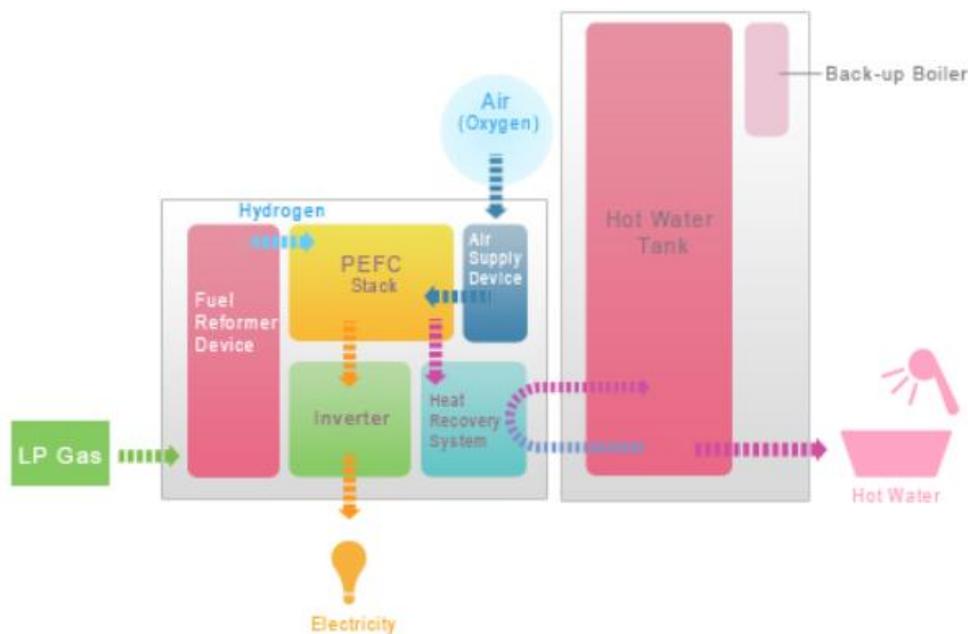
²² METI, 27 September 2019: <https://www.meti.go.jp/press/2019/09/20190927003/20190927003-5.pdf>.

3.1. STATIONARY FUEL CELLS

In order Japan can achieve its GHG emissions target by 2030, it is essential to reduce the emissions from the residential and commercial sectors. In 2030, the government aims to reduce emissions by 39% in the residential sector and by 40% in the commercial sector compared to the emissions in 2013 [18].

Japan’s interest in residential fuel cell dates back to 1999, leading the research and development of this system. Through the Large-scale Stationary Fuel Cell Demonstration Project conducted by NEDO and subsidized by METI from FY2005 to FY2008, close to 3,000 residential fuel cell micro combined heat and power (CHP) systems were installed in Japan. They extract hydrogen from LP gas and combine it together with ambient oxygen to generate electrical power, while simultaneously capturing residual heat that is used to heat up water (Figure 12). In comparison to conventional electrical supply grid systems, it has the capability for a very high-efficiency ratio and significant reduction of CO₂ gas emissions. They got around 23% reduction in primary energy use and 38% reduction in CO₂ emissions, with a high potential to help the country achieve its CO₂ reduction targets with large-scale deployment and to become an important power supply source in case of natural disaster [9].

Figure 12: Operation of a Fuel Cell CHP



Source: Japan LP Gas Association²³.

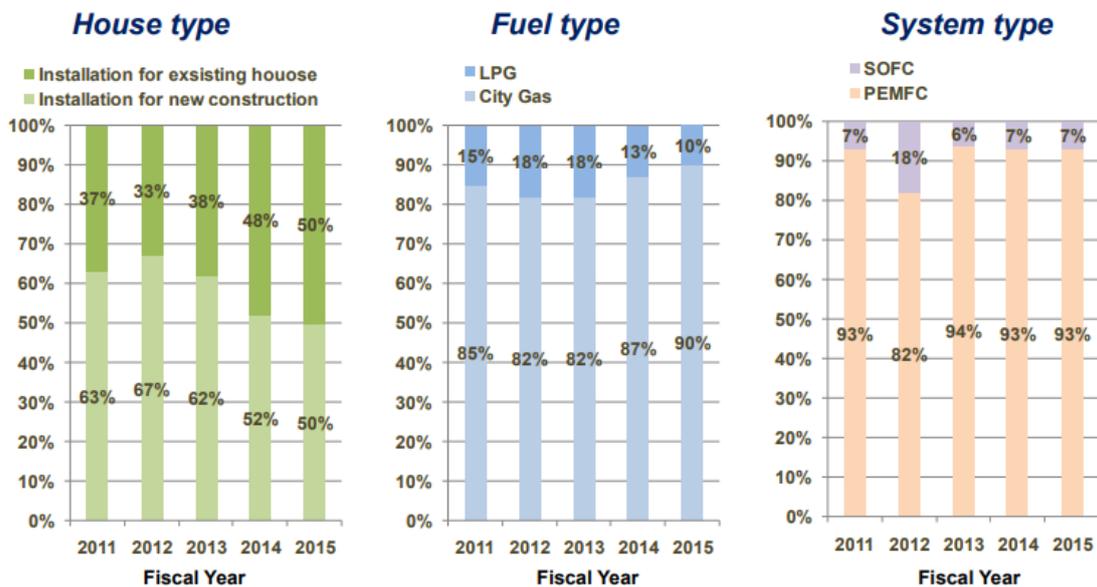
²³ Japan LP Gas Association: <http://www.j-lpgas.gr.jp/en/appliances/>.

Therefore, a consortium of major Japanese energy suppliers and fuel cell manufacturers, such as Panasonic and Toshiba Fuel Cell Power Systems (Toshiba FCP) began the sales of commercial products of the residential fuel cell co-branded as “ENE-FARM” from 2009, with support of governmental subsidies for installation, and leading the world in this sector. Distribution and installation are done by the regional gas suppliers, such as Tokyo Gas and Osaka Gas.

There are several types, but the Polymer Electrolyte Fuel Cell (PEFC), or Polymer Electrolyte Membrane Fuel Cell (PEMFC), from 2009, and the Solid Oxide Fuel Cell (SOFC), from 2011, are the most used ones in Japan, with the first one reaching up more than 90% of cumulative sales (Figure 13).

PEFCs are smaller and lighter because they can start quickly because of low operating temperature and high power output, mainly used for household fuel cell cogeneration systems and FCVs. With an electrical output between 700 W and 1,000 W, the system is not intended to cover the entire demand of an apartment or family house, but to significantly contribute to reducing it, and to fully cover the hot water demand. SOFCs do not need an expensive precious metal medium, such as platinum, due to their reaction easily progresses, whereas the operating temperature could reach 1,000 °C.

Figure 13: Ene-farm Market Trends



Source: Technova and the Fuel Cell Association [9].

Main manufactures of ene-farms in Japan are Panasonic (PEFC), which accounts for more than 50% of the market, about 140,000 units from 270,000 units by June 2018 [19], Aisin Seiki (SOFC) and Toshiba Fuel Cell Power Systems Corporation (PEFC), which stopped manufacture

and sales of ene-farm residential fuel cell systems in July 2017 but continued its pure hydrogen fuel cell system business²⁴. Aisin Seiki's models, between 50 and 700 W, have a rated power generation efficiency of 52% and a total efficiency between 85% and 87%²⁵.

Panasonic's products, with an output from 200 to 700 W, have a combined efficiency of 95%, with 5% of non-usable heat²⁶. Its units provide a reduction of CO₂ emissions of 1.3 ton per year, and an annual saving between JPY 60,000 and 95,000 per year (EUR 500 - 770) on energy bills [19]. Panasonic expects to start the sales of its pure hydrogen fuel cells by 2021, with an output power of 700 W and 5 kW, and power generation efficiencies of 53% and 57% respectively. Panasonic is using ene-farms and other products in two projects to minimize the dependence on the electric grid, increase the energy-saving and reduce CO₂ emissions. These are Fujisawa Sustainable Smart Town from 2014²⁷ and T-Grid from 2017. Ene-farms will become thus in important resources for virtual power plants in Japan [6].

Toshiba Energy System & Solutions (Toshiba ESS) sells a pure hydrogen PEFC system called H₂REX with high efficiency (electric efficiency between 50 and 55%, and total efficiency of 95%), that can start and stop in just a few minutes, facilitating the daily operation. It is available in 700 W for residential applications (ene-farm), 3.5 kW, and 100 kW, and 1 MW is under development²⁸. If no hydrogen is available, Toshiba's H₂One™ system will produce and store its own using renewable energy. Since it is an independent system, it could supply electricity and hot water in times of emergency for evacuation sites to about 300 people for a week. Besides, as a hydrogen local production and consumption system, it also contributes to regional revitalization²⁹. Toshiba started the demonstration operation of H₂One at the Kawasaki Marien public facility and Higashi-Ogishima-Naka Park in the Kawasaki Port area, in Kanagawa Prefecture. Later, it was also installed at Musashi-Mizonokuchi Station on the JR Nambu Line in Kawasaki City, in the Rakuten Kobo Stadium in Sendai, in Tsuruga City in Fukui Prefecture, and in the Tokyu Construction Institute of Technology, Kanagawa Prefecture.

Toshiba ESS installed a pure hydrogen fuel cell system in a new Kawasaki King Skyfront Tokyu REI hotel that helps to meet the energy needs and cogenerated hot water for the bath and shower in each room (Chapter 3.4.5). The hydrogen is provided by Showa Denko K.K. (SDK), a Tokyo-based chemical company that has developed a method of extracting hydrogen gas from recycled used plastic, using the gas as material for ammonia³⁰.

Manufacturers' aim is the standardization of the product and the mass production to reduce the cost. On the other hand, they have continuously improved the performance of their products, making them also more compact. For example, the first generation Panasonic's model in 2009 weighed 125 kg, occupied 3.9 m² and had a durability of 40,000 hours, while its fifth-generation

²⁴ Toshiba, 14 June 2017: https://www.toshiba.co.jp/about/press/2017_06/pr1401.htm.

²⁵ Aisin Seiki: <http://www.aisin.co.jp/cogene/enefarm/products/> (in Japanese).

²⁶ Panasonic: <https://panasonic.biz/appliance/FC/lineup/select.html> (in Japanese).

²⁷ Fujisawa SST: <https://fujisawasst.com/EN/>.

²⁸ Toshiba: <https://www.toshiba-energy.com/en/hydrogen/product/fuel-cell.htm>.

²⁹ Toshiba, 20 April 2015: http://www.toshiba.co.jp/about/press/2015_04/pr2001.htm.

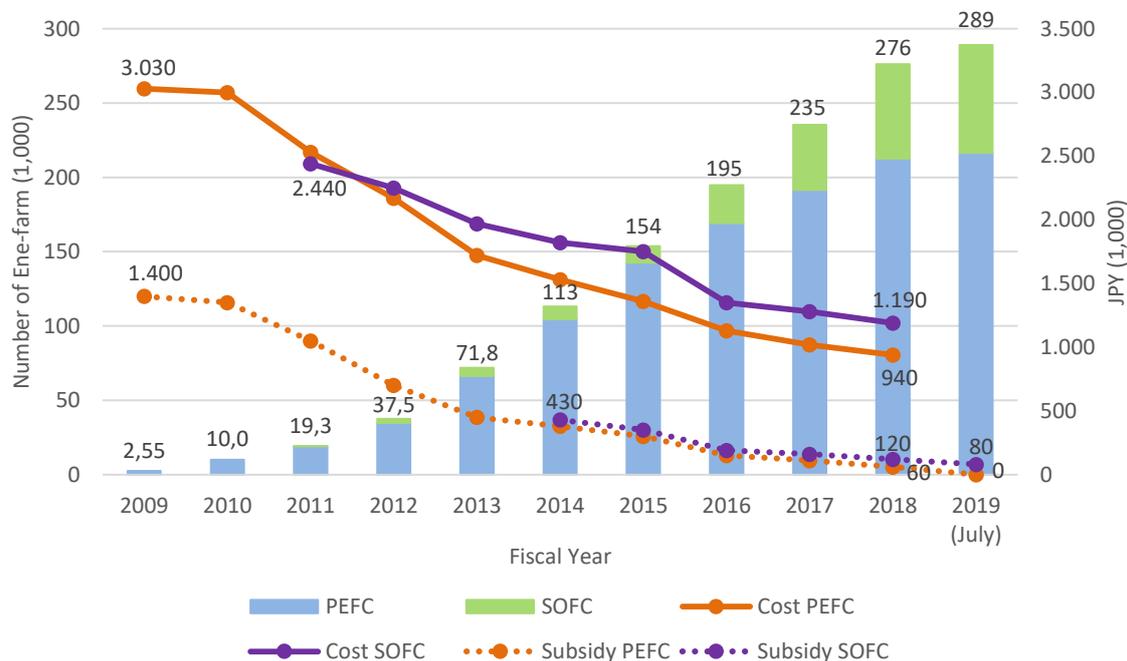
³⁰ Toshiba, 30 May 2018: https://www.toshiba-energy.com/en/info/info2018_0530.htm.

model weighs 65 kg, occupies 1.7 m² and has a durability of 90,000 h, with a cost reduction ratio of 1/4 [19]. The frequency of maintenance has been reduced from once every five years to over ten years, increasing the maintenance’s period, that can be done also by remote, which reduces this cost for the customers.

In March 2018, IHI Corporation, in collaboration with Kyoto University, Toyota Industries, ceramics manufacturer Noritake Co., chemical companies Tokuyama, Nippon Shokubai, and Mitsui Chemicals, announced the successful in the development of a residential SOFC of 1 kW that directly uses ammonia for hydrogen power generation instead of natural gas without requiring a reformer to convert the fuel to hydrogen. The efficiency was comparable to that of residential fuel cells already in use³¹. Based on that result, they aim to increase the size of the system for business and industrial applications. This project is part of the SIP’s Energy Carriers program (Chapter 3.4.1).

The total number of ene-farms deployed (and subsidized) up to July 2019 was 289,125. They are contributing to the energy conservation and emissions reduction in the residential sector, and they could also become into important virtual power plant (VPP) resources [6].

Figure 14: Dissemination of Ene-farms in Japan. Evolution of Costs and Subsidies



Source: Author, with data from METI.

³¹ IHI, 16 May 2018: https://www.ihico.jp/ihico/all_news/2018/technology/2018-5-16/index.html (in Japanese).

As the volume of installations increased, the average unit installation cost dropped 69% for PEFC, from JPY 3.03 million in 2009 to JPY 940,000 in 2018, and 51% for SOFC, from JPY 2.44 million in 2011 to JPY 1.19 million in 2018. Therefore, the subsidy, which was initially set at JPY 1.4 million in 2009 for PEFC and at JPY 430,000 in 2014 for SOFC, was also progressively reduced over time until JPY 60,000 for PEFC and JPY 120,000 for SOFC in 2018. From 2019, there is no fixed subsidy for PEFC since they reached their target price (Figure 14 and Table 2).

Table 2: Number, Costs and Subsidies of Ene-farms in Japan

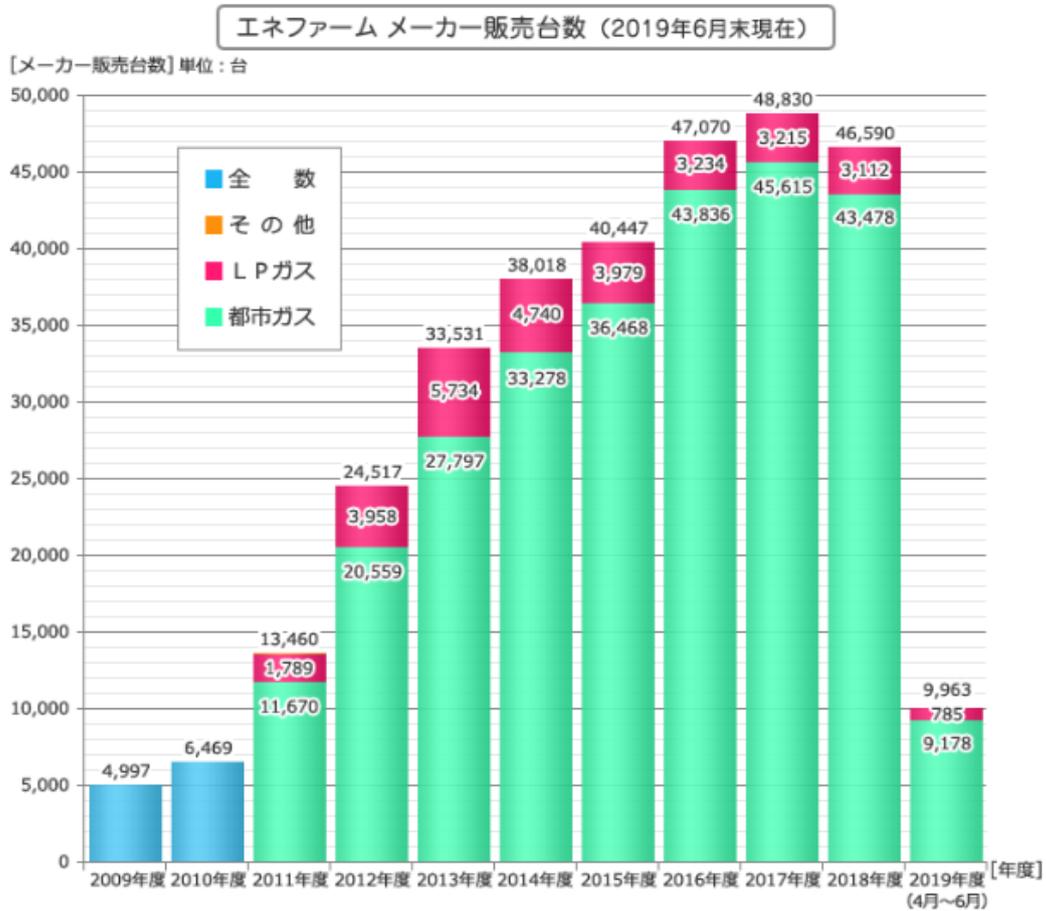
FY	Units				Sale Price (JPY 1,000)		Subsidy (JPY 10,00)	
	PEFC	SOFC	Total	Per Year	PEFC	SOFC	PEFC	SOFC
2009	2,550	0	2,550	2,550	3,030		1,400	
2010	9,998	0	9,998	7,448	3,000		1,350	
2011	18,958	324	19,282	9,284	2,530	2,440	1,050	
2012	34,628	2,897	37,525	18,243	2,170	2,250	700	
2013	66,217	5,588	71,805	34,280	1,720	1,970	450	
2014	104,564	8,471	113,035	41,230	1,530	1,820	380	430
2015	142,494	11,182	153,676	40,641	1,360	1,750	300	350
2016	169,142	25,568	194,710	41,034	1,130	1,350	150	190
2017	191,556	43,720	235,276	40,566	1,020	1,280	110	160
2018	212,519	63,698	276,217	40,941	940	1,190	60	120
2019 (July)	216,460	72,665	289,125	12,908			0	80

Source: Author, with data from METI.

The fiscal year ends in March, which could bring discrepancies with data depending on the source. There is also a slight difference compared to the total units shipped and delivered by manufacturers (Figure 15), which include ene-farms that were installed without subsidies. According to the Advanced Cogeneration and Energy Utilization Center Japan, the number of units shipped and delivered by manufactures was 313,891 by June 2019.

The target is to reach 1.4 million of cumulative sales of ene-farms by 2020, a number that will clearly not be met, and 5.3 million by 2030, equal to around 10% of households, which will reduce the total residential energy demand by 3% and the emissions by 4% compared to the use of gas boilers and grid electricity. Later, it expects these products to replace traditional residential systems. The government aims to lower the price to JPY 800,000 for PEFC (already achieved) and to JPY 1 million for SOFC by 2020 to secure their later autonomous diffusion and achieve a period for recovering the investment of between 7 and 8 by 2020, and of 5 years by 2030. From 2030, the target is to diffuse pure hydrogen fuel cell cogeneration systems using CO₂-free hydrogen.

Figure 15: Ene-farm Manufacturers Sales Volume Annually (only in Japanese)



Source: Advanced Cogeneration and Energy Utilization Center Japan³².

To achieve these targets, Japan encourages technological development to further improve the power generation efficiency for SOFC and the fuel heat utilization factor for PEFC. Japan will also explore other markets such as apartment buildings, cold regions, Europe and other regions out of Japan with high heat demand; expand initiatives to promote the surplus electricity trade; promote the introduction of commercial and industrial fuel cells; and review the regulations for simplifying, for example, the electrical work. From 2030, Japan will attempt to diffuse pure hydrogen fuel cell co-generation systems using CO₂-free hydrogen.

Indeed, major Japanese ene-farm manufacturers started sales overseas through an alliance with boiler manufacturers in Europe, though the devices require an adaptation to manage, for example, the impure substances that the European natural gas has, and some regulatory differences [19]:

³² Advanced Cogeneration and Energy Utilization Center Japan: https://www.ace.or.jp/web/works/works_0090.html (only in Japanese).

- Panasonic: residential FC system jointly-developed with Viessmann, a major heating German company, was released in Germany from April 2004, launching a new model corresponding to wider gas types in April 2016. Under the initiative of ADEME, the French Environment & Energy Management Agency, Engie and Viessmann/Panasonic tested the reliability and usability of FC systems all across France since 2015.
- Toshiba: in the spring of 2014, Toshiba announced the development of residential FC system and marketing alliance with BAXI Innotech GmbH, an affiliated company of BDR Thermea Group, to provide PEFC units in Europe. They started distribution in Korea in March 2015.
- Aisi Seiki: Provided residential SOFC for Bosch in Germany as part of the Enefield Project³³.

Commercialization of cogeneration systems for industry and building use also started in 2017, where SOFC occupies the majority of the market, and which it is expected to greatly contribute with the energy conservation and CO₂ emissions reduction targets in the commercial and industrial sectors. The government aims to have 1 GW of these larger systems by 2030.

As examples, Hitachi Zosen Corporation is conducting a NEDO's demonstration test to evaluate the safety and reliability of the SOFC power system for commercial and industrial use through at least 4,000 hours of continuous operation. It installed the system in two locations in Osaka. This demonstration test is part of Hitachi Zosen Corporation's efforts as a participant in the "H2Osaka Vision Promotion Conference", which is a joint effort between Osaka Prefecture and Osaka City that aims to create advanced hydrogen projects³⁴. Hitachi Zosen had previously signed a business development agreement with the Finish Wärtsilä in March 2010 to develop and market fuel cell-based power plant solutions for distributed power generation applications in Japan. The combined heat and power applications, which can be run on either city gas or biogas, feature the use of Wärtsilä's SOFC technology³⁵.

In October 2017, Miura Co., Ltd. started the sales of a 4.2 kW SOFC cogeneration system for commercial use which achieved 48% electrical efficiency and 90% overall energy efficiency, and which was developed based on the results of a NEDO project³⁶ (Figure 16). In June 2019, it announced the market launch of the new version with a higher electrical efficiency of 50% and developed in partnership with the English Ceres Power. This unit will operate on mains gas supply³⁷.

³³ Enefield Project was a promoting program to disseminate micro FC for CHP by installing about 1,000 units into houses in 11 participating European countries on a trial basis and validating its usefulness and economic efficiency from 2012 to 2017.

³⁴ NEDO, 29 March 2017: https://www.nedo.go.jp/english/news/AA5en_100200.html.

³⁵ Wärtsilä, 2 March 2010: <https://www.wartsila.com/media/news/02-03-2010-wartsila-and-hitachi-zosen-sign-agreement-to-develop-and-market-fuel-cell-based-power-plant-solutions-in-japan>.

³⁶ NEDO, 7 August 2017: https://www.nedo.go.jp/english/news/AA5en_100255.html.

³⁷ Ceres Power, 20 June 2019: <https://www.cerespower.com/news/latest-news/miura-to-launch-new-chp-fuel-cell-product-for-the-commercial-building-sector-in-japan/>.

In June 2014, Mitsubishi Hitachi Power Systems, Ltd. (MHPS) and NGK Spark Plug Co., LTD. (NGK), a manufacturer primarily of ceramic products, signed an agreement on a business tie-up creating SOLIDIA and targeting cost-competitive mass production of cylindrical cell stacks, power-generating elements used in SOFC³⁸. Later, in September 2016 and under a NEDO program, MHPS started demonstration testing of a pressurized hybrid power generation system integrating a SOFC stack and a micro gas turbine that generates power and makes effective use of waste heat. The 250 kW system was installed in Tokyo Gas Co., Ltd. Senju Techno Station, in Kyushu University Ito Campus, in a factory of Toyota Motor Corporation, which is jointly developing the hybrid system, in a plant of NGK, and in a facility of Taisei Corporation. At the various venues, demonstration testing will focus on the operating efficiency, operability and durability in diverse environments³⁹. A new 1,000 kW class unit is under consideration.

Figure 16: Examples of Fuel Cell for Commercial and Industrial Application

Manufacturer	Denso	Miura	Fuji Electric	Hitachi Zosen	Mitsubishi Hitachi Power Systems (MHPS)	(Reference) Bloom Energy
	Demonstration model					Business model
Appearance						
Output	5 kW	5 kW	20 kW	50 kW	250 kW	200 kW
Type	Cogeneration (under consideration)	Cogeneration	Cogeneration (under consideration)	Cogeneration	Cogeneration	Mono-generation
Electrical generation efficiency (target value)	50 %	50 %	50 %	50 %	55 %	50 - 60 % (Actual performance)
Total efficiency (target value)	(under consideration)	90 %	(under consideration)	80 %	73% (hot water) 65% (steam)	-
Major envisioned demand	Barbers and hair salons, small stores, family restaurants		Gym, welfare facilities, hospitals, small buildings		Data centers, large buildings, and hotels	

Source: Technova [20].

Toshiba has also developed solutions for larger-scale applications, such as the Alkaline Water Electrolysis Hydrogen Production System (AEC), which is cheaper than other methods because does not contain noble metals and can operate in cold regions, and a next-generation water electrolyzer called Solid Oxide Electrolysis Cell (SOEC) for producing large quantities of high-quality hydrogen, with a 30% higher efficiency and lower power consumption than conventional PEFC. Its hydrogen energy storage systems, H2Omega™, employs SOFC and SOEC and can supply 10,000 households with electricity for eight hours with its 5 MW of grid power and 32 MWh of storage capacity⁴⁰.

³⁸ MHPS, 20 June 2014: <https://www.mhps.com/news/20140620.html>.

³⁹ MPHS, 21 September 2016: <https://www.mhps.com/news/20160921.html>.

⁴⁰ Toshiba: <https://www.toshiba-energy.com/en/hydrogen/rd/index.htm>.

In March 2019, four companies in the Morimura Group (Noritake, Toto, NGK Insulators and NGK Spark Plug) concluded an MoU regarding the establishment of a joint venture for accelerating the commercialization of SOFC in Japan⁴¹.

In September 2019, Toyota developed a stationary fuel cell generator based on the Mirai FC system. It installed the generator at its Honsha Plant in Toyota City, Aichi Prefecture, with the aim of verifying its applicability in offices, plants, and other commercial scenarios⁴².

The Basic Hydrogen Strategy calls for improving the efficiency and durability of this commercial and industrial systems, achieving an efficiency over 55% by 2025 and over 65% in the future, and a durability from 90,000 hours to 130,000 hours by 2025. It aims to realize of grid-parity in these sectors combining the utilization of exhaust heat by 2025 by developing of fuel cell stack technologies for getting higher efficiencies and power densities, and for eliminating the cause of degradation. For low voltage, the target is capital expenditures (CAPEX) of JPY 500,000 per kW and a power generation cost of JPY 25 per kWh, while for high voltage, it expects a CAPEX of JPY 300,000 per kW and a power generation cost of JPY 17 per kWh [9].

Regarding subsidies, the original plan of the government was to provide subsidies for five years, which were extended later up to ten years. However, since ene-farms contribute to reducing the energy consumption, it is one of the technologies that can get subsidies from the ZEH program, which is a hot topic in Japan [6]. The minimum subsidy for ZEH is JPY 700,000 (around EUR 5,600) in FY 2019, and it is available from different ministries and local governments.

From FY 2016, the government established an incentive program that depends on the difference between the base price of the product and the target price, which is the level at which self-sustaining dissemination can be achieved, set at JPY 800,000 for PEFC and JPY 1 million for SOFC. The fixed amount of subsidy paid is about 1/3 of that difference. Because the base price is reduced year by year, the fixed subsidy also decreases. In the FY 2019 incentive program, subsidies vary according to the reference and upper-limit prices shown in Table 3⁴³:

Therefore, the subsidy amount for SOFC is JPY 80,000 (JPY 120,000 in FY 2018) when the total cost, including equipment and installation that has to be differentiated, is below the reference price. If the cost exceeds the base price but is below the ceiling price, the subsidy will be the half, JPY 40,000. This means that customers are incentivized with higher subsidies to purchase cheaper systems in order to increase cost competitiveness. There is no fixed subsidy for PEFC (JPY 60,000 in FY 2018) since the base price already got the target price set by the government.

⁴¹ NGK Insulators, 4 March 2019: https://www.ngk-insulators.com/en/news/asset/20190304_1E.pdf.

⁴² Toyota, 18 September 2019: <https://global.toyota/en/newsroom/corporate/29246629.html>.

⁴³ Fuel Cell Association: <http://www.fca-enefarm.org/subsidy31/outline/page05.html>.

Table 3: Subsidies for Ene-farms in FY 2019

- PEFC base price: JPY 800,000
- PEFC ceiling price: JPY 960,000
- SOFC base price: JPY 1,230,000
- SOFC ceiling price: JPY 1,340,000

	If the price is below the base	If the price is below the ceiling	If the price is above the ceiling
PEFC	no fixed amount		none
SOFC	JPY 80,000 (EUR 650)	JPY 40,000 (EUR 325)	none

Source: Author, with data from the Fuel Cell Association.

In addition, there are additional incentives of JPY 30,000 for units, both PEFC and SOFC, installed in already built buildings, in apartments buildings, in regions classified as cold, and if the fuel is LP gas. And the base and upper-limit prices may shift depending on the system configuration shown in Table 4.

Table 4: System Configuration of Ene-farms and Limit's Increment

Parameter		Increment (JPY)
Specification for cold regions		+ 300,000
Equipment for independent operation	Type A: integrated	+ 50,000
	Type B: not integrated	+ 40,000
Residential building (a steel frame reinforced concrete structure, divided into dwelling units independently occupied)		+ 120,000
Small or medium-size gas supplier (classified as SMEs)		+ 100,000
Fuel used	LPG	+ 120,000
	Domestic natural gas	+ 60,000
Use of an existing water heater as a backup water heater	PEFC	- 270,000
	SOFC	- 300,000

Source: Author, with data from the Fuel Cell Association.

The total budget from the government for accelerating the dissemination and cost reduction of ene-farm, including the support for its business and industrial use from FY 2017, was JPY 8.9 billion in FY 2018, reduced from JPY 9.36 billion the previous year (Table 1).

Additionally, some regional/local governments also offer subsidies for the installation of Ene-farms⁴⁴. For example, TMG offers 1/5 of the equipment cost, with an upper limit of JPY 100,000 for detached houses and JPY 150,000 JPY for apartment complexes, Sapporo City (Hokkaido Island) offers JPY 150,000 for houses, and Fukuoka City (Kyushu Island) offers JPY 50,000.

⁴⁴ Kankyo-business: <https://www.kankyo-business.jp/subsidy/enefarm/> (only in Japanese).

3.2. MOBILITY

The transportation sector contributed 19% to entire CO₂ emissions in Japan in 2015, with vehicles (passenger cars and trucks) accounting for 85% of those. The government target is to reduce it 25% by 2030 increasing the popularization of the next-generation vehicles and reaching a share in the new car sales between 50% and 70% by 2030 (Table 5). Expecting to effectively reduce CO₂ emissions and bringing new value, including contributions to disaster response, METI published the Road Map for EVs and PHVs toward the Dissemination of Electric Vehicles and Plug-in Hybrid Vehicles in March 2016⁴⁵.

Table 5: Next-generation Vehicles Target in 2030

Year	2017	2030
Conventional cars	63.97%	30 - 50%
Next generation cars	36.02%	50 - 70%
Hybrid Electric Vehicles (HEV)	31.2%	30 - 40%
Battery Electric Vehicles (BEV)	0.41%	20 - 30%
Plug-in Hybrid Electric Vehicles (PHV)	0.82%	
Fuel Cell Vehicle (FCV)	0.02%	3%
Clean Diesel Vehicle (CDV)	3.52%	5 - 10%

Source: Author, with data from METI [21].

The government set the target to increase the number of BEVs and PHVs to up to one million by 2020, though, according to the Japan Automobile Manufacturers Association (JAMA), there were only around 255,000 units at the end of 2018 (Table 6), so it looks difficult that Japan meets that target, in contrast to the target for HEV that has already been achieved successfully. Bloomberg's estimation is that EVs will make up 17% of all new vehicle sales in Japan by 2030. Therefore, at this stage, policy support from the government is still indispensable in Japan.

As an active member of Electric Vehicles Initiative (EVI), a multi-governmental policy forum dedicated to accelerating the deployment of EV worldwide, and because of the Government Fleet Declaration announced at the Marrakech Climate Change Conference in November 2016 [23], the Japanese government is making efforts to ensure that all government vehicles will be next-generation vehicles by 2030. As an intermediate goal, approximately 40% of the government vehicle fleet, around 9,000 units, will be next-generation vehicles by 2020, which will contribute to Japan's one million target by 2020.

⁴⁵ METI, March 23, 2016: http://www.meti.go.jp/english/press/2016/0323_01.html.

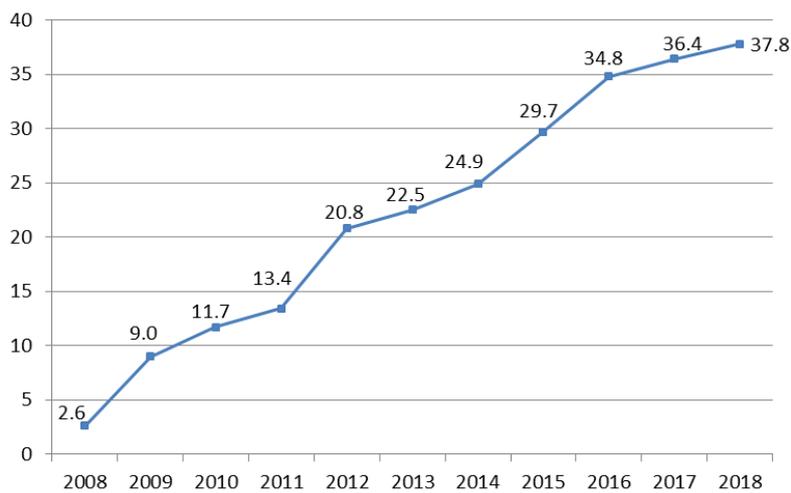
Table 6: Next-generation Passenger Car New Registrations

Year	HEV	PHV	BEV	FCV	CDV	Total
2008	108,518	0	0	0	0	108,518
2009	347,999	0	1,078	0	4,364	353,441
2010	481,221	0	2,442	0	8,927	492,590
2011	451,308	15	12,607	0	8,797	472,727
2012	887,863	10,968	13,469	0	40,201	952,501
2013	921,045	14,122	14,756	0	75,430	1,025,353
2014	1,058,402	16,178	16,110	7	78,822	1,169,519
2015	1,074,926	14,188	10,467	411	153,768	1,253,760
2016	1,275,560	9,390	15,299	1,054	143,468	1,444,771
2017	1,385,343	36,004	18,092	849	154,803	1,595,091
2018	1,431,980	23,230	26,533	612	176,725	1,659,080
Total	9,424,165	124,095	130,853	2,933	845,305	10,527,351

Source: Author, with data from JAMA [22].

Figure 17 shows the share of next-generation vehicles in new passenger car registration in Japan from 2008 to 2018.

Figure 17: Share of Next-generation Vehicles in New Passenger Car Registration (in %)



Source: Author, with data from JAMA [22].

In April 2018, a Strategic Commission for the New Era of Automobiles was launched by METI and has been studying the strategies that the Japanese automobile industry should take to lead global innovations and proactively contribute to solutions to global issues including climate change. In August 2018, METI released a report with the conclusions, setting long-term goals such as having all new passenger cars be electric by 2050 and reducing GHG emissions of a single passenger vehicle by 90% by 2050. Realize a “Well-to-Wheel Zero Emission” policy to reduce vehicles’ total emissions footprint to zero, from fuel and power production to automobile operation, is also a target. It established policies and key actions to achieve these goals⁴⁶.

In April 2019, METI, in collaboration with 38 organizations including car manufacturers, energy companies, municipalities and other entities proactively engaging in efforts for utilizing of next-generation vehicles and willing to share information on current situations of their own efforts and challenges, decided to launch a new body called the “Council for Promoting Society Utilizing of Electrified Vehicles” to advance dissemination of these vehicles⁴⁷.

There is also a growing expectation in Japanese society about the function of BEVs, PHVs and FCVs to supply electricity not only in case of disasters but also as important resources of the energy system through the Vehicle-to-Grid (V2G) connection [6].

3.2.1. Fuel Cell Vehicles

Compared to BEVs, the deployment of FCVs is being slower because they are more difficult to produce, they are much expensive, and there are not enough refueling stations. However, hydrogen features more energy density than lithium-ion batteries, what makes FCVs better than other zero-emission vehicles for long-range transportation, especially useful for heavy goods trucks and buses because they are very hard to electrify with batteries. FCVs can also be recharged in just some minutes. Therefore, their usability is comparable to that of gasoline-powered vehicles, which represents a high advantage compare to electric vehicles.

Globally, FCVs’ stock exceeded 12,900 units as of end 2018, showing an 80% increase compared to the previous year. The US, mainly California, had the largest fleet with 5,899 units, following by Japan and China, with 2,933 and 1,791 units respectively⁴⁸ (Figure 18).

The Strategic Road Map for Hydrogen and Fuel Cells, including the deployment of FCVs, was published in March 2016, establishing a target of 40,000 FCVs by 2020, 200,000 by 2025 and 800,000 by 2030. Regarding the infrastructure, it included the installation of 160 refueling

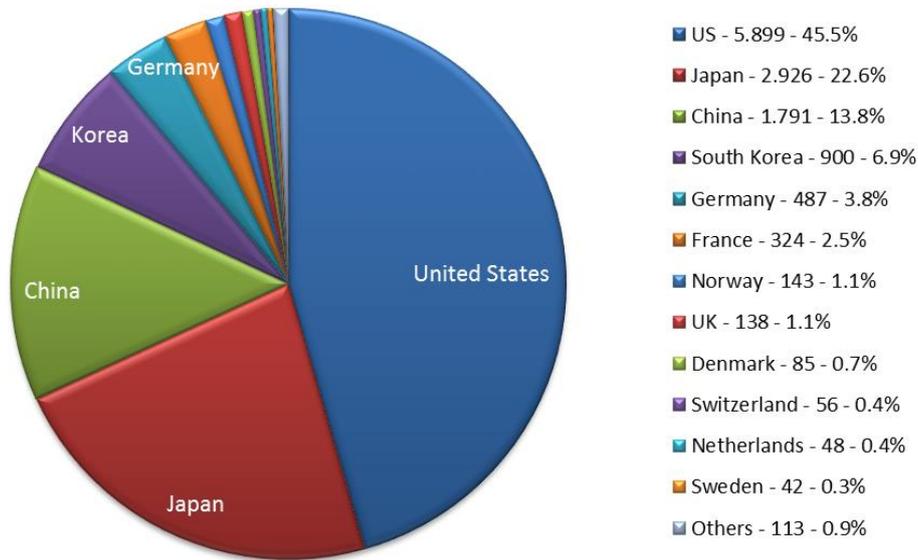
⁴⁶ METI, August 31, 2018: http://www.meti.go.jp/english/press/2018/0831_003.html.

⁴⁷ METI, 8 April 2019: https://www.meti.go.jp/english/press/2019/0408_006.html.

⁴⁸ IEA AFC TCP, 26 April 2019: http://www.ieafuelcell.com/fileadmin/publications/2019-04_AFC_TCP_survey_status_FCEV_2018.pdf

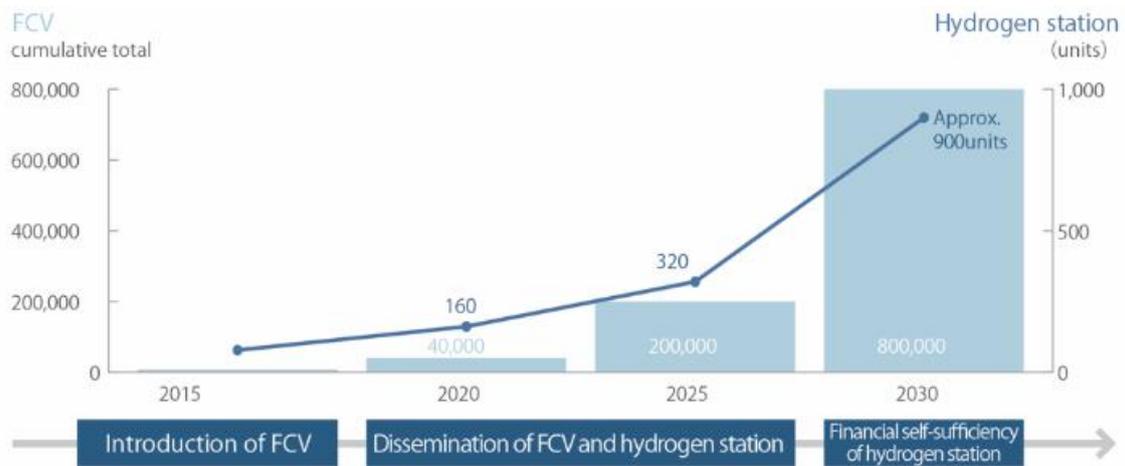
stations by 2020, 320 by 2025 and around 900 stations by 2030, making them financially independent by the second half of the 2020s (Figure 19).

Figure 18: Stock of FCEV as of end 2018



Source: Author, with data from the IEA Technology Collaboration Programme, Advanced fuel Cells.

Figure 19: Targets for the Dissemination of FCVs and HRS in Japan



Source: Japan Hydrogen Station Network Joint Company or Japan H2 Mobility (JHyM)⁴⁹.

⁴⁹ JyHM: <https://www.jhym.co.jp/en/nav-about/>.

According to The Association of Hydrogen Supply and Utilization Technology (HySUT), the number of FCEVs in Japan has grown until 3,433 as of the end of August 2019 [24], so it is clear that the government's target by 2020 will not be met. The Japanese market is comprised entirely of Japanese auto manufacturers, with 3,182 Toyota Mirai and 251 Honda Clarity.

Toyota Motor Corporation leads the Japanese mobility hydrogen market, releasing the first fuel cell vehicle, forklift and bus in Japan. In 2015, it allowed the royalty-free use of around 5,680 patent licenses during five years regarding fuel stacks, hydrogen tanks and fueling infrastructure to stimulate the development of low-cost technology among domestic and international manufacturers.

Toyota started sales of its Mirai ("future" in Japanese) fuel cell sedan model in December 2014. It uses the Toyota Fuel Cell System (TFCS), which combines hybrid technology with fuel cell technology and it is composed of Toyota FC stacks and two high-pressure (70 MPa) hydrogen tanks with a total volume of 122.4 litres, which can be recharged in just three minutes. They provide a travel range of about 650 km on one charge⁵⁰, around 500 km under real conditions according to the American EPA⁵¹. The TFCS is more energy-efficient than internal combustion engines and does not emit CO₂ or other substances of concern (SOCs) when driven. However, its main disadvantages are its price, JPY 7.24 million including taxes (EUR 58,900) minus the government's subsidy of JPY 2.02 million for environmentally friendly cars, and the lack of refueling stations.

Toyota and BMW have been cooperating on fuel cell technology since 2013. Under this partnership, BMW is developing a way to compress hydrogen at ultra-low temperatures to increase its storage volume, using as a base a fuel cell stack developed by Toyota. BMW expects to have its own fuel cell model sometime after 2020⁵².

Toyota aims to increase its annual sales of FCVs globally from around 3,000 units in 2017 to 30,000 units. In the Japanese market, it wants to reach sales of at least 1,000 units per month and about 10,000 units annually from 2020⁵³. To prepare for this growth, the company is building two new facilities, one for expanding fuel cell stack mass production, and a new line in an existing plant to manufacture high-pressure hydrogen tanks. Manufacturing both components at scale is critical to achieving lower system costs and wider availability.

The other available model in Japan is the Honda Clarity Fuel Cell, which was launched in March 2016⁵⁴, and has a travel range of around 750 km (580 km under real conditions according to the American EPA) and a price of JPY 7.66 million (EUR 62,300). At the moment, this

⁵⁰ Toyota, 18 November 2014: <https://global.toyota/en/detail/4198334>.

⁵¹ Fueleconomy – US EPA: https://www.fueleconomy.gov/feg/fcv_sbs.shtml.

⁵² Reuters, 29 October 2015: <https://www.reuters.com/article/autoshow-japan-bmw/bmw-plans-to-market-sedan-fuel-cell-vehicle-after-2020-idUSL3N12T3TN20151029>.

⁵³ Toyota, 24 May 2018: https://global.toyota/en/newsroom/corporate/22647198.html?_ga=2.201033063.85894042.1557724027-1278002982.1557724027

⁵⁴ Honda, 10 March 2016: <https://global.honda/newsroom/news/2016/4160310eng.html>.

model is available only for corporate lease for around JPY 100,000 per month, and if they are leased for a minimum of 4 years, they are also eligible for the same national and prefectural subsidies calculated on a monthly basis [25].

Honda Motor Co. began leasing of the Honda FCX in 2002 in the US and Japan, including its successor, the FCX Clarity. In July 2013, Honda and General Motors (GM) announced a long-term, agreement to co-develop next-generation fuel cell system and hydrogen storage technologies, aiming for the 2020 time frame. The collaboration expects to succeed by sharing expertise, economies of scale and common sourcing strategies⁵⁵.

Finally, Nissan Motor Co., Ltd. signed a three-way agreement with Daimler AG and Ford Motor Company in January 2013 for the joint development of a common fuel cell system to speed up the availability of the zero-emission technology and significantly reduce investment costs⁵⁶. It also signed a partnership with the English Ceres Power, a fuel cell technology and engineering company, and The Welding Institute to further develop fuel cell technology for EV application in the UK⁵⁷.

In addition to the national subsidy of JPY 2.02 million provided by METI, each prefecture also offers a subsidy of up to half the national one, depending on its budget. For example, the Tokyo Metropolitan Government (TMG) offers the full JPY 1.01 million subsidy for all FCVs, reducing the cost of a Toyota Mirai to around JPY 4.21 million (EUR 34,200). Subsidies are slightly higher for taxi operators, with a national subsidy between JPY 2.23 and 2.36 million provided by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), and local subsidies between JPY 1.11 and 1.18 million, bringing the cost of the Mirai to between JPY 3.9 and 3.7 million [25].

In June 2019, TGM started an open call for car sharing and rental car businesses operators with EVs and FCVs, subsidizing part of the operation costs. Those options are expanding in recent years as an easy way of using cars in Tokyo. This measure will help TMG to achieve its target of 50% of zero-emissions vehicles (ZEV) in new passenger car sales by 2030. The name of the project is “ZEV introduction in car rental and car sharing promotion business”, and it is planned for 100 units, 60 EVs and 40 FCVs⁵⁸.

In terms of fuel cost, a kilogram of hydrogen costs between JPY 1,000 and 1,200 (EUR 8.13 and 9.76). For example, in the centre of Tokyo, besides the famous Tokyo Tower, there is a hydrogen refueling station (HRS) owned by Iwatani with a fixed price of JPY 1,100 per kilogram. One kilogram of hydrogen has approximately the same energy as one gallon of

⁵⁵ Honda: <https://www.hondanews.ca/en/news/release/GM-Honda-to-Collaborate-on-NextGeneration-Fuel-Cell-Technologies>

⁵⁶ Renault Nissan Mitsubishi, 28 January 2013: <https://www.alliance-2022.com/news/the-strategic-cooperation-between-daimler-and-the-renault-nissan-alliance-forms-agreement-with-ford-to-accelerate-commercialization-of-fuel-cell-electric-vehicle-technology-2/>.

⁵⁷ Ceres Power: <https://www.cerespower.com/news/latest-news/ceres-wins-7m-uk-funding-to-support-electric-vehicle-application-with-nissan/>.

⁵⁸ TMG, 19 June 2019: <http://www.metro.tokyo.jp/tosei/hodohappyo/press/2019/06/19/12.html>.

gasoline. Because FCVs are two or three times as efficient as a gasoline vehicle, they do not need as much fuel⁵⁹. Given that Toyota Mirai holds approximately 5 kilograms of hydrogen, a full tank costs between JPY 5,000 and 6,000 (EUR 40.6 – 48.8), a similar price or even lower than a gasoline vehicle tank, taking account an average cost per litre around JPY 140 in Japan (EUR 1.14).

It is obvious that the expansion of the FCVs will need a notable reduction in its price. The government aims to achieve a cost similar than HEVs by around 2025, reducing the price difference from the current JPY 3 million to JPY 700,000. It has targets for reducing the cost of the main components, such as the cost of the fuel cell system from around JPY 20 k/kW to JPY 5 k/kW, and the cost of the hydrogen storage system from around JPY 700,000 to JPY 300,000 [9].

This effort will need cooperation among stakeholders, developing technologies for reducing the amount of platinum used, and the amount of carbon fibre used in the hydrogen storage system. NEDO is developing technologies for reducing the amount of platinum in the electrode catalyst and increasing the performance of the membrane electrode assembly used in the fuel cells. Toyota is also working on an alternative platinum catalyst. It expects to cut platinum by two-thirds in its next Mirai's version to around 10 grams per vehicle, down from 30 grams in the current model. This area also represents an opportunity for European stakeholders. For example, Bosch signed a deal with Powercell Sweden AB to mass-produce fuel cells using only as much platinum as a diesel catalytic converter, which typically uses three to seven grams⁶⁰.

Purchases of next-generation cars are also encouraged through taxation and subsidies. In Japan, three kinds of taxes are imposed on vehicles: the acquisition tax imposed at the time of new or used vehicle purchase, the automobile tonnage tax imposed according to the weight of the vehicle at new registration and at every vehicle inspection, and the consumption tax, imposed on the owner every year. New next-generation vehicles including FCVs are exempt of the acquisition and tonnage (initial and first inspections) taxes, both called as the “eco-car tax reduction”. The acquisition tax will be abolished effective from October 1, 2019, in tandem with the scheduled rate increase to 10% in the consumption tax.

Additionally, Figure 20 shows how to calculate the subsidy for the purchase of a clean energy vehicle depending on the type.

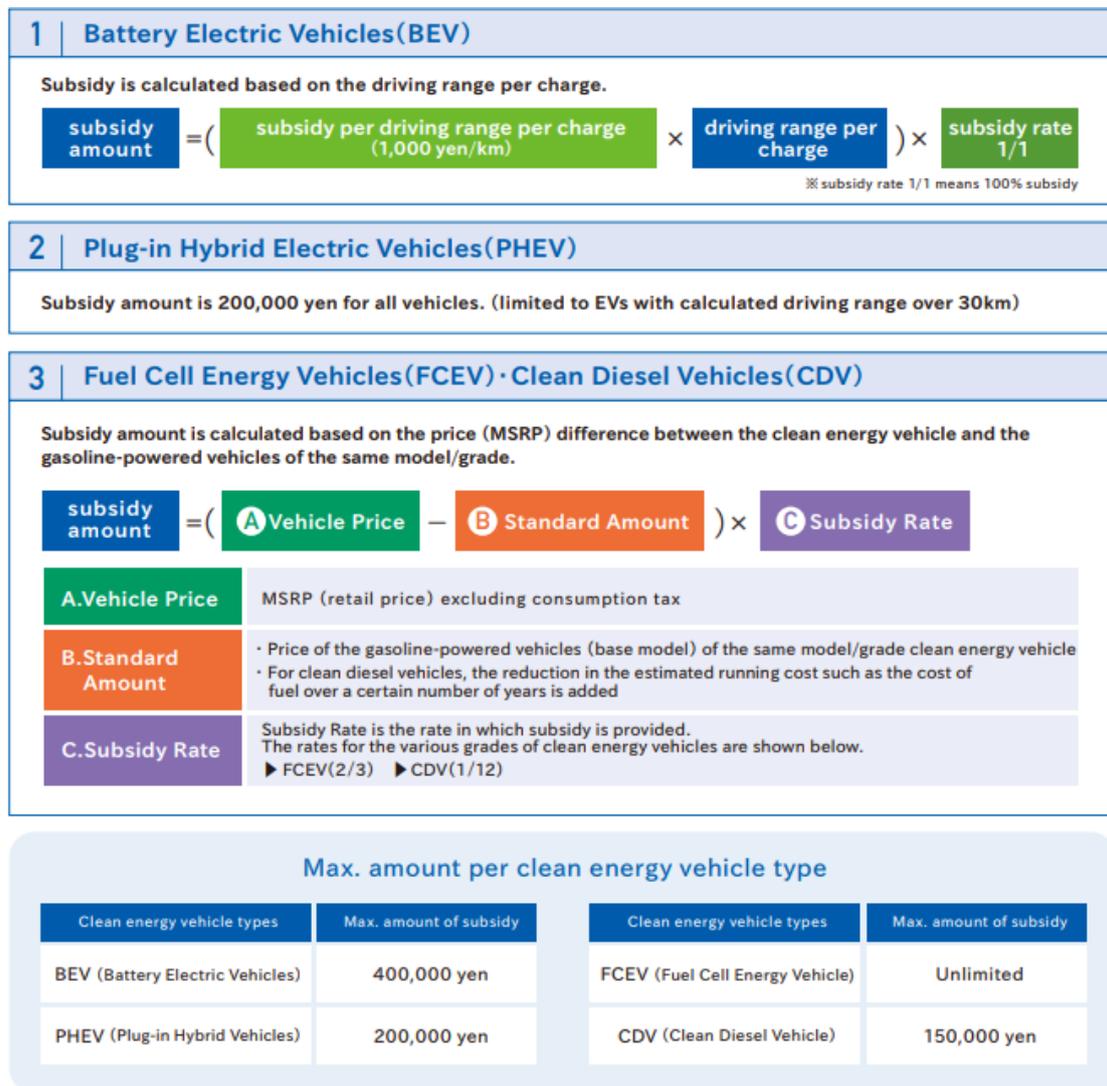
Toyota also introduced the first two fuel cell forklifts in 2017 at its Motomachi plant, Aichi Prefecture, followed by an additional twenty in 2018 and fifty in 2019, and with a target of 170 or 180 units by around 2020. The Japanese government aims to increase the number of FC forklifts to around 500 by 2020 and to around 10,000 by 2030, expanding this technology to overseas markets. There were 160 units by June 2019.

⁵⁹ Mirai Fueling: https://ssl.toyota.com/mirai/Mirai_Fueling.pdf.

⁶⁰ Reuters, 13 May 2019: <https://www.reuters.com/article/us-platinum-week-bosch-fuelcells-exclusi/exclusive-bosch-goes-for-platinum-light-fuel-cells-idUSKCN1SJ0FG>.

Toyota started the sales of its fuel cell bus, developed in collaboration with its bus and truck subsidiary Hino Motors, to TMG in February 2017, and introduced the final version, the Sora FC bus (Sky, Ocean, River, Air, representing the earth’s water cycle) in March 2018⁶¹. It aims to deliver over 100 units ahead of the Tokyo 2020 Olympic and Paralympic Games. It has a capacity for 79 people, and 10 tanks with a nominal working pressure of 70 MPa carrying 600 litres of hydrogen, which provide a travel range of around 200 km. There were 18 FC-buses by June 2019.

Figure 20: How to Calculate the Subsidy for the Purchase of Clean Energy Vehicles in 2018



Source: Nex Generation Vehicle Promotion Center (NeV)⁶².

⁶¹ Toyota, 28 March 2018: <https://global.toyota/en/newsroom/corporate/21863761.html>.

⁶² NeV: <http://www.cev-pc.or.jp/english/cev-subsidy.html>.

With an external power feeding system of 9 kW / 235 kWh, this bus has also potential use as an emergency power source following disasters, covering 4.5 days of power supply for an evacuation centre. Figure 21 shows a comparison of the power supply capacity that fuel cells buses and vehicles, and electric vehicles have for disaster response facilities in Japan, which are hospitals, convenience stores and evacuation shelters (schools).

The bus costs around JPY 105 million (about EUR 854,000), though the subsidies from MoE JPY 35 million, one third of the cost, and from local governments, expected between JPY 35 and 50 million, would eventually reduce the price to between JPY 20 and 35 million (EUR 163,000 and 285,000) [25]. The targets of the government are to reduce that cost of JPY 105 million by half in the early 2020s, have 1,200 FC buses on the road by 2030, and expand the regions where they run. To achieve this, it promotes the deployment of refueling stations for FC buses, the development of new technology that enhances fuel efficiency and durability, and the expansion of types other than city buses.

Figure 21: Fuel Cell Vehicles and Buses as Emergency Power Source

Facility	Ordinary Power Consumption	Emergency Power Consumption	FC Buses needed for emergency (455 kWh/day)	FCVs needed for emergency (120 kWh/day)	EVs needed for emergency (24 kWh/day)
Hospital	9,628 kWh/day	963 kWh/day (10% capacity: emergency equipment only)	2 buses 	8 FCVs 	40 EVs 
24/7 h Convenience Store	500 kWh/day	235 kWh/day (47% capacity: refrigeration only)	0.5 buses 	2 FCVs 	10 EVs 
Evacuation Shelter (School)	-	100 kWh/day (lighting, hot water for 200 people)	0.22 buses 	0.83 FCVs 	4 EVs 

Source: Author, with data from METI⁶³.

TGM plans to have 6,000 FCVs, 100 FC buses and 35 HRSs by 2020, spending around JPY 45.2 billion in subsidies to support efforts towards this target until the Tokyo 2020 Olympic and

⁶³ METI, “About Fuel Cells Vehicles”, 4 March 2014: https://www.meti.go.jp/committee/kenkyukai/energy/suiso_nenryodenchi/suiso_nenryodenchi_wg/pdf/003_02_00.pdf (in Japanese).

Paralympic Games. It aims to have 100,000 FCVs and 80 HRSs by 2025, and 200,000 FCVs and 150 HRSs by 2030 [26]. From June 2019, it subsidizes up to JPY 50 million per FC bus, which can be combined with the national subsidy⁶⁴. It also provides JPY 1.01 million to FCVs' buyers and more than 80% of the costs of building an HRS, capping the costs at around JPY 100 million, similar than building a gasoline station⁶⁵.

Fukushima Prefecture also launched subsidies to support some of the costs for introducing FC buses in the prefecture in June 2019 in order to promote the realization of the hydrogen society⁶⁶.

In addition, the Japanese government will promote the development of guidelines and technologies for the expansion of hydrogen use in the fields of FC trucks, ships and trains.

Toyota provided two small fuel-cell trucks to convenience store chain Seven-Eleven in 2019 for restocking outlets in the Tokyo metropolitan area, planning to deploy more after confirming their performance. They have a load capacity of 3 tons, can cover 200 km per full charge and it takes about 5 minutes to be charged⁶⁷. Since trucks both for business and personal uses accounted for 36% of the transport sector's total CO₂ emissions [9], there is great potential to reduce emissions for this category. Regarding the travel range, FC trucks have advantages over electric trucks.

MOE has also been supporting the development of FC truck technology, collaborating with Tokyo R&D Co., Ltd (FC truck's basic performances and practicality, and demonstrated on public roads for its mass production) and Flat Field Co., Ltd (developed a FC garbage truck, tested its basic performances and identified optimal uses in actual garbage collection).

Besides, Toyota is collaborating with truck maker Kenworth, a unit of Paccar Inc., to build a demonstration fleet of 10 FC trucks with a travel range of about 500 km and a capacity of 36 ton to run at the Port of Los Angeles. They are part of a million-dollar initiative funded by California Air Resources Board⁶⁸. On the other hand, a group of companies including Toyota, Shell, Hyundai, Nikola Motors, Norwegian hydrogen station builder NEL Hydrogen Fueling, and French industrial gas maker Air Liquide signed an MoU to work together to standardize hydrogen-fueling components that could get FC trucks on the road faster. The group wants the fueling nozzle, vehicle receptacle, dispenser hose and other components to be useable in all

⁶⁴ Tokyo-CO₂: 28 June 2019: <https://www.tokyo-co2down.jp/company/subsidy/fc-bus/index.html> (in Japanese).

⁶⁵ The Japan Times, 20 January 2015: <https://www.japantimes.co.jp/news/2015/01/20/business/tokyo-to-spend-%C2%A545-billion-on-hydrogen-stations-subsidies-ahead-of-olympics/#.XNp0EuUzbIV>.

⁶⁶ Kankyo-business, 14 June 2019: https://www.kankyo-business.jp/news/022603.php?utm_source=mail&utm_medium=mail190617_d&utm_campaign=mail (in Japanese).

⁶⁷ The Japan Times, 7 Junio 2018: <https://www.japantimes.co.jp/news/2018/06/07/business/seven-eleven-use-toyota-fuel-cell-trucks-deliveries-next-year/#.XNpecuUzbIU>.

⁶⁸ Kenworth: <https://www.kenworth.com/news/news-releases/2019/april/kenworth-toyota-pola/>.

FCVs⁶⁹. Nikola Motors Company developed an FC truck in the US with a travel range of 1,900 km, though its commercialization will not start until 2021⁷⁰.

Finally, Toyota is working with other entities on other mobility projects:

- With East Japan Railway Company (JR East) to create a hydrogen-based mobility partnership between railways and automobiles. Discussions are centred on the construction of hydrogen stations on land owned by JR East, the introduction of FCVs and FC buses for local transportation, and the application of fuel cell technologies in railway carriages⁷¹. Indeed, JR East announced the test of FC trains from FY 2021, spending around JPY 4 billion on this project, and aiming to commercialize it by FY 2024⁷². It tested the world's first hydrogen FC train in 2006, but it cancelled the development.

Alstom's Coradia iLint, the world's first hydrogen-powered train already in operation in Germany⁷³ is an example that this will be also a real future in Japan with potential opportunities.

- With The Japan Fisheries Research and Education Agency (FRA) to develop a fishing boat powered by hydrogen fuel cells in FY 2019 that will be tested in FY 2022⁷⁴. It will be used at a tuna farm on the Goto Island chain, in Nagasaki Prefecture. The hydrogen will be produced through electrolysis with the surplus energy of a closed offshore wind farm that Toda Corp. constructed off Fukuejima Island.

The government will also prepare a roadmap for expanding fuel cells for ships and conduct demonstration tests based on that roadmap.

Between 2014 and 2016, Toda Corporation, with MOE's support, developed and tested a scale model of a low-carbon small-sized ship that utilized fuel cells. It also developed water- and salt-proof FC unit for vessels and demonstrated at sea.

- Regarding with FC motorcycle, it was reported that Suzuki Motor Corporation started testing its model on public roads in 2016⁷⁵, though there has not been news about a commercialization date. It also jointed Intelligent Energy Holdings, a British company, to produce an FC scooter.

⁶⁹ Trucks, 21 February 2019: <https://www.trucks.com/2019/02/21/toyota-nikola-hydrogen-truck-fueling/>.

⁷⁰ Nikola Motors Company: <https://nikolamotor.com/motor>.

⁷¹ Toyota, 27 Septiembere 2018: <https://global.toyota/en/newsroom/corporate/24687658.html>.

⁷² The Japan Times, 5 June 2019: <https://www.japantimes.co.jp/news/2019/06/05/business/corporate-business/jr-east-test-hydrogen-fuel-cell-trains/#.XPnaFNizbIU>.

⁷³ Alstom: <https://www.alstom.com/our-solutions/rolling-stock/coradia-ilint-worlds-1st-hydrogen-powered-train>.

⁷⁴ Fuel CellsWorks, 4 January 2019: <https://fuelcellsworks.com/news/japan-to-power-fishing-boats-with-toyotas-hydrogen-fuel-cells/>.

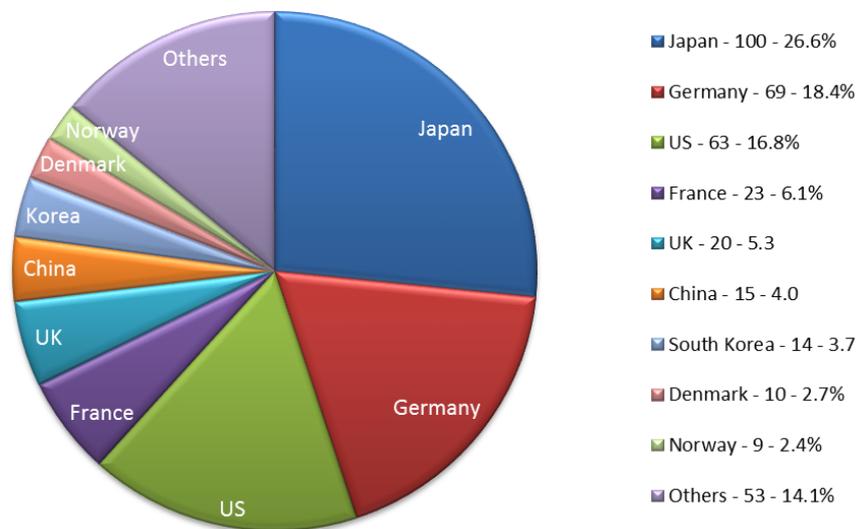
⁷⁵ Nikkei Asian Review, 27 December 2015: <https://asia.nikkei.com/Business/Companies/Suzuki-to-test-hydrogen-motorcycle-on-public-roads>.

3.2.2. Refueling Stations

The dissemination of FCVs depends greatly on the increasing number of accessible HRSs since this is the main concern of users, apart from the higher price of FCVs compare to electric options. However, the network of HRSs is not being deployed as fast as the electric charging points due to the high initial costs derived from the stringent regulatory framework.

Worldwide, there were 376 hydrogen refueling stations in operation as of end 2018. Japan led the deployment with 100 stations.

Figure 22: Stock of HRS as of end 2018



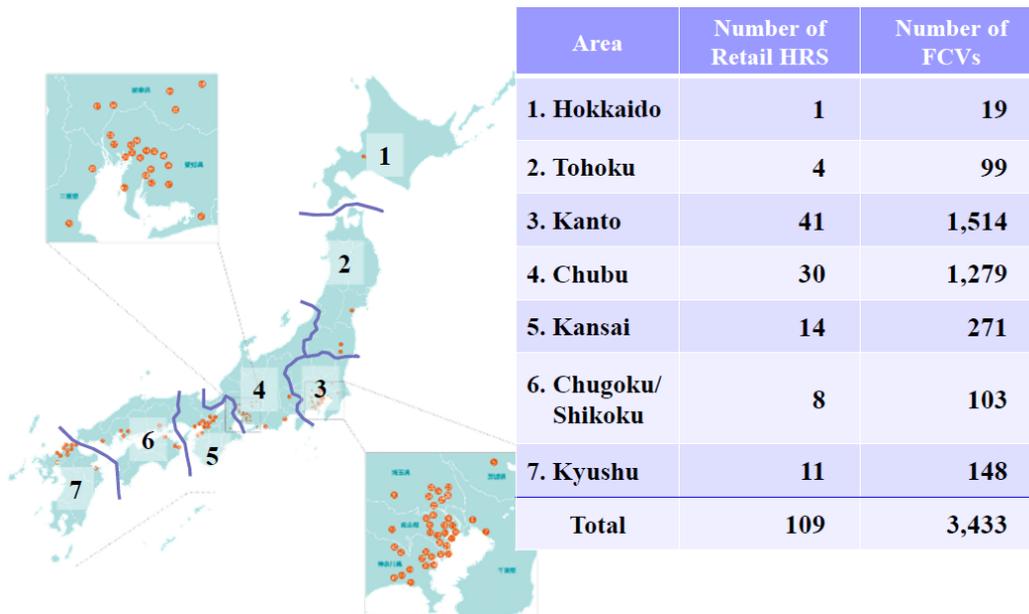
Source: Author, with data from the IEA Technology Collaboration Programme, Advanced fuel Cells.

According to HySUT [24], there are 109 HRSs in Japan as of end of August 2019, concentrated in four hubs (see Figure 23): Tokyo (Kanto), Nagoya (Chubu), Osaka (Kansai) and Fukuoka (Kyushu), from which 17 stations have on-site H₂ production, 53 stations have off-site H₂ production, and 39 are mobile stations. In FY 2019, there are 21 HRS installation plans⁷⁶. A frequently updated list can be found in <http://fccj.jp/hystation/index.html#list>. This number does not include private stations. The future goal is to replace the filling stations by 2050.

Table 7 shows that the main developers in Japan are JXTG Nippon Energy and Iwatani and that most of the hydrogen stations are integrated into a multi-fuel station.

⁷⁶ JHyM, 8 May 2019: https://www.jhym.co.jp/en/wp-content/uploads/2019/05/EN-JHyM_20190508-HRS-installation-plan.pdf.

Figure 23: Location and Number of HRS and FCVs in Japan as of the end of August 2019



Source: HySUT [24].

Table 7: Breakdown of Retail HRSs in Japan as of the end of March 2019

HRS Operator	N° of HRS	Features	HRS
JXTG Nippon Energy	41 (1)	Multi-Fuel (Integrated gas station)	18 HRS by JXTG
Iwatani	21.5 (4) *	Multi-Fuel (hydrogen, gasoline, CNG, LPG)	Nissin HRS by Toho Gas
Nippon Mobile Hydrogen Station Services	6	Multi-Fuel (hydrogen, CNG)	2 HRS by Tokyo Gas
Air Liquide Japan	6 (2)	Multi-Fuel (hydrogen, LPG)	Otsu HRS by Iwatani
Seiryu Power Energy	4	Station with convenience store	2 HRS by Iwatani
Toho Gas	3.5 *	Near the highway	4 HRS by JXTG 1 HRS by Toyota Tsusho
Tokyo Gas	3	Airport	Narita HRS by Idemitsu Kosan Kansai Airport HRS by Iwatani
Osaka Gas, Shikoku Taiyo Nippon Station, Toyota Tsusho Air Liquide Hydrogen Energy, Chubu Gas, Hiroshima Toyota Trading, Mie Hydrogen Station, Fukushima Hydro	each 2 [Total 14]		
Idemitsu Kosan, Oita EBL Hydrogen Station, Air Water, Shizuoka Gas, Takamatsu Teisan, Saibu Gas, Tomoe Shokai, Nemoto Tsusho, Hiroshima Toyopet, Yamamoto Oil	each 1 [Total 10 (1)]		
Total	109 (8)		

The numbers in () indicate the number of stations jointly operated with Japan Hydrogen Station Network (JHyM).
** There is one station operated jointly by Iwatani and Toho Gas.

Source: Author, with data from HySUT [24].

Honda Motor improved its Smart Hydrogen Station design, which creates hydrogen on-site from the electrolysis of water using solar power and other renewable energy resources. In addition, the hydrogen gas is pressurized without using a mechanical compressor, making the

stations small and quiet compared with other HRSs, and reducing also its cost. Honda says this station can be installed for just between JPY 50 and 70 million (around EUR 400,000 and 570,000), after taking into account the subsidies. Honda started its installation across the country in 2018, aiming to have around 100 stations by 2020 with the cooperation of local governments⁷⁷.

Toyota has been running a hydrogen station at Motomachi plant, Aichi Prefecture, since March 2018 in conjunction with the increasing numbers of FC forklifts in use there. Additionally, from April 2019, and thanks to the subsidy of MOE - "Subsidy for Business Costs, etc. for Measures Combating Carbon Dioxide Emissions (Project to Promote Low Carbon Social Infrastructures that Utilize Renewable Energy-based Hydrogen)" – it also introduced SimpleFuel™. This is a simplified hydrogen station that uses electricity from solar panels at the plant site to produce and store hydrogen through the electrolysis of water, which is then supplied to FC forklifts⁷⁸. It can produce up to 99 Nm³/day of hydrogen, around 8.8 kg/day, enough to fuel seven or eight FC forklifts. SimpleFuel™ is jointly manufactured by IVYS Energy Solutions and PDC Machines in the US.

Figure 24: Hydrogen Station SimpleFuel™



Source: Toyota.

And from March 2019, Toshiba ESS installed a similar technology, Toshiba ESS “H2PLAZA”, at Toyota Takahama plant also in Aichi Prefecture. This facility produces hydrogen made from

⁷⁷ Nikkei Asian Review, 25 October 2017: <https://asia.nikkei.com/Business/Companies/Honda-to-install-faster-filling-hydrogen-stations-across-Japan>.

⁷⁸ Toyota, 4 April 2019:

https://global.toyota/en/newsroom/corporate/27528557.html?_ga=2.21332338.85894042.1557724027-1278002982.1557724027.

solar power panels and supplies it to 13 FC forklifts used at that plant⁷⁹. The system controls the amounts of production and compression of hydrogen using Toshiba ESS's hydrogen energy management system, which includes a hydrogen demand prediction function that forecasts supply requirements for each FC forklift, allowing efficient use of energy.

In Chapter 3.1, it was mentioned that Toshiba ESS's H₂One™ system is able to produce and store its own hydrogen using renewable energy, and given that it is an independent system, it could supply electricity and hot water in times of emergency for evacuation sites. Local hydrogen production for local consumption.

In April 2018, Iwatani Corporation achieved to reduce cost and footprint by limiting the on-site construction required through its Iwatani Hydrogen Refueling Station installed in Okayama Prefecture, which uses a system that arranges major equipment into units and offers them as a single package. Additionally, future increases in vehicle filling volume linked to the widespread uptake of FCVs can be handled by increasing compressed hydrogen storage capacity. Therefore, this station model is appropriate for regional cities as well as for urban areas subject to numerous land restrictions⁸⁰.

Chiyoda is also working on another project funded by NEDO for developing compact-type dehydrogenation facilities for HRSs that will use methylcyclohexane (MCH), expecting to complete it by 2020 [27]. Each unit will have a capacity of 30 m³ of hydrogen per hour, and since each FCV needs around 50 m³, Chiyoda expects to combine several units to process 300 m³ per hour. The company announced the intention to spend between JPY 200 and 300 million to install a test equipment at Yokohama R&D site in 2017⁸¹.

Nevertheless, the main issue for the dissemination of HRSs is the high cost of the initial investment required, around JPY 500 million (about EUR 4.06 million), meaning a cost five times higher than a standard gasoline station. TMG, for example, is thus focusing on providing financial assistance by taking advantage of support from both the national and metropolitan governments, reducing the cost of building an HRS more than 80%, capping the costs at around JPY 100 million (about EUR 813,000), similar than building a gasoline station⁸². The metropolitan authorities aim to increase the number of HRSs to 35 by 2020, making it possible to reach a station within 15 minutes from most places in the city.

In any case, both the construction cost, between JPY 400 and 500 million, and operation cost, between JPY 40 and 50 million, were reported to be between two or three times higher than in Europe due to strict regulations from the government. Pressure accumulator, construction and compressor are the highest costs for the installation of an HRS, while repair expense and

⁷⁹ Toshiba ESS, 5 October 2018: https://www.toshiba-energy.com/en/info/info2019_0322.htm.

⁸⁰ Iwatani Corporation, 26 April 2018: http://www.iwatani.co.jp/img/eng/pdf/newsrelease/88/20180426_news_e1.pdf.

⁸¹ Nikkei Asian Review, 16 March 2017: <https://asia.nikkei.com/Business/Technology/Japan-s-engineering-giants-aim-to-make-clean-energy-cheap>.

⁸² The Government of Japan, Spring 2016: https://www.japan.go.jp/tomodachi/2016/spring2016/tokyo_realize_hydrogen_by_2020.html.

employment cost are the highest costs of the HRS's operation. Even with subsidies, profitability is difficult to reach because of the low number of FCVs on the road nowadays. Subsidies are shown in Table 9 and Table 10 and are calculated based on the characteristics of the station (size, stationary or mobile, production of hydrogen on-site or off-site).

As an example, HySUT reported that the cost of an on-site station with a capacity of 300 Nm³/h or more was originally around USD 6 million, and thus its subsidy was USD 2.9 million maximum, one half. That cost is currently around USD 4 million, and it is expected to keep decreasing up to USD 2 million by 2020 though an improve of the technology, a higher number of FCVs on the road and an appropriate regulation.

The Japanese government aims to make HRSs independent by the second half of the 2020s, and reduce the construction cost to JPY 200 million and the operation cost to JPY 15 million per year by 2025, setting a cost target for each component. As an example, it expects to reduce the compressor cost from JPY 90 million to JPY 50 million, and the high-pressure vessels cost from JPY 50 million to JPY 10 million, what also supposes an opportunity for European manufacturers. To achieve this progress, it is promoting a regulatory reform and technological developments, such as the use of inexpensive steel material, the realization of the self-service regulation with remote monitoring to extend the opening hours and thus to increase the benefit, and to allow the installation in gasoline stations and convenience stores. Japan is also promoting international collaboration to achieve harmonization and international standardization, which will help to reduce costs.

To achieve the costs reduction's targets, NEDO has different projects to develop, for example, polymer materials for gas seals and dispensing hoses, life-extension methods of ground storage pressure vessels, refueling methods for reducing cost (possibility of higher temperature, etc.), and a new type of compressors, such as electro-chemical compressor.

In collaboration with universities and private companies, NEDO is conducting R&D on low-cost equipment and parts for the next generation of ultra-high pressure hydrogen stations from FY 2018 to 2022 through the "2018 Super High-Pressure Hydrogen Infrastructure Full-scale Technology R&D Project"⁸³. This technology would allow a safe, inexpensive production, storage and transportation of hydrogen about 1,000 times the atmospheric pressure, and contributing to reducing hydrogen station maintenance and operation costs in anticipation of full-scale spread and independence of HRSs. It will include domestic regulation optimization, standardization of specifications and interfaces, high pressure hydrogen-compatible polymer technology, electrochemical pumps, device packaging studies, new large-sized, thin-walled high-pressure hydrogen tanks that contributes to the cost reduction of hydrogen stations, or ultra-high pressure hydrogen trailers equipped with lightweight containers for the large-scale and efficient hydrogen transport, among others.

⁸³ NEDO, 10 May 2019: https://www.nedo.go.jp/activities/ZZJP_100144.html.

The strict Japanese regulation is one of the main reasons for the high cost of HRSs. Hydrogen is regulated as an industrial gas, with standards intended for large-scale chemical plants with high explosive risks, but which are also currently applied to HRSs. Hydrogen cars need a prescribed space around them during fuelling. Therefore, hydrogen stations are required to be surrounded by much more space than a standard gasoline station, which greatly increases the cost in cities. However, hydrogen dissipates quickly into the atmosphere, and the stations are equipped with sensors that immediately shut down the pump if any leak is detected.

Operation staffs must be licensed in handling high-pressure gases, and there must be one qualified supervisor under the High-Pressure Gas Safety Act., which limit the working hours of the fueling stations, many of which close during the night or at weekends. And records must be kept of who handles and purchases the fuel.

METI is reviewing the regulation that affects to HRSs to achieve lower costs. One point is the requirements for station supervisors, who having experience with natural gas and other high-pressure gases will suffice. Another point that would reduce labour costs will be that stations will no longer be required to have an employee who takes down cars' license plates and keeps track of who buys hydrogen.

METI is also studying legalize self-service pumps with remote monitoring given that the process of filling a car is highly automated, which would extend the opening hours and thus the benefit. The Japan Petroleum Energy Center (JPEC) released the Self-hydrogen Station Guidelines (JPEC-TD 0004), which showed specific self-filling requirements and methods under the current laws and regulations. In the future, and based on these guidelines, a contract will be signed between the business operator and the driver, who will receive the safety education required and training to mount and demount of the nozzle in order to fill the hydrogen tank. Only in that case, the driver will be able to perform self-filling⁸⁴.

Regarding stations themselves, some localities require for them to have roofs for keeping hydrogen storage vessels out of direct sunlight, but METI will waive that requirement if certain conditions are met, such as having the vessels' temperature controlled. It will also reevaluate safety standards by FY 2019, incorporating the latest technology and knowledge to avoid strict rules⁸⁵. Japan allows stations that fill FCVs at 70 MPa increase their storage pressure at 82 MPa since 2016 in line with the international practice. Previously, HRSs stored hydrogen at 35 MPa and 70 MPa [25].

According to the Fire Service Act., refueling stations for FCVs must be about 10 meters away from a gas pump, which limits especially to the small stations. The separation distance between hydrogen dispensers and public roads is around 6 and 8 meters, which is longer than that for gasoline dispensers, between 4 and 5 meters. But METI is also revising the standards to let gas

⁸⁴ Kankyo-business, 2 July 2018: <https://www.kankyo-business.jp/column/020668.php?cat=hydrogen> (only in Japanese).

⁸⁵ Nikkei Asian Review, 22 September 2017: <https://asia.nikkei.com/Politics-Economy/Policy-Politics/Japan-to-speed-growth-of-hydrogen-refueling-stations>.

stations set up hydrogen refueling terminals alongside gas pumps regardless of space. The code would be relaxed on a trial basis while monitoring safety, with pilot programs likely to be conducted in special deregulation zones. METI is also considering to allow the introduction of convenience stores, supermarkets and package delivery depots in filling stations that would help diversify their revenue streams⁸⁶.

HySUT is also promoting a cost reduction through a new industry standard category based on fueling capacity. The current standard category is based on the supply capacity, divided in medium-scale (compressor capacity of 300 Nm³/h or more) and small scale (compressor capacity between 50 Nm³/h and 300 Nm³/h). The new category will divide stations in large scale (fueling capacity of 10 to 12 vehicles/h), medium-scale (fueling capacity of 5 to 6 vehicles/h) and small scale (fueling capacity of 1 to 2 vehicles/h) [28].

HySUT is an industrial association to develop and promote hydrogen infrastructure for FCVs, ensuring a stable and safe supply of hydrogen by conducting technology development, research, regulation review, industrial standardization and public awareness, and aiming to get a cost reduction and a reliability improvement for the next generation of HRSs⁸⁷. It was established in February 2016, when its predecessor, The Research Association of Hydrogen Supply/Utilization Technology, which was founded in 2009, finished its activity. HySUT has 46 members by September 2019, including energy and engineering companies, automakers, hydrogen station operators and two related organizations. It also supports activities to stimulate demand for FCVs, and international cooperation for the development of ISO/TC197 Hydrogen Energy Technology Standardization Project with NEDO's support.

Because one of the HySUT's activities is to develop new technologies to contribute to the further safety and security of hydrogen, and to research on cost reduction of HRSs, the Hydrogen Technical Center was built in Kofu, Yamanashi Prefecture, under a NEDO project and to carry out tests in a real environment (Chapter 3.5.3). Two examples are the increase of the maximum operating pressure to 87.5 MPa (cylinder bundle, compressor, pressure vessel and dispenser), and the standardization of equipment, individually designed by each contractor, and design specifications.

In Japan, HRSs (layout, materials, manufacturing, inspection, safety distances, etc.) are under the regulation of the High-Pressure Gas Safety Act. It regulates the production, storage, consumption, disposal, sale and transportation of high pressured gas. METI is the regulatory authority. MLIT is the regulatory authority of the Building Standards Act, which restricts the location of HRSs depending on use district, such as residential district, commercial district, or exclusive industrial district, determined by city planning. The Fire Service Act regulates HRSs which are installed in gas stations. The regulatory authority is the Fire and Disaster Management Agency (FDMA) [29].

⁸⁶ Nikkei Asian Review, 21 February 2018: <https://asia.nikkei.com/Politics-Economy/Policy-Politics/Japan-paves-way-for-gas-stations-to-charge-up-electric-cars>.

⁸⁷ HySUT: <http://hysut.or.jp/en/index.html>.

Table 8: Regulations, Standards and Guidelines for HRSs

Laws and Regulations	Technical Standards	Self-Guidelines
• High Pressure Gas Safety Act	• Exemplified Standard	• HySUT
> Security Regulation for General High Pressure Gas	• Japan Industrial Standard (JIS)	> Quality Control (HySUT-G 0001)
> Ordinance on Safety of Gas Containers	• International Standard (ISO/TC 197*)	> Hydrogen Metering (HySUT-G 0002)
> Ordinance on Designated Equipment Inspection	• The High Pressure Gas Safety Institute of Japan (KHK-S)	> Fueling Performance Validation (HySUT-G 0003)
> Ordinance on Safety of Industrial Complexes	• Japan Petroleum Energy Center (JPEC-S)	> Inspection Apparatus (HySUT-G 0004)
• Fire Service Act	• Japan Industrial and Medical Gases Association (JIMGA-S)	> HPIT - Hydrogen Powered Industrial Truck - (HySUT-G 0005)
• Building Standards Act		
• Act on the Prevention of Disaster in Petroleum Industrial Complex and Other Petroleum Facilities		
• Industrial Safety and Health Act		
• Road Transport Vehicle Act		
• Road Traffic Act		
• Act on Port Regulations		

Safety of HRSs

Reliability of Retail HRSs

* ISO TC 197 is a technical committee developing international standards in the field of systems and devices for the production, storage, transport, measurement and use of hydrogen.

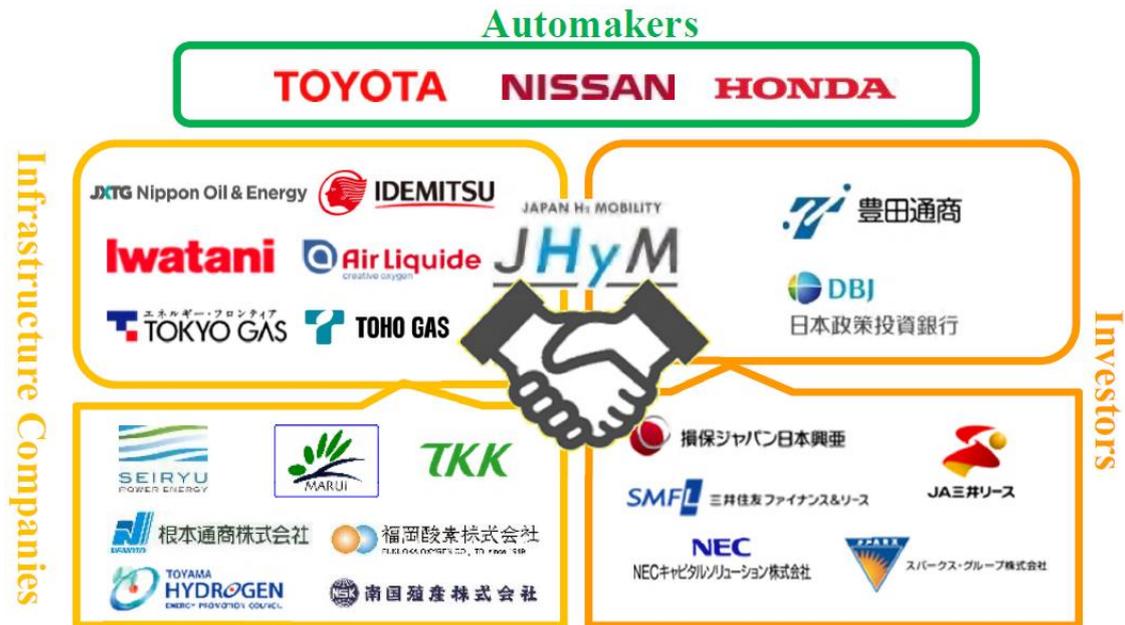
Source: Author, with data from HySUT [28].

To address the financing problem, in February 2018, a group of 11 Japanese companies established the Japan H2 Mobility (JHyM) to build 80 stations nationwide for 4 years from FY 2018 to FY 2021, in line with the Strategic Roadmap of the government. It already installed 33 HRS by May 2019 and 21 stations more are planned for the FY 2019⁸⁸. Its ultimate goal is to improve convenience for FCV users, contribute to accelerating the adoption of FCVs in the country and to the efficient operation of hydrogen stations. It also collaborates with the Fuel Cell Commercialization Conference of Japan (FCCJ) and the Association of Hydrogen Supply and Utilization Technology (HySUT) to reduce costs by addressing issues such as the standardization of equipment and revision of regulations.

Those eleven firms were the automakers Toyota, Nissan and Honda, the infrastructure developers JXTG Nippon Oil & Energy, Idemitsu Kosan, Iwatani, Tokyo Gas, Toho Gas and Air Liquide Japan, and the investors Toyota Tsusho and the Development Bank of Japan. Later, seven more infrastructure developers (Nemoto Tsusho, Seiryu Power Energy, Tama Koun, Toyama Hydrogen Energy Promotion Council, Nangoku Corporation, Fukuoka Oxygen, and Marui Transport) and five more investors (JA Mitsui Lease, Sompo Japan Nipponkoa Insurance, Mitsui Sumitomo Finance & Leasing, NEC Capital Solutions Limited, and Mirai Creation Fund (Operator: SPARX Group)) joined the company, for a of 23 members, including 13 HRS firms.

⁸⁸ JHyM, 8 May 2019: https://www.jhym.co.jp/en/wp-content/uploads/2019/05/EN-JHyM_20190508-HRS-installation-plan.pdf.

Figure 25: Members of JHyM as of May 2019



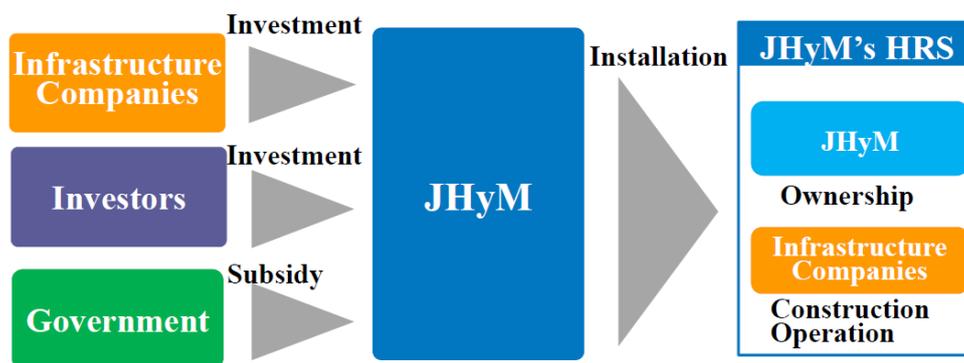
Source: JHyM.

The requirements for infrastructure providers participating in JHyM are to install at least one new HRS and to pay the annual fee. Each infrastructure provider has to submit an installation plan according to JHyM’s Annual Hydrogen Station Development Planning Policy formulated for each fiscal year, which includes, for example, the areas where stations will be built. After approval, both the HRS firm and JHyM will jointly apply for subsidies. The infrastructure provider will handle the construction, and once completed, JHyM will own the station while the HRS firm operates it. Therefore, JHyM offers participants the business schemes shown in Figure 26 and Figure 27, with the following benefits, especially a cost reduction between 10% and 20%⁸⁹:

- A reduction of the initial cost by using METI’s subsidy, “Hydrogen Supply Facility Installation Project for Fuel Cell Vehicles”, and investments from JHyM financial investors. Furthermore, it has a special burden mitigation system for small and medium-sized enterprises.

⁸⁹ JHyM: <https://www.jhym.co.jp/en/nav-about/>.

Figure 26: JHyM's Business Scheme for HRS's Construction



Source: JHyM [24].

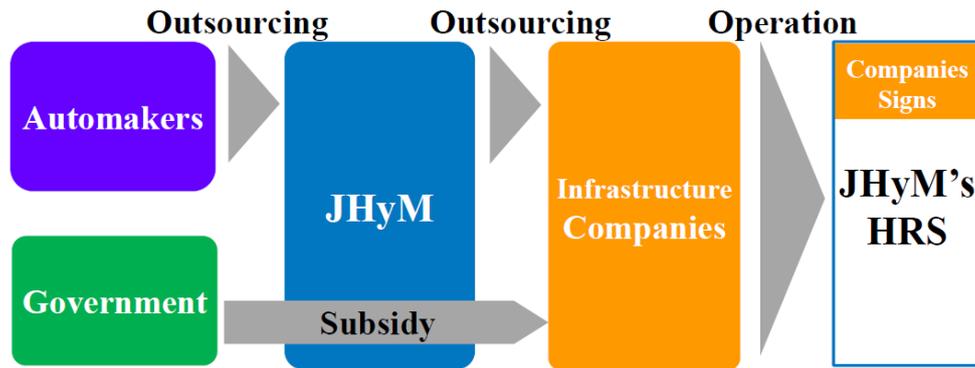
Table 9: Support Program for HRS Construction by NeV (sponsored by METI)

Facility	Capacity	Type	Support	Max. Amount (Million US\$)
HRS	300 Nm ³ /h or more (medium scale)	On-site (for bus refueling)	1/2	3.9
		Off-site (for bus refueling)	1/2	3.5
		On-site (compact type)	2/3	2.9
		Off-site (compact type)	2/3	2.5
		On-site (others)	1/2	2.9
		Off-site (others)	1/2	2.5
		Mobile	2/3	2.5
	50 Nm ³ /h or more and less than 300 Nm ³ /h (small scale)	On-site (compact type)	2/3	2.2
		Off-site (compact type)	2/3	1.8
		On-site (others)	1/2	2.2
		Off-site (others)	1/2	1.8
Mobile		2/3	1.8	
Gaseous Hydrogen Production and Shipping			1/2	0.6
Liquefied Hydrogen Shipping			1/2	0.4

Source: HySUT [24].

- A reduction of the operation cost by using METI's subsidy, "Fuel Cell Vehicle New Demand Creation Activity Support Project", and outsourcing expenses from JHyM, providing the infrastructure companies with a long-term stable operation environment.

Figure 27: JHyM’s Business Scheme for HRS’s Operation



Source: JHyM [24].

Table 10: Support Program for HRS Operation

Program by NeV (sponsored by METI) - 2/3 of the total

Type	Max. Amount per HRS (Million US\$)
On-site HRS	0.22
Off-site HRS	0.22
Mobile (Refueling site: 1)	0.22
Mobile (Refueling sites: 2 or more)	0.26
Capacity (Nm ³ /h): 50 or more and less than 100	0.16

Program by HySUT (sponsored by automakers) - 1/3 of the total

Type	Max. Amount per HRS (Million US\$)
On-site HRS	0.11
Off-site HRS	0.11
Mobile (Refueling site: 1)	0.11
Mobile (Refueling sites: 2 or more)	0.13
Capacity (Nm ³ /h): 50 or more and less than 100	0.08

Source: HySUT [24].

The target areas for these subsidy programs from the government have been expanded to all prefecture from FY 2019 from the four major metropolitan areas in order to create a nationwide network of HRSs.

More companies are entering this market. Tokyo Electric Power Company (TEPCO) is one example, which will build one of the world's biggest hydrogen stations in Tokyo before the Olympic Games in 2020 together with JXTG Energy⁹⁰. Also, JERA, a fuel joint venture between TEPCO and Chubu Electric Power, will build a production site to supply hydrogen to FCVs and FC buses by 2020.

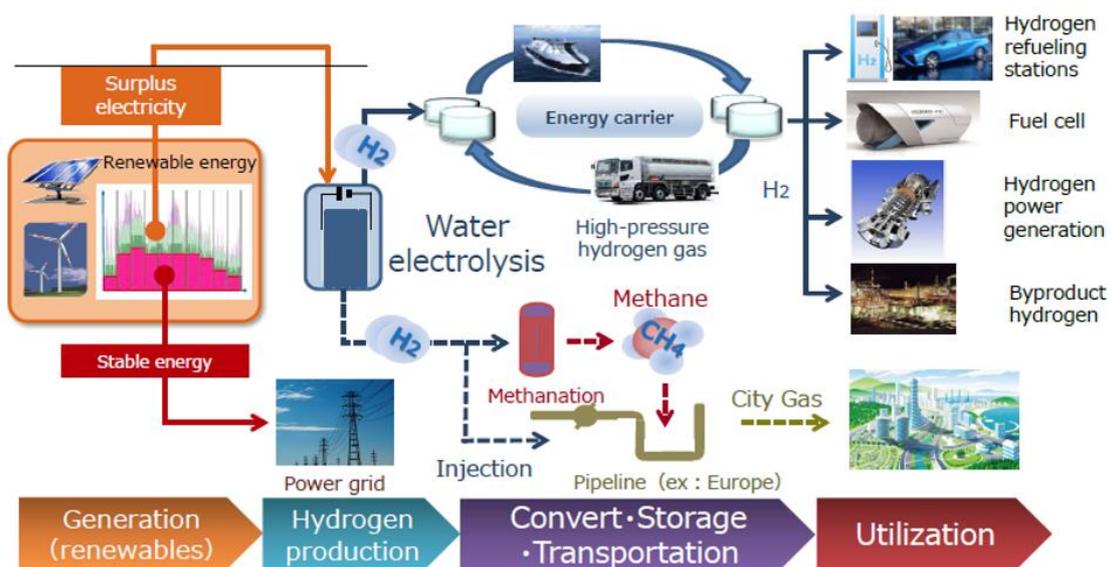
⁹⁰ Reuters, 22 March 2019: <https://www.reuters.com/article/japan-hydrogen/update-1-japans-tepc-to-enter-hydrogen-fuel-business-with-jxtg-idUSL3N21928L>.

3.3. POWER GENERATION

Power generation sector accounts for 40% of total national CO₂ emissions [9]. Power-to-Gas will allow to improve the domestic energy production rate and to reduce CO₂ emissions in the power generation sector, and thus help to decarbonize the power generation and heat demand sectors in Japan. P2G, which converts renewable electricity (power) into hydrogen (gas) by electrolysis, is generating a growing expectation as a way to use the surplus electricity generated with variable renewable energy (VRE) and thereby produce inexpensive and local green hydrogen. This hydrogen could work as a baseload power source in the same way as natural gas (regulated power supply and backup power source), allowing, in turn, a higher expansion of VRE. Fukushima’s P2G demonstration project is the biggest in Japan (Chapter 3.5.2).

Hydrogen has the potential to store electricity for large scale and long-term applications, due to small energy loss over time and high expandability compared to battery storage systems (Figure 2). Therefore, P2G is expected to be one of the countermeasures against problems related to grid stability and reliability due to the higher penetration of renewables in Japan. The government aims to commercialize P2G technology from 2030 based on the achievements of the Fukushima’s project (3.5.2). The hydrogen produced could also be injected into the natural gas system in specific quantities, be synthesized into ammonia for used it directly as a fuel, or combine with CO₂ to get methane (synthetic natural gas or syngas) though the methanation process. Syngas, which has 50% of the energy density of natural gas, can be used as a fuel source or as an intermediate to produce other chemicals, and can use the existing energy supply infrastructure, including city gas pipelines and LNG power plants.

Figure 28: Power-to-Gas



Source: NEDO.

Japan aims to commercialize hydrogen power generation by around 2030, cutting the hydrogen power generation cost to JPY 17 per kWh. This will require to establish an international hydrogen supply chain to procure 300,000 tons of hydrogen annually, amounting to 1 GW in power generation capacity, and reduce the hydrogen supply cost to JPY 30 per Nm³ by that time. Beyond that, the target is to procure between 5 and 10 million tons of hydrogen annually at JPY 20 per Nm³, which will account between 15 and 30 GW in power generation capacity, replacing the gas power generation. In this scenery, the production cost from brown coal gasification will be reduced to JPY 12 per Nm³.

The Japanese government is considering clarifying the position of hydrogen use in the Energy Conservation Act⁹¹ or positioning hydrogen power generation⁹² as a non-fossil power source in the Energy Supply Structure Sophistication Act⁹³ [9].

According to IEEJ [30], the renewable surplus electricity in 2030 (based on METI's power generation mix by 2030, with 64 GW of solar PV and 10 GW of wind) will be small to rely on it to produce hydrogen. A reduction in the renewable power generation cost and capital cost of electrolysis will be also needed. Nevertheless, demonstration projects in this field are being carried out, and the fast introduction of renewable generation, especially solar, during the last years because of the FIT program [6], could make bring it ahead of 2040 given that hydrogen production is one of the grid integration measures.

The fact that hydrogen gas can be blended into the existing natural gas pipeline network is an economic advantage since investment can be avoided. However, and according to IEEJ [30], since Japan has been developing pipelines in connection with LNG receiving terminals, the pipeline network is still undeveloped and much less interconnected across the country, and the Japanese standard allows lower mixing concentrations than in Europe, for example. It also pointed out that Japan has fewer underground storage facilities and new ones should be constructed to receive the gas from P2G.

The power generation will directly lead to massive hydrogen consumption, which will contribute to cost reduction. Due to the commercialization of hydrogen power generation is included among the targets of the Basic Hydrogen Strategy by 2030, there are several R&D and demonstration projects ongoing. However, its implementation still needs to reduce costs and increase efficiency.

Electricity can be generated burning pure hydrogen or a hydrogen-based fuel such as ammonia, or a mixture of hydrogen and natural gas or coal. Globally, Enel started the operation of the first industrial-scale pure hydrogen-fuelled combined cycle power plant at Fusina, Venice, in 2010⁹⁴.

⁹¹ Act on the Rational Use of Energy (Law n° 49 of 1979).

⁹² The government will consider issues regarding the Act on Promotion of Global Warming Countermeasure (Law n° 117 of 1998).

⁹³ Act on the Promotion of Use of Non-Fossil Energy Sources and Effective Use of Fossil Energy Materials by Energy Suppliers (Law n° 72 of 2009).

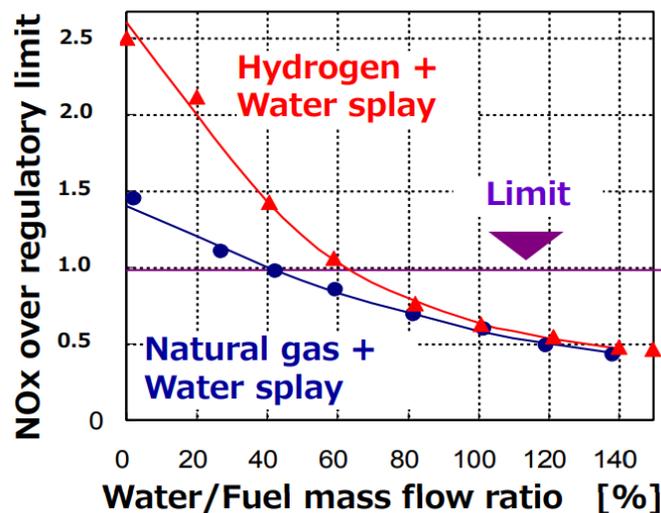
⁹⁴ Enel, 12 July 2010: <https://www.enel.com/media/press/d/2010/07/enel-at-fusina-venice-inauguration-of-first-industrial-scale-hydrogen-plant-in-the-world>.

In Japan, three main technologies for hydrogen gas turbine power generation are being developed in anticipation of the large consumption of hydrogen: the co-combustion of hydrogen and natural gas, and hydrogen firing power generation, both led by NEDO and with KHI and MHPS working on that; and the direct use of ammonia for combustion, led by Strategic Innovation Promotion Program, which is managed by the Cabinet Office [16]. Ammonia can be also co-fired in coal-fired power plants to reduce coal usage and CO₂ emissions.

There are also several issues during the hydrogen combustion that need to be solved, such as a higher combustion temperature than that of natural gas (hot spot in the combustion chamber), which led to higher nitrogen oxides (NO_x) emissions; a higher flame propagation velocity than that of natural gas, and a shorter flame quenching distance, which could led to structural burnout and flashback [31].

CO₂ is not generated when hydrogen burns, but NO_x is, which is another GHG and an air pollutant, and it is generated in a quantity almost two times higher than when natural gas is burnt if it is burnt in a gas turbine. This is due to hydrogen burns at a higher speed, destabilizing burning, and because the flame temperature is high. As countermeasures against this, cooling the flame by spraying water or diluting the fuel by inert gas is considered. Indeed, KHI proved that NO_x emissions can be suppressed to a lower level than the limit with water injection to lower the flame temperature, but this worsens the fuel economy [31] (Figure 29). Then, it developed a pure hydrogen-fueled Dry Low NO_x combustion technology in which the hydrogen is supplied in small doses that burn in “microflames” (“micromix” technology) and which allow a 100% pure hydrogen-burn while suppressing NO_x emissions without water injection [32].

Figure 29: NO_x Emissions Using Water Injection during the Hydrogen and Natural Gas Combustion



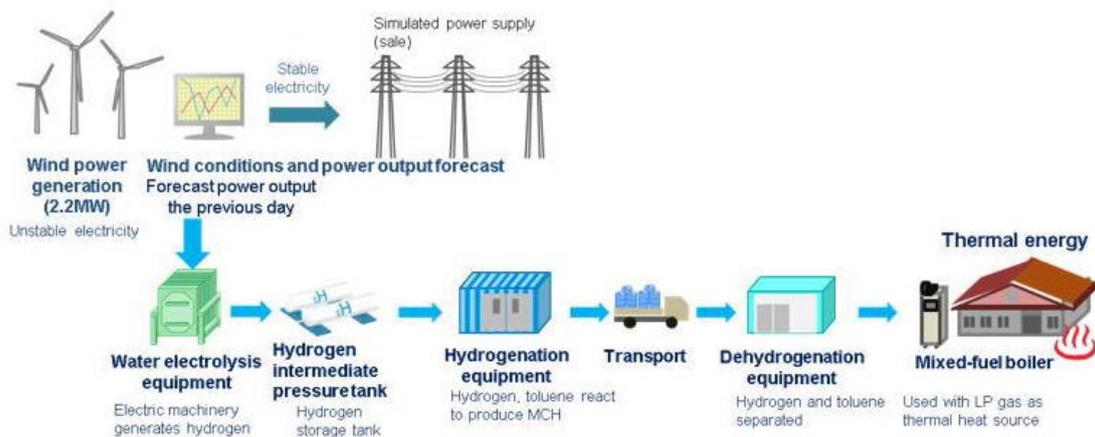
Source: Kawasaki Heavy Industries [31].

In November 2017, NEDO, Toyota Tsusho Corporation, NTT Facilities, Inc., KHI, Hrein Energy Inc., company devoted to hydrogen storage and supply systems, Technova Inc., and Muroran Institute of Technology started a P2G hydrogen energy demonstration project at Yuhigaoka Wind Farm "Furaibo" in Tomamae Town, Hokkaido, using hydrogen to maximize wind power's potential⁹⁵ (Figure 30).

This demonstration aims to develop a new energy system and business model, which improves the utilization of wind power, whose output power fluctuates depending on wind conditions, by effectively converting unstable part of the power to hydrogen for thermal application, allowing the production of low-CO₂ hydrogen while also expanding the use of renewable energy.

Regarding the demonstration, operations will begin by using NTT Facilities' forecasting system to estimate the following day's wind conditions and electricity output. Based on the forecast, the control system, developed by KHI, splits the electric power into a stable part, fed into the grid, and an unstable part, fed to the water electrolyzer, which was developed also by KHI. Using Hrein Energy's hydrogenation system, the hydrogen produced by the electrolyzer reacts with toluene to become MCH. After this, the MCH is delivered to the application site, where it is separated into hydrogen and toluene by Hrein Energy's dehydrogenation system. Finally, the regenerated hydrogen is mixed with liquid petroleum gas (LPG) to produce heat using a mixed-fuel boiler⁹⁶.

Figure 30: P2G Demonstration Project in Hokkaido



Source: NEDO.

Hrein Energy Inc. had already demonstrated a technology to store hydrogen in the form of MCH under the project "Promotion for developing industrial technology aiming at the

⁹⁵ NEDO, 29 September 2017: https://www.nedo.go.jp/english/news/AA5en_100291.html.

⁹⁶ Toyota Tsusho Corporation, 29 September 2017: https://www.toyota-tsusho.com/english/press/detail/170929_004155.html.

achievement of Kyoto Protocol Goals" by the International Center for Environmental Technology Transfer in FY 2006 and 2007. In July 2008, and in collaboration with Wakkanai Alternative and Renewable Energy Study Group, it demonstrated the same technology to produce MCH from hydrogen generated through a water electrolysis power cell by a wind power generation facility in Wakkanai, Hokkaido⁹⁷.

In January 2018, MHPS successfully passed a firing test using a 30% hydrogen fuel mix with natural gas in a large-scale 700 MW (with temperature at turbine inlet at 1600°C) of output gas turbine used in power generation, achieving also a 10% reduction in CO₂ emissions compared to standard natural-gas-fired power generation, and meeting the threshold in NO_x emissions. The test results confirmed that by using MHPS's proprietary burner, which was newly developed to burn hydrogen, stable combustion can be attained even when hydrogen is mixed with natural gas. As part of a project of NEDO, the test was carried out at MHPS's Takasago Works using actual-pressure combustion testing facilities⁹⁸. A fuel mix of 20% hydrogen can be used without any technological improvements.

The stable hydrogen-mixed firing technology applied in the large-scale gas turbine uses MHPS's proprietary dry low-NO_x combustor developed for this project as an improved version of the company's natural-gas-fired combustors. The combustor's fuel nozzle creates a rotational airflow that enables the formation of a more uniform premixed gas, leading to low NO_x. Other than the combustor, the equipment currently in place can be used without modification, thereby lowering the potential costs and other obstacles of converting a natural-gas-fired power plant to a hydrogen plant.

The next objective of MHPS is the CO₂-free power generation with a 100% hydrogen power generation technology. Indeed, it is taking part in a feasibility study in the Netherlands, where a 440 MW large-scale natural-gas-fired gas turbine combined cycle (GTCC) of Nuon /Vattenfall's Magnum power plant, in Groningen, is being converted into a 100% hydrogen-fired power generation plant by 2023. This will reduce the current CO₂ emissions around 1.3 million tons per year, to almost zero. Within this project, Norwegian oil major Statoil will produce hydrogen by converting Norwegian natural gas into hydrogen and carbon dioxide. CO₂ will be stored in underground facilities off the Norwegian coast, allowing carbon-neutral production. European natural gas pipeline operator Gasunie is carrying out research into how the hydrogen can be transported to and stored at the Magnum power station⁹⁹.

In April 2018, Obayashi Corporation and KHI achieved the world's first delivery of electricity and heat to four nearby facilities (Kobe City Medical Center General Hospital, Kobe Port Island Sports Center, Kobe International Exhibition Hall, and Port Island Sewage Treatment Plant) in a city area generated using a gas turbine fueled by 100% hydrogen¹⁰⁰ (Figure 31). This newly

⁹⁷ Japan for Sustainability, 30 November 2008:

https://www.japanfs.org/sp/en/news/archives/news_id028536.html.

⁹⁸ MHPS, 19 January 2018: <https://www.mhps.com/news/20180119.html>.

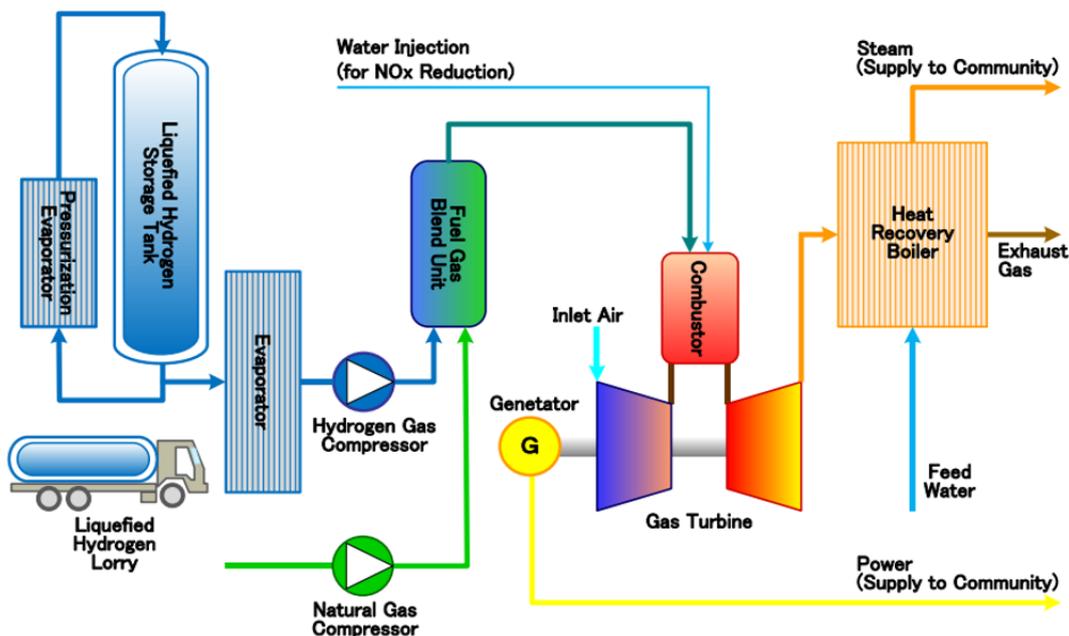
⁹⁹ MHPS, 8 March 2018: <https://www.mhps.com/news/20180308.html>.

¹⁰⁰ NEDO, 20 April 2018: https://www.nedo.go.jp/english/news/AA5en_100382.html.

developed combustion technology enables the existing natural gas turbine to be utilized without modifications to its main body, and the whole turbine system to be capable of adapting to the hydrogen’s unique combustion properties. Kansai Electric Power (KEPCO), Iwatani, Kenes, Kobe City and Osaka University also cooperated in this project.

Tests had been carried out since the Kobe Port Island hydrogen cogeneration system (CGS) demonstration plant was completed in December 2017. Previous tests demonstrated independent generator operation using a mixture of hydrogen and natural gas, and hydrogen gas alone, as well as heat and electricity delivery using natural gas as a fuel.

Figure 31: Demonstration Project in Kobe



Source: Kawasaki Heavy Industries [31].

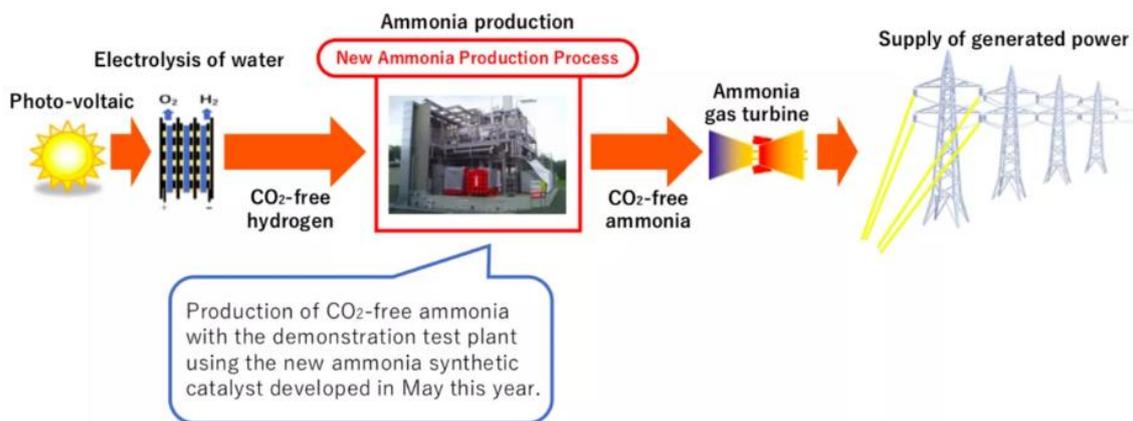
The system is equipped with a 1.7 MW hydrogen gas turbine, and an integrated energy management system (EMS) that comprehensively manages electricity and heat using hydrogen and natural gas as fuel to optimally control the supply from an economic and ecological standpoint. Verification tests will continue with the aim to build a new energy supply system that will lead to efficient energy use in local communities.

It was part of a NEDO project carried out from FY 2015 to FY 2018 and called “Technology Development Project for Building a Hydrogen-based Society / Technology Development Project for Large-Scale Utilization of Hydrogen / Smart Community Technology Development Project Utilizing Hydrogen Cogeneration Systems”.

In May 2018, JGC Corporation, together with its subsidiary JGC Catalysts & Chemicals Ltd., the AIST, the National Institute of Technology, and Numazu College, developed a “new ruthenium catalyst capable of efficiently synthesizing ammonia at a low temperature and low pressure through the improvement of carrier and catalyst production methods using catalysts”. They constructed a demonstration plant in Koriyama capable of producing 20 kg of ammonia per day, where they verified the “enabling of a change in ammonia production volume through rapid operational condition changes when using renewable energy”.

In late 2018, JGC Corporation announced the successful in demonstrating the synthesis of green ammonia with hydrogen produced through the electrolysis of water by intermittent renewable energy, and the generation of electricity at a demonstration plant of 47 kW of power generation through gas turbines fueled by this synthesized ammonia (Figure 32). This project, which is part of the SIP’s Energy Carriers program (Chapter 3.4.1), demonstrated the feasibility of ammonia for establishment of an energy chain without CO₂ emissions from production to power generation¹⁰¹.

Figure 32: Energy Chain Utilizing CO₂-free Ammonia Test



Source: JGC Corporation.

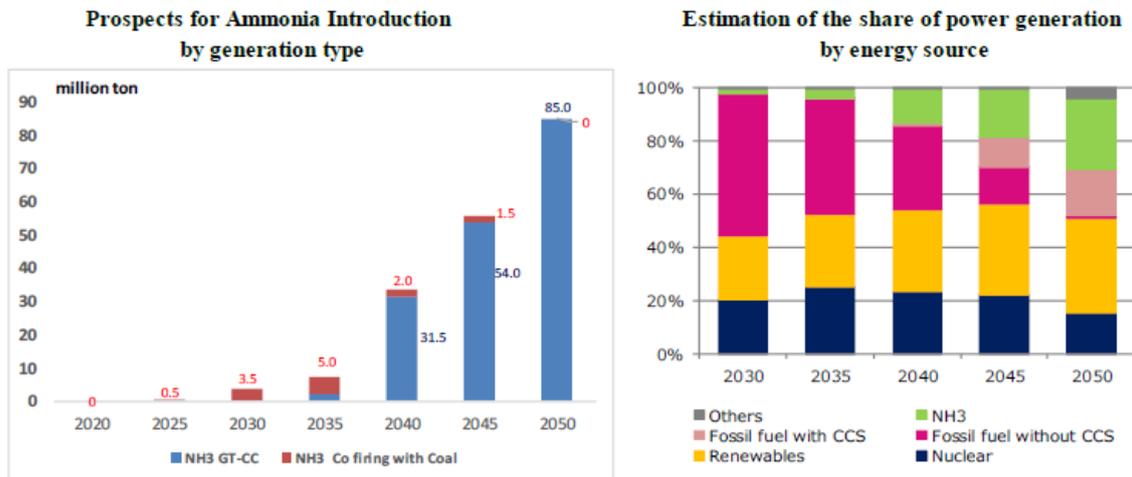
JGC continues with the R&D toward cost reduction of ammonia, and it will perform a commercial-scale plant design and cost study in order to define the roadmap for deployment of renewable ammonia production plants.

During 2016 and 2017, IEEJ conducted a study [33] to figure out how to reduce CO₂ emissions by 80% by 2050, concluding that the power generation sector, which emits nearly half of the total emissions, must achieve almost zero emissions by that date. According to that study, coal

¹⁰¹ Ammonia Industry, 3 January 2019: <https://ammoniaindustry.com/jgc-corporation-demonstrates-worlds-first-carbon-free-ammonia-energy-cycle/>.

co-firing with 20%¹⁰² CO₂-free ammonia will play an important role from 2030, and power generation with ammonia-fired gas turbine combined cycles (GTCC) will do it after 2040.

Figure 33: Prospect for Power Generation and Ammonia Introduction in Japan (80% CO₂ reduction target by 2050)



Source: IEEJ [33]

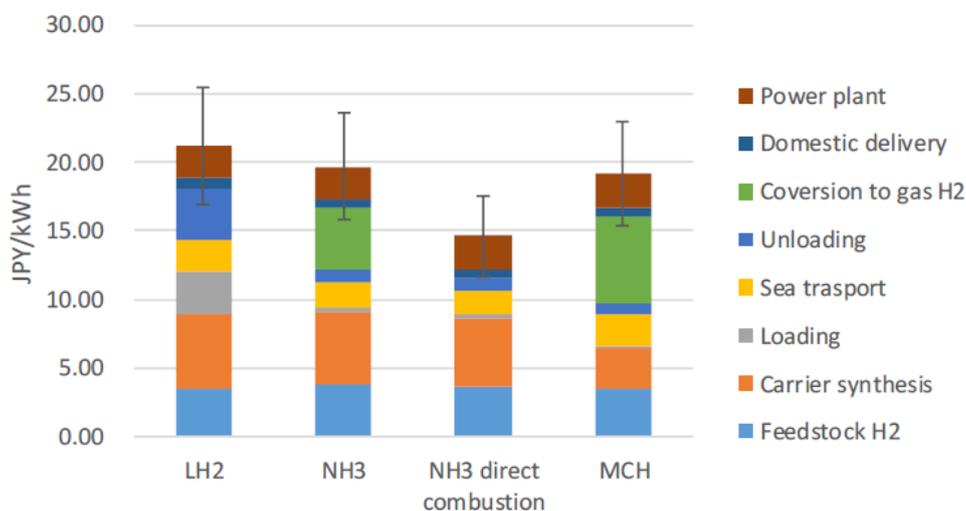
IEEJ [34] estimated the power generation cost using hydrogen-related fuels in 2030 with a clear conclusion: ammonia would be the cheapest option if it can be directly used for power generation (

Figure 34). The supply cost of hydrogen for power generation would be around JPY 35 per Nm³, though in the case of direct combustion of ammonia, this price will be reduced up to around JPY 25 per Nm³ (Figure 35).

This study concluded that for ammonia power generation to be comparable to LNG/coal-fired power generation in Japan, the price of the CO₂-free ammonia must be around JPY 35 per kilogram (USD 350 per ton of ammonia) after delivery to the power generation sites, including a CCS cost of around USD 50 per ton of CO₂. It would be possible to achieve a price between USD 250 and 350 per ton of ammonia for non-CO₂-free ammonia. This price would be acceptable for both suppliers and users, and would be lower than the target cost of hydrogen set by the Strategic Plan of the government by 2030 for cost-competitive power generation, around USD 3 per kilogram of hydrogen, or USD 480 per ton of ammonia (equivalent price in terms of energy contents).

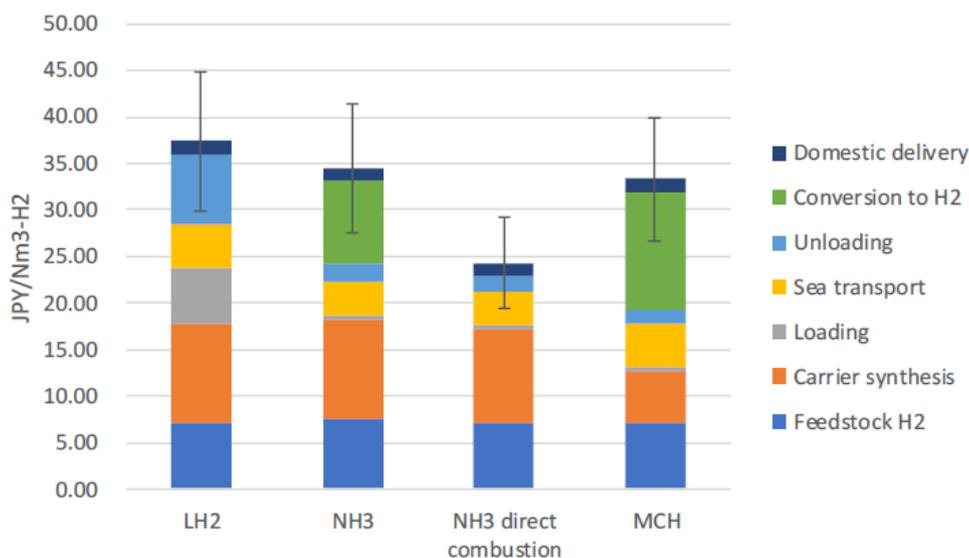
¹⁰² A 50% co-firing study is being currently carried out.

Figure 34: Estimation of Hydrogen Power Generation Cost in 2030



Source: IEEJ [34].

Figure 35: Estimation of Supply Cost of Hydrogen for Power Generation in 2030



Source: IEEJ [34].

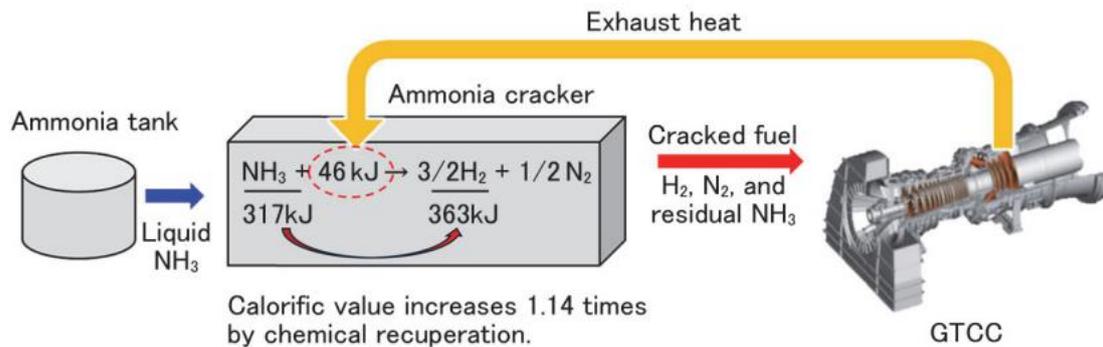
The world's first ammonia fuel power generation was realized in August 2014 using an ammonia micro gas turbine with a maximum output of 50 kW at the test facility of The Fukushima Renewable Energy Institute (FREI) of The National Institute of Advanced Industrial Science and Technology (AIST) and in collaboration with the Institute of Fluid

Science of the Tohoku University (IFS) and Toyota Energy Solutions. Initially, they achieved a stable power output of 21 kW burning a mixture of 70% kerosene and 30% ammonia. In September 2015, they reached a power of 41.8 kW using both a methane-ammonia mixed gas, and 100% ammonia fuel, indicating that ammonia could be used as a fuel for thermal power¹⁰³. In both tests, it was possible to reduce NOx emissions well below MOE's NOx emission standards by adding an appropriate amount of ammonia to the post-combustion exhaust gas and processing the NOx in a NOx removal unit.

Later, IFS found that using a combustion concept in two stages, rich and lean, NOx and unburnt ammonia concentrations in the exhaust gas could be simultaneously reduced in a gas turbine using the model swirl burner [35]. This study was supported by the Council for Science, Technology and Innovation (CSTI) and the Ammonia Direct Combustion research theme of the SIP's Energy Carrier project (Chapter 3.4.1).

MHPS has been also participating in the SIP's Energy Carrier program and studying gas turbine systems using ammonia as a fuel in micro and small gas turbines. The system thermally cracks ammonia to hydrogen and burns it in a gas turbine without efficiency reduction (Figure 36). Because the major development equipment is the ammonia cracker, only relatively small number of modifications on the gas turbine side, such in the hydrogen combustor, have to be done, making this system applicable to high-efficiency large-capacity GTCC systems, and thereby contribute to a large reduction of the CO₂ emissions by using CO₂-free ammonia [32].

Figure 36: Concept of Ammonia Decomposition Gas Turbine Cycle



Source: MHPS [32].

The gas turbine power was enlarged to 2 MW power output by IHI in March 2018. IHI and IFS developed the world's first technology for direct combustion of ammonia in a gas turbine (ammonia-fired gas turbines - AGTs), establishing a technology for stably burning ammonia

¹⁰³ Japan Science and Technology Agency: <https://www.jst.go.jp/EN/achievements/research/bt111-112.html>.

while suppressing the production of NO_x¹⁰⁴. They used a 20% NH₃ co-firing with city gas (methane - CH₄).

The roadmap of ammonia supply chain established the commercialization target of small size AGTs, around 0.3 MW, by 2020, middle size AGTs, around 2 MW, in the mid-2020s and of large-scale AGTs, around 100 MW, in the late 2020s (Figure 46).

Regarding industrial furnaces, Osaka University and Taiyo Nippon Sanso Corporation conducted joint research in 2016 about using ammonia as a fuel in industrial furnaces, achieving a combustion technology that reduces CO₂ emissions, NO_x generation below environmental standards, and increases the heat transfer from the flame¹⁰⁵. They used methane (CH₄) and 30% ammonia mixed fuel, achieving an equivalent heating efficiency of 55% with that of 100% CH₄ fueled industrial furnace. For this experiment, Taiyo Nippon Sanso Co. built a burner for oxygen-enriched air designed for single ammonia combustion and methane co-combustion in a 10kW model combustion furnace.

Later, researchers from Taiyo Nippon Sanso Corporation, Nisshin Steel Co. Ltd., and Osaka University, developed a burner for ammonia combustion that can be used for pretreatment (degreasing) of galvanized steel sheets. They verified that methane combustion with 30% of ammonia increased energy efficiency and reduce CO₂ emissions by 50% compared to existing furnaces, achieving also the same or even better level of degreasing than using only methane¹⁰⁶.

3.3.1. Co-firing of ammonia in coal power plants

Japan aims to co-fire ammonia and coal at coal power plants by around 2020 and use ammonia for gas turbines by around 2030. Co-firing ammonia in a coal-fired power plant is under demonstration in Japan. IEA expects that around 1,250 GW of coal power plants worldwide currently in operation or under construction could have an extra life after 2030 using a 20% share of ammonia as fuel, reducing the same percentage of CO₂ emissions [36]. In Japan, reaching a 20% blending share would result in an annual ammonia demand of 35 million tonnes and around 3% reduction of total national CO₂ emissions, about 40 million tons per year¹⁰⁷.

Coal accounts for about 30% of the national total power generation. Reconditioning old coal power plants with ammonia combustion technology would probably increase energy generation

¹⁰⁴ NH₃ Fuel Association, 1 October 2017: <https://nh3fuelassociation.org/2017/10/01/methods-for-low-nox-combustion-in-ammonia-natural-gas-dual-fuel-gas-turbine-combustor/>.

¹⁰⁵ Research at Osaka University, 31 October 2016: https://resou.osaka-u.ac.jp/en/research/2016/20161031_5.

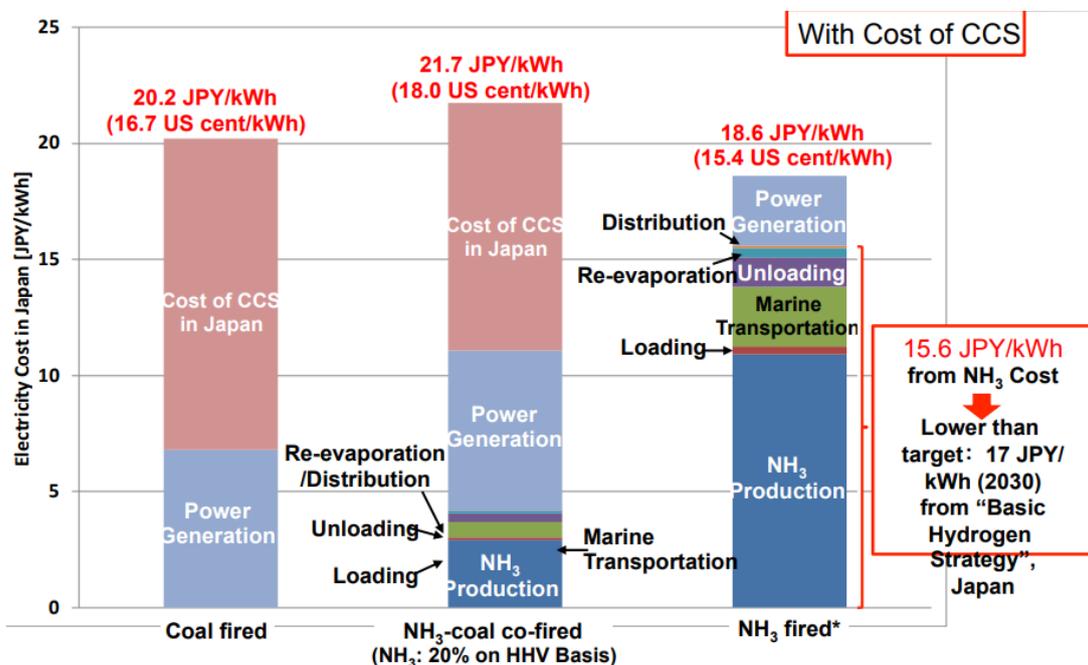
¹⁰⁶ Research at Osaka University, 26 June 2017: https://resou.osaka-u.ac.jp/en/research/2017/20170626_2.

¹⁰⁷ Ammonia Energy, 18 July 2019: <https://www.ammoniaenergy.org/the-evolving-context-of-ammonia-coal-co-firing/>.

costs by 30% to around JPY 7 per kWh, but still cheaper than the energy generated by nuclear plants, around JPY 10 per kWh, and natural gas plants, about JPY 14 per kWh¹⁰⁸.

According to the Japanese engineering company JGC [37], the current electricity cost of coal-fired generation in Japan is around JPY 6.5 per kWh, increasing up to an estimated JPY 20.2 per kWh if the cost of CCS in Japan is included. If ammonia for 20% co-firing rate (intermediate goal) is produced in the United Arab Emirates in combination with CCS, the electricity cost would be about JPY 21.7 per kWh, being competitive compared to the previous option. Furthermore, it estimated that burning imported green ammonia (ultimate goal) will have a cost of around JPY 18.6 per kWh, what means that the cost of the hydrogen supply chain would be lower than the target set by the Basic Hydrogen Strategy by 2030 (Figure 37).

Figure 37: Estimation of Electricity Cost with Coal-fired, Ammonia-fired and a Mix-fired Generation



Source: JGC [37].

In January 2017, the Central Research Institute Electric Power Industry (CRIEPI) disclosed technical data of co-firing experiments. In these experiments, the feeding condition of ammonia was studied to minimize NOx concentration by using the same type of pulverized coal burner used in mayor coal power plants in Japan. When ammonia was injected into the appropriate position from the sidewall of the furnace, co-firing of pulverized coal and 20% ammonia could be performed stably without increasing NOx in the exhaust gas.

¹⁰⁸ Nikkei Asian Review, 2 March 2017: <https://asia.nikkei.com/Business/Deals/Japanese-utilities-team-on-CO2-reducing-tech-for-coal-plants>.

In March 2017, it was reported that KEPCO, Chubu Electric Power, Tohoku Electric Power and other three utilities joined efforts to commercialize the technology for co-firing ammonia with coal in power plants in the early 2020s, which could reduce CO₂ emissions by at least 20%¹⁰⁹. They are participating in the government's research on ammonia as an energy source, based on the results got by Tohoku University and other institutions. The project also seeks to limit NO_x emissions from ammonia to levels that can be handled with existing scrubber technology.

In July 2017, Chugoku Electric Power Corporation, with support from the Japan Science and Technology Agency, conducted a test to co-firing ammonia and coal at Unit 2 of its Mizushima power plant in Kurashiki City, Okayama Prefecture. This was the first time that ammonia was burned in a commercial power plant in Japan, and it was part of the Ammonia Direct Combustion project under the SIP Energy Carrier program¹¹⁰ (Chapter 3.4.1).

Ammonia was added continuously to the 155 MW coal-fired plant at the rate of 450 kg/hour, equivalent to 400 kilograms of coal, representing 0.6% of total fuel in terms of total energy content. The power efficiency was maintained with the addition of the ammonia even when a decrease in CO₂ was observed. By reducing the plant's output to 120 MW, the added ammonia represented 0.8%, equivalent to 1 MW. It was not observed an increase of NO_x nor NH₃ concentration in the exhaust gas. Along with this, the concentration of NO_x tended to decrease under certain conditions in the combustion method. Therefore, it was proved that this ammonia co-firing technology enables to reduce CO₂ emissions from coal power generation utilizing existing facilities, including existing denitration equipment, and thus will be cost-effective [38].

In September of that year, Chugoku announced that it had filed a patent application for a “clean-power technology that involves co-firing ammonia with coal”. The announcement also mentioned the company's intention to develop the co-firing method so that mixtures of up to 20% ammonia could be applied¹¹¹. Higher blending shares of up to 20% ammonia in energy terms might be feasible with only minor adjustments to a coal power plant. In smaller furnaces with a capacity of 10 MW thermal, blending shares of 20% ammonia have been achieved without problems, and in particular without any slippage of ammonia into exhaust gas [36].

In December 2017, the Japanese manufacturer IHI Corporation started the demonstration of the co-firing of coal and 20% of ammonia at its large-capacity combustion facility of 10 MW in Aioi City, Hyogo Prefecture. This is also part of the Ammonia Direct Combustion project under the SIP Energy Carrier program¹¹². It developed its own system for delivering ammonia to the combustion zone, including the shape of the piping, optimized to suppress NO_x emissions. In March 2018, IHI announced that it reached the 20% goal maintaining NO_x emissions at a

¹⁰⁹ Nikkei Asian Review, 2 March 2017: <https://asia.nikkei.com/Business/Deals/Japanese-utilities-team-on-CO2-reducing-tech-for-coal-plants>.

¹¹⁰ Chugoku Electric Power Co., 8 September 2017: <http://www.energia.co.jp/press/2017/10697.html> (in Japanese).

¹¹¹ Ammonia Energy, 12 April 2018: <https://www.ammoniaenergy.org/ihi-first-to-reach-20-ammonia-coal-co-firing-milestone/>.

¹¹² IHI Corporation, 28 March 2018: https://www.ihi.co.jp/ihi/all_news/2017/technology/2018-3-28/index.html.

similar rate that a coal-only firing, while greatly reducing CO₂ emissions. In the meantime, it has been studying pertinent aspects of co-firing combustion in collaboration with Osaka University and Tohoku University.

IHI's aim is to commercialize the system by 2020, considering also “the possibility of further lowering NO_x by evaluating the impact on boiler performance and selection of operating conditions”. Its ultimate goal is to build a value chain that connects the production and use of ammonia, using it as fuel for gas turbines and coal-fired boilers, and for SOFC. It is also proceeding with a demonstrating technology for producing hydrogen from biomass in Indonesia by means of the twin IHI gasifier TIGAR¹¹³.

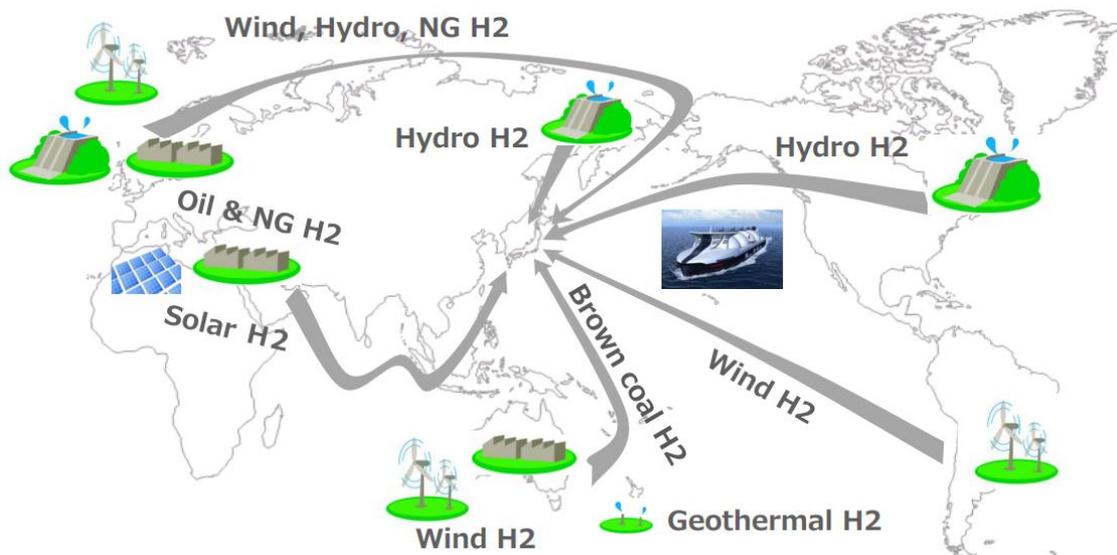
¹¹³ IHI Corporation: <https://www.ihico.jp/csr/english/realize/future.html>.

3.4. SUPPLY CHAINS AND HYDROGEN CARRIERS

Realize a hydrogen society in Japan implies the necessity of both expanding hydrogen demand and the construction of reliable supply chains to meet that demand at a low cost. The Japanese government has been supporting demonstration projects for building supply chains from overseas to produce green hydrogen from renewable sources or from fossil fuels plus the carbon capture and storage. Indeed, the government has increased the budget for the hydrogen supply chain year over year (Table 1). It was JPY 2.8 billion in FY 2016, JPY 4.7 billion in FY 2017 and JPY 9.4 in FY 2018. Australia, Brunei, Saudi Arabia and Norway are countries where Japanese firms are working on the production, conversion, transportation, storage and utilization of hydrogen, with the collaboration and funds from the government.

The use of brown coal and other fossil fuels implies environmental concerns that could compromise their future unless combining with the CCS technology. On the other hand, hydrogen can be a way to transport renewable energy over long distances. This is, regions with abundant and cheap renewable potential, such as Australia, Chile, Argentina, Canada or Middle Eastern countries could produce hydrogen and transport it to regions with high demand but either less renewable potential and/or higher costs of generating it, such as Japan and South Korea.

Figure 38: Global Hydrogen Supply Chain



Source: Kawasaki Heavy Industries.

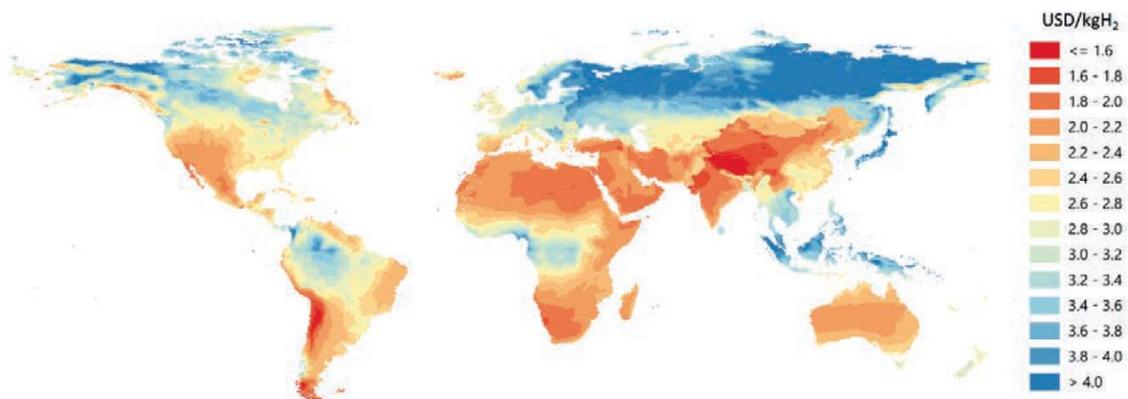
Though the government’s Strategy did not mention any supply chain for importing hydrogen produced through renewable energies, there are two demonstration projects in Australia and

Norway studying this option. Additionally, New Zealand, another country rich in renewable resources that could produce hydrogen for both domestic and export purposes, signed a Memorandum of Cooperation on Hydrogen with Japan in October 2018¹¹⁴.

Research, development and demonstration of hydrogen technologies with industry-academia-government collaboration under the leadership of the government will contribute significantly to solve energy and environment problems in Japan, and it will lead Japan a world leader in hydrogen utilization and related industries.

IEA forecasted that hydrogen produced in Australia through electrolyzers powered by solar and wind could replace 3% of the world's gas consumption. The cost could come in at USD 3 per kilogram of hydrogen in 2040 (Figure 39). This makes it cheaper than doing so using natural gas through steam methane reformation when the costs of CCUS are included. IEA pointed out that costs could be lower if the Australian's government provided support for such projects, or solar, wind and/or electrolyzer costs declined quicker than expected¹¹⁵.

Figure 39: Hydrogen Costs from Hybrid Solar PV and Onshore Wind Systems in the Long Term



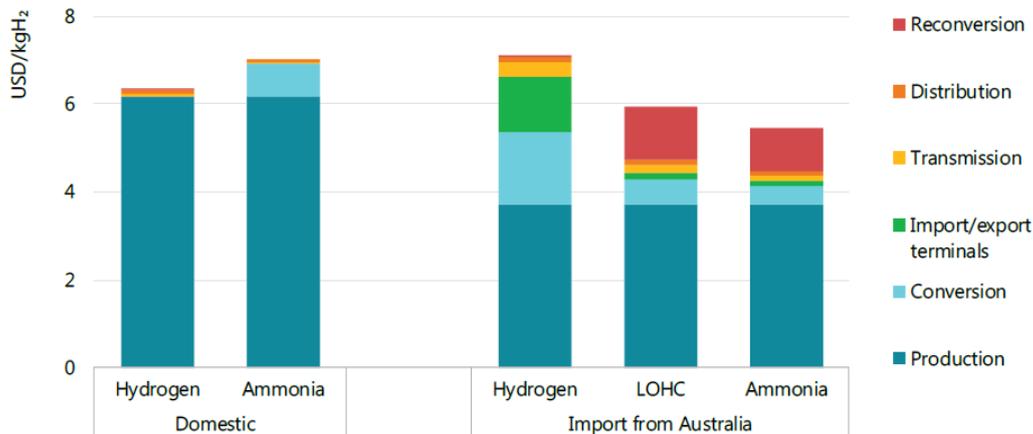
Source: IEA [36].

According to IEA, domestic production of hydrogen in Japan using electrolyzers and its distribution could cost around USD 6.5 per kilogram in 2030, while importing it from Australia could cost around USD 5.5 per kilogram (Figure 40). The latter includes also the conversion, transportation and reconversion costs, around USD 1.5 per kilogram. In this sense, ammonia will be even more attractive since it could be used directly, avoiding the additional costs of reconverting it back into hydrogen, and becoming the cheapest mechanism for import hydrogen from Australia or other locations to Japan [36].

¹¹⁴ METI, 23 October 2018: https://www.meti.go.jp/english/press/2018/1023_006.html.

¹¹⁵ PV Magazine, 13 November 2018: <https://www.pv-magazine-australia.com/2018/11/13/iea-world-energy-outlook-highlights-viability-of-australian-green-hydrogen/>.

Figure 40: Cost of Hydrogen and Ammonia in Japan and exported from Australia to Japan in 2030



Source: IEA [36].

In September 2018, the Australian Renewable Energy Agency (ARENA) offered USD 22.1 million in funding 16 green hydrogen export research projects to nine Australian universities and research organizations including: the Australian National University, Macquarie University, Monash University, Queensland University of Technology, RMIT University, The University of Melbourne, University of New South Wales, The University of Western Australia and the Commonwealth Scientific and Industrial Research Organization (CSIRO)¹¹⁶. ARENA pointed out that Australia could build an export industry worth USD 1.7 billion by 2030, with employment for 2,800 people, becoming the world’s largest producer and exporter of green hydrogen using solar and wind power¹¹⁷. Additionally, the Queensland government launched a USD 19 million five-year plan to help drive the development of a renewable hydrogen industry¹¹⁸.

The Asian Renewable Energy Hub project will also build 7.5 GW of wind generation and 3.5 GW of solar generation in Western Australia, with 8 GW of those used to produce green hydrogen for domestic and overseas markets¹¹⁹.

According to the estimations of the Asia Pacific Energy Research Center (APERC) in its economic analysis of hydrogen supply in the APEC Region [39], the production of hydrogen from fossil fuels plus CCS will cost between USD 7 cents/Nm³ and 23 cents/Nm³ by 2030, and between USD 7 cents/Nm³ and 23 cents/Nm³ from renewable sources (Figure 41). Although several assumptions were done in that analysis that could lead to not accurate calculations that

¹¹⁶ ARENA, 12 September 2018: <https://arena.gov.au/blog/22-million-to-unlock-hydrogen-potential/>.

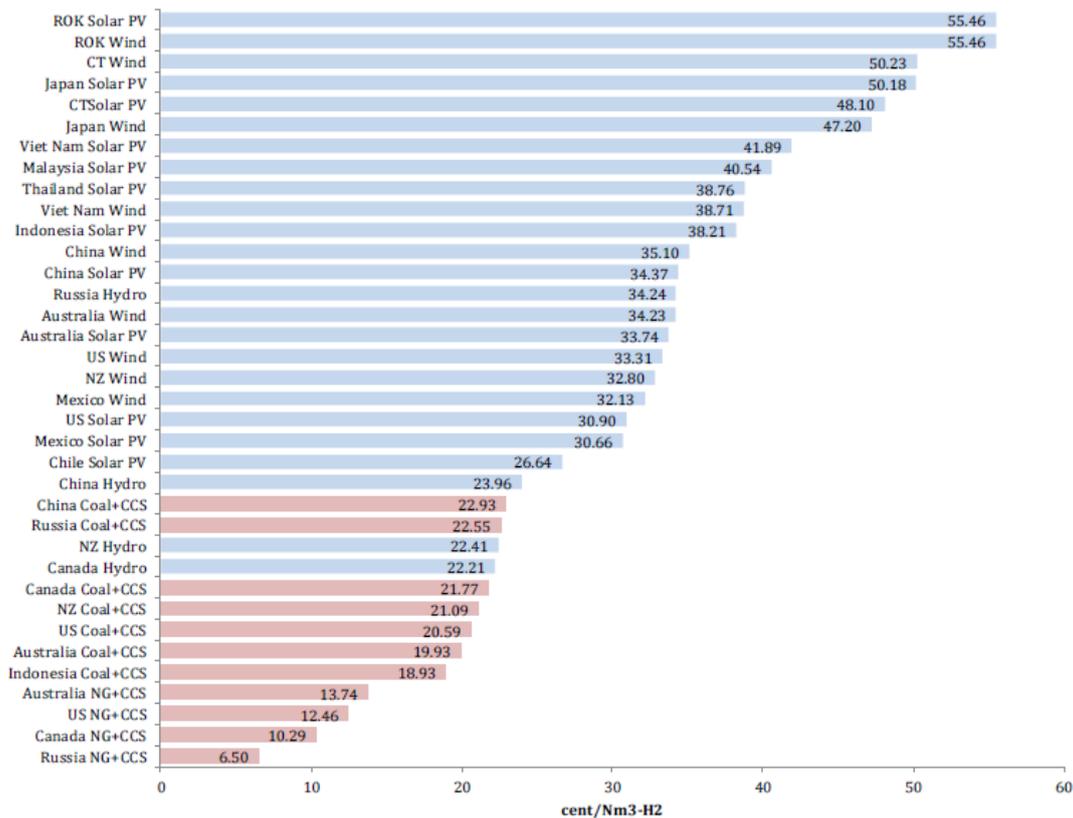
¹¹⁷ PV Magazine, 18 August 2018: <https://www.pv-magazine-australia.com/2018/08/18/australia-has-big-hydrogen-export-opportunity/>.

¹¹⁸ PV Magazine, 1 June 2019: <https://www.pv-magazine-australia.com/2019/06/01/queensland-launches-19-million-hydrogen-strategy/>.

¹¹⁹ The Asian Renewable Energy Hub: <https://asianrehub.com/about/>.

will need to be updated when more data become available, it is enough to get a reference about which countries and sources will have the cheapest costs in the APEC Region. This is especially important for Japan in order to estimate the feasibility of international supply chains that will fulfil future demand.

Figure 41: Production Cost of CO₂-free Hydrogen in APEC Region in 2030

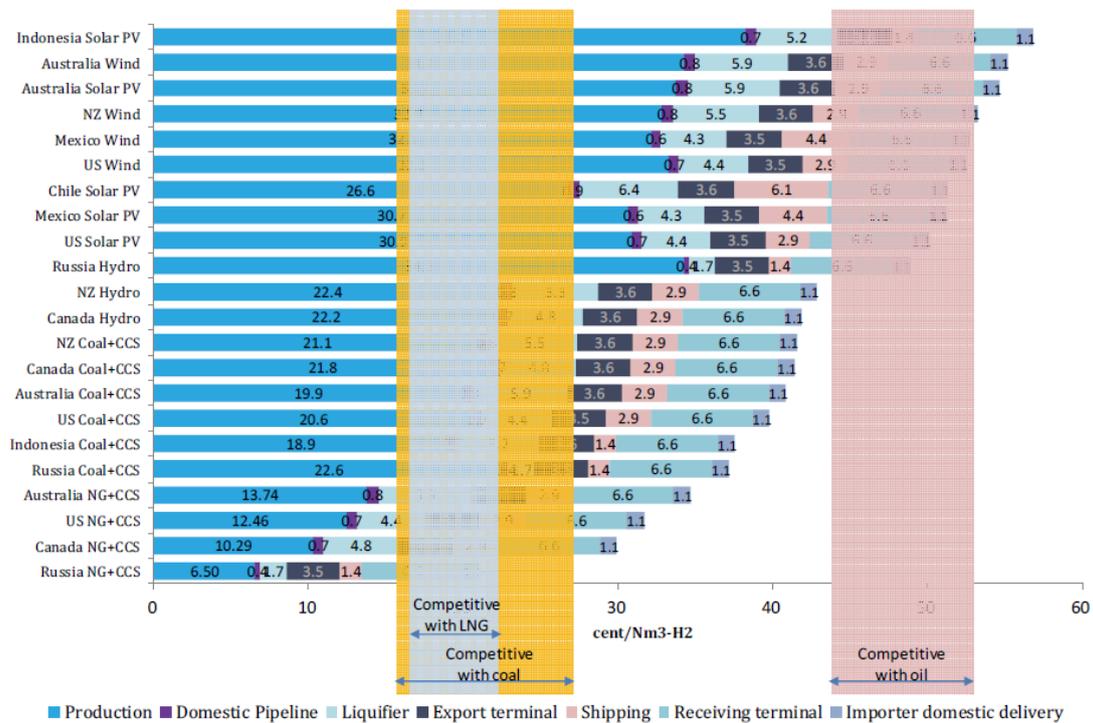


Source: APERC [39].

According to that calculation, the cost of supply liquefied hydrogen (energy carrier selected for all the options) for power generation would need to be between USD 16 cents/Nm³ and 27 cents/Nm³ or less by 2030 to compete with coal-fired power generation, between USD 17 cents/Nm³ and 22 cents/Nm³ or less to compete with LNG power generation, and between USD 44 cents/Nm³ and 53 cents/Nm³ or less to compete with oil-fired power generation (Figure 42). They included the environmental cost of thermal power generation, this is, the cost of CO₂ emission countermeasures.

Hydrogen from Russia produced from natural gas combined with CCS would offer the lowest price. The cost of importing hydrogen from Canada or New Zealand produced from hydropower could be comparable to the one imported from Australia and produced from coal plus CCS, saving the environmental implications and the risk of the CCS technology.

Figure 42: Hydrogen Supply Cost for Power Generation and Required Hydrogen Fuel Price for Competing with Fossil Fuel Thermal Power Generation in Japan in 2030



Source: APERC [39].

Finally, supply CO₂-free hydrogen for FCVs in a station with a capacity of 300 Nm³/h or less, the more extended in Japan, will cost between USD 69 cents/Nm³ and 105 cents/Nm³. For a bigger one, the cost will drop to between USD 36 cents/Nm³ and 72 cents/Nm³ due to lower maintenance and operation costs (Figure 43). Produce hydrogen from Japanese renewable sources could be comparable to import it from overseas when it is also produced from renewable sources, though more expensive when it is produced from fossil fuels plus CCS. This cost is added to the hydrogen import cost mentioned above.

3.4.1. Energy Carriers

Since hydrogen is difficult to handle being gaseous at normal state, energy carriers are the technology to efficiently store and transport it, including liquid hydrogen, compressed hydrogen, methylcyclohexane (MCH) and anhydrous ammonia (NH₃). Pipelines, trailers, ships and railroads are transport means. Today, compressed or liquefied hydrogen are utilized for supply, while liquid hydrogen, MCH and ammonia are regarded as the most promising hydrogen carriers. Besides, ammonia is also available for direct use. Japan is also studying how best to

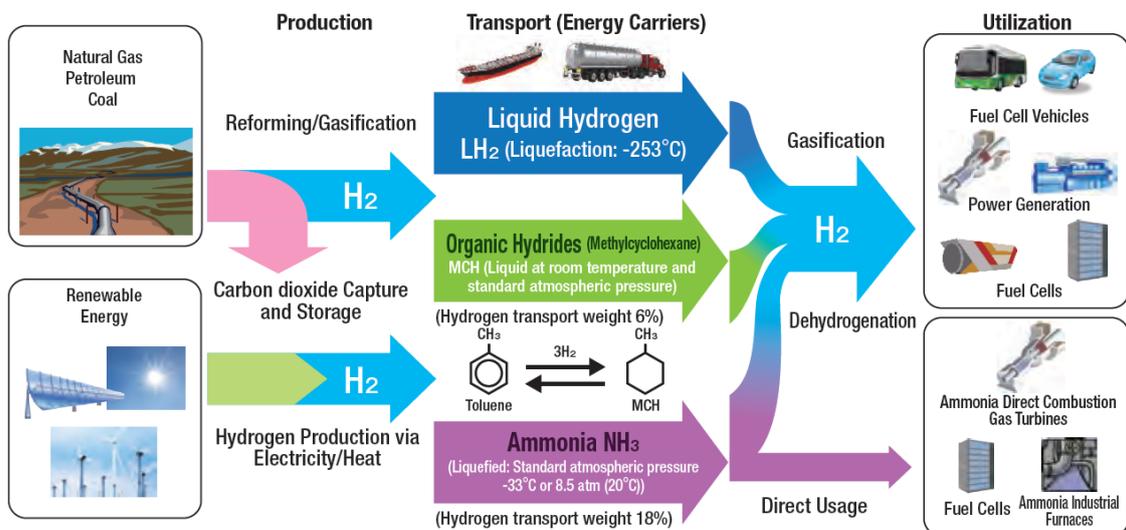
disseminate methane, which is assumed to be available exclusively for direct use. It is produced through the methanation process, which can use CO₂-free hydrogen generated from renewable resources. Figure 44 shows the strategy of the Japanese government to develop a CO₂-free hydrogen value chain, and Table 11 shows the properties of the main energy carriers.

Figure 43: Hydrogen Fuel Cost for FCV in Japan in 2030



Source: APERC [39].

Figure 44: Strategy of Energy Carriers – Development of CO₂-free Hydrogen Value Chain



Source: Cross-Ministerial SIP [15].

Table 11: Physic-chemical properties of Hydrogen Carriers

		Liquid Hydrogen	Organic Hydride (MCH)	Ammonia
Molecular Weight		2.0	98.2	17.0
H ₂ Content (wt %)		100	6.2	17.8
Volumetric H ₂ Density (kg-H ₂ /m ₃)		70.8	47.3	121
Boiling Point (°C)		-253	101	-33.4
H ₂ Release Enthalpy Change (KJ/mol-H ₂)		0.9	67.5	30.6
Other Properties		High purity Low energy to pressurize	Existing oil infrastructures can be utilized	High H ₂ density Direct use for combustion
Process and Technology Maturity*	Conversion	Small scale: High Large Scale: Low	Medium	High
	Tank Storage	High	High	High
	Transport	Ship: Low Pipeline: High Trucks: High	Ship: High Pipeline: High Trucks: High	Ship: High Pipeline: High Trucks: High
	Reconversion	High	Medium	Medium
	Supply Chain Integration	Medium / High	Medium	High

* High = proven and commercial; Medium = prototype demonstrated; Low = validated or under development;
Small scale ≤ 5 tonnes per day; Large scale ≥ 100 tonnes per day.

Source: Author, with data from Cross-Ministerial SIP [15] and IEA [36].

Pipelines could become in the best way to transport massive amounts of hydrogen, and there are several projects going on about that. From 2030, local hydrogen networks will be needed in coastal regions in line with the commercialization of the international hydrogen supply chains. At present, hydrogen for pipeline supply to residential, commercial and other ordinary users must be odorized by law to allow verification of gas leaks, but odorants could damage the fuel cell stacks. The government is considering revising regulations on this area [9].

The government leads the industry-academia-government R&D collaboration program “SIP Energy Carriers”, which was launched in FY 2014 and during five years, until FY 2018, as one of the eleven themes of the Cross-ministerial Strategic Innovation Promotion Program (SIP), created by the Council for Science, Technology and Innovation of the Cabinet Office. Its budget is around USD 30 million per year.

The scope of the Energy Carriers program covers ten themes divided into five main topics that encompass the full CO₂-free hydrogen value chain, from basic research to practical application and commercialization, creating a competitive advantage for its national industries, and

promoting the introduction of hydrogen and hydrogen energy carriers in society (Figure 45). These are 1) the development of hydrogen production through solar thermal energy, 2) the development of ammonia production/usage technologies, 3) the development of organic hydride production/usage technologies, 4) the development of liquid hydrogen usage technologies, and 5) the development of safety evaluation systems for energy carriers¹²⁰.

Figure 45: R&D Schedule until FY 2018

FY	2014	2015	2016	2017	2018
Hydrogen Production Using Solar Thermal Energy					
① High-Temperature Solar Heat Supply System	Component Technology Development (solar thermal receiver tubes, heat transfer fluid material, thermochemical energy storage system, etc.)				Feasibility Study
② Hydrogen Production via Heat	Component Technology Development (IS process, steam electrolysis)			Systemization/Improvement	Demonstration Evaluation
Ammonia Production/Usage Technologies					
③ Ammonia Using CO ₂ -Free Hydrogen	Component Technology Development, System Design			Systemization	System Demonstration
④ Ammonia Hydrogen Station Infrastructure Technology	Component Technology Development			Systemization	Feasibility Study
⑤ Ammonia Fuel Cells	SOFC Component Technology Development, Stack Prototype Evaluation		SOFC Module Prototyping/Systemization		System Demonstration
⑥ Ammonia-Based Direct-Combustion	Component Technology Development (heat transfer enhancement of the flame, low-NO _x -emission, etc.)			Equipment Design, Prototyping, Improvement	System Demonstration
Organic Hydride Production/Usage					
⑦ Develop Hydrogen Supply Technology Using Organic Hydride	Component Technology Development			Optimization/Establishment of Mass Production Technology	
	Dehydrogenation Pilot Equipment Production/Operation Verification			Design of Commercial Prototype, Acquisition of Safety Data	Feasibility Study
Liquid Hydrogen Usage Technologies					
⑧ Develop Loading Systems and Rules for Liquefied Hydrogen	Basic Research into System, Specifications and Structure; Measures for Loading/Unloading Procedures		Production and Performance Testing, Accident Scenarios, Risk Assessment Studies, Development of Operational Conditions, etc.		System Demonstration, Making a Draft International Standards
⑨ Develop Hydrogen Engine Technologies	Component Technology Development (hydrogen spark plug, high-efficiency combustion technology, hydrogen injectors, etc.)				Model Demonstration
Development of Energy Carrier Safety Evaluation Systems					
⑩ Energy Carrier Safety Evaluation Research	Social Risk Assessment, Safety Assessment for Each Carrier, Database Construction			Safety Requirements and Countermeasures Study	Comprehensive Evaluation

Source: Cross-Ministerial SIP¹²¹.

Each of these ten projects is described in the following lines [15]:

1. High-Temperature Solar Thermal Energy Supply System

Research Director: Yukitaka Kato - Professor Laboratory for Advanced Nuclear Energy, Tokyo Institute of Technology.

Purpose: Development of high-temperature (650°C) solar thermal energy supply system to produce H₂ efficiently by the introduction of a new solar thermal corrector, collecting tube, heat transfer media and thermal energy storage technologies.

Research outline: The team is aiming that ammonia which has high volume hydrogen density is produced as an energy carrier by hydrogen produced from solar thermal energy supply system. High-temperature (650°C) solar thermal energy collection system with more than 70% of solar radiation and heat collection efficiency in which the temperature is

¹²⁰ Cross-ministerial SIP: <http://www.jst.go.jp/sip/> (in Japanese).

¹²¹ Cross-ministerial SIP: https://www8.cao.go.jp/cstp/panhu/sip_english/21-24.pdf.

higher than the conventional solar thermal system is developed. Elemental technologies of a solar corrector, heat transfer fluid, solar thermal energy correction tube, and thermal energy storage for 24-hour heat supply to H₂ production system are developed.

1. Hydrogen Production Technology Using Solar Heat

Research Director: Nariaki Sakaba - Group Leader, HTGR Hydrogen & Heat Application Research Center, Japan Atomic Energy Agency.

Purpose: Development of highly efficient hydrogen production technologies by water splitting without CO₂ emission using solar heat at around 650°C.

Research outline: Development of elemental technologies and demonstration of technical feasibility will be performed for the following two hydrogen production methods: 1) Membrane IS Process: hydrogen production by thermal water splitting using chemical reactions with iodine and sulfur, and membrane technologies, and 2) New steam electrolysis: hydrogen production by steam splitting with proton conducting oxide using electricity and heat.

2. Development of Ammonia Synthesis Process from CO₂- Free Hydrogen

Research Director: Yasushi Fujimura - General Manager, R&D Center, Technology Innovation Center, JGC Corporation.

Purpose: Development of high-efficiency ammonia synthesis process from CO₂-free hydrogen produced from renewable energy or fossil fuel.

Research outline: Major R&D item is the development of ammonia synthesis catalyst with high activity at low temperature. The pilot plant will be constructed and operated in 2018 to confirm the performance of the new catalyst and process.

3. Basic Technology for Hydrogen Station Utilizing Ammonia

Research Director: Yoshitsugu Kojima - Director, Institute for Advanced Materials Research, Hiroshima University.

Purpose: The purpose of this research is to develop ammonia decomposition and high purity H₂ supply system for a hydrogen filling station.

Research outline: High purity H₂ supply system with low-cost hydrogen transportation is a key issue to spread fuel cell vehicles (FCVs) and FC forklifts. In this theme, we focused on ammonia as a hydrogen carrier because of high gravimetric and volumetric H₂ densities. We will develop a high purity H₂ supply system, which satisfies hydrogen fuel specifications for FCVs (ISO 14687-2) by NH₃ decomposition and separation technologies.

4. Ammonia Fuel Cell

Research Director: Koichi Eguchi - Professor, Graduate School of Engineering, Kyoto University.

Purpose: Development and demonstration of highly effective ammonia-fueled fuel cell systems.

Research outline: Developing the direct ammonia-fueled SOFC systems and demonstrating 1 kW-scale power generation systems (main target). Investigating the combined systems as follows: (1) ammonia auto-thermal cracker and SOFC; (2) ammonia cracker and AEMFC

(sub-target). Elucidating the compatibility of ammonia for the fuel cell systems and the degradation behaviour of the ammonia-fueled fuel cells.

5. Ammonia Direct Combustion

Research Director: Hideaki Kobayashi - Professor, Institute of Fluid Science, Tohoku University.

Purpose: To develop ammonia direct combustion technology to utilize ammonia which is a hydrogen energy carrier as well as a CO₂ - free fuel.

Research outline: Highly efficient utilization of ammonia combustion such as 1) Gas turbine power generation using ammonia alone and ammonia/natural-gas mixed fuel, 2) Application of ammonia reciprocal engines for transportations, and 3) Heat utilization in industrial furnaces using ammonia as a fuel This project performs technology development and verification tests based on fundamental combustion research.

6. Development of Hydrogen Supplying Technology Based on Organic Hydride

Research Director: Hideshi Iki - Principal Researcher, Central Technical Research Laboratory, JX Nippon Oil & Energy Corporation.

Purpose: To develop a practical hydrogen refueling station and hydrogen supplying system based on organic hydride technology.

Research outline: The followings are focused to develop a modular dehydrogenation system for hydrogen refueling stations: (1) Improving performance of the dehydrogenation catalyst; (2) Improving efficiency & reducing the size of modular dehydrogenation system; (3) Developing low-cost hydrogen purification system; (4) Conducting safety assessments Technologies for efficient organic hydride production are also being developed. A further goal is to develop organic-hydride based hydrogen refueling stations and to promote widespread adoption of FCVs.

7. Development of Cargo Loading/unloading System for Liquid Hydrogen and the Relevant Rules for Operation

Research Director: Tetsuya Senda - Deputy Managing Director, Japan Ship Technology Research Association.

Purpose: This research aims to develop a loading and unloading system for liquid hydrogen and to establish relevant rules for the operation of the system.

Research outline: In the research, swivel joints and emergency release systems for liquid hydrogen are to be developed, based on the existing LNG handling technology, and a loading and unloading system for liquid hydrogen integrating the developed equipment will be constructed. Operational safety measures are also specified and rules and standards will be established for the safe operation of the world-first system. The rules and standards will be internationalized, as necessary.

8. Development of Hydrogen Engine Technology

Research Director: Masahide Kazari - Senior Manager, Technical Institute, Kawasaki Heavy Industries, Ltd.

Purpose: We conduct the research for high efficiency and low-NOx emission hydrogen engine realization.

Research outline: We conduct the following research items for high efficiency and low-NOx-emission open-cycle hydrogen engine which shall be used for power generation or ship propulsion: hydrogen combustion control technology; low-NOx technology; high-pressure hydrogen injector; high-pressure hydrogen pump.

9. Safety Assessment of Energy Carrier

Research Director: Atsumi Miyake - Professor, Center for Creation of Symbiosis Society with Risk, Yokohama National University.

Purpose: The purpose is to build a vital society in which hydrogen energy can be operated safely and sustainably within an acceptable cost in a suitable area.

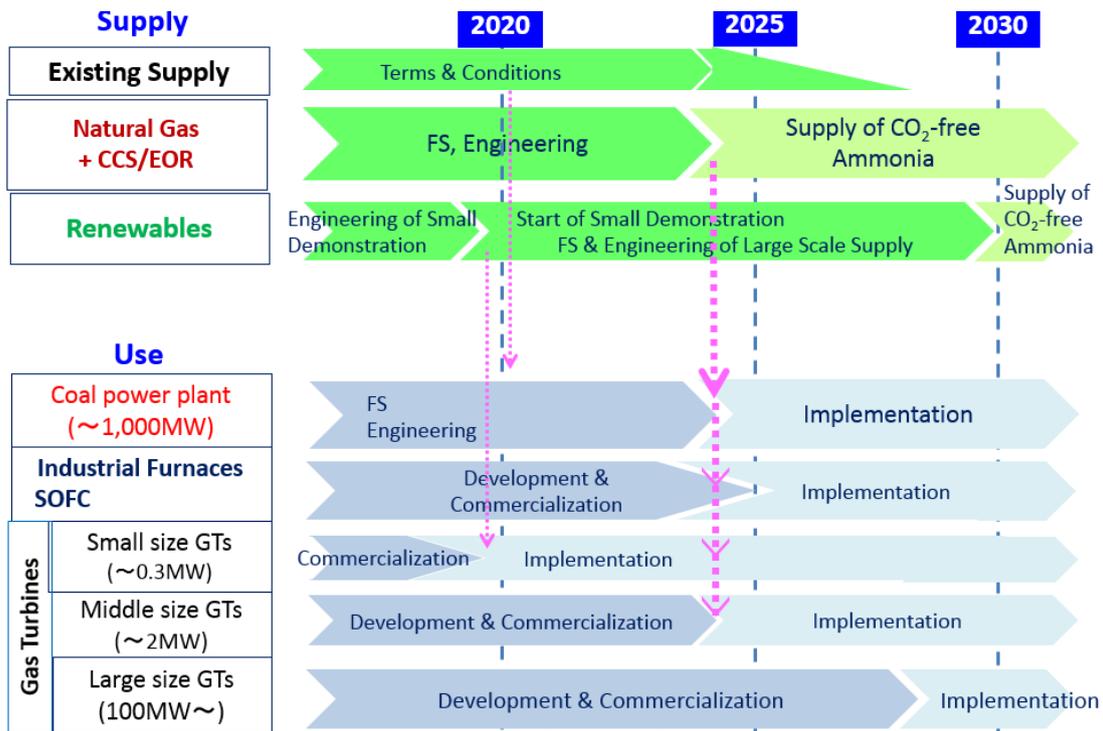
Research outline: Risk assessment and management of the following three supply chain in the transportation, storage, and supply processes are carried out not only from the perspective of the operators and manufacturers but also from the perspective of the citizens: 1) Compressed hydrogen supply chain; 2) Liquid hydrogen supply chain; 3) Organic hydride supply chain.

Ammonia is one of the promising energy carriers as a direct energy source, and the research of its use has produced several accomplishments toward implementation in society. They concluded: “We have found that ammonia has a high potential to play an important role towards the hydrogen society”. Therefore, after the program ended in March 2019, The Green Ammonia Consortium (GAC) was established to support the next phase and with the aim of developing a commercial CO₂-free ammonia value chain toward low carbon society, mainly focusing of its direct use as a CO₂-free fuel.

GAC was originally established in July 2017, though at that time, it was under SIP and membership was only open for the entities participating in SIP “Energy Carriers”¹²². The members developed the Roadmap of Ammonia Supply Chain in 2018 (Figure 46). GAC became an independent organization opened for the global industry in April 2019. By June 2019, it has 66 members among energy, trading, logistics, chemicals and materials, civil engineering, machinery and engineering companies, research institutions and public organizations. Five of them are foreign companies (Equinor ASA, KBR, The Hydrogen Utility, Woodside Energy and Yara International).

¹²² JST, 25 July 2017: https://www.jst.go.jp/report/2017/170802_e.html.

Figure 46: Roadmap of CO₂-free NH₃ Supply Chain



Source: The Green Ammonia Consortium [38].

3.4.2. Liquefied Hydrogen

Liquefied hydrogen (LH₂), as well as compressed hydrogen, have the highest purity among the energy carriers, so they do not need to be processed and can be supplied to fuel cells. Pure hydrogen can be blended into natural gas pipeline networks, though transportation infrastructure from overseas to Japan and nationwide has to be established. When cryogenically cooled to -253 °C, hydrogen changes its phase from a gaseous to a liquid state, shrinking to 1/800 of its original volume. At its reduced volume, storage and transportation efficiency increases, enabling much greater distribution of hydrogen.

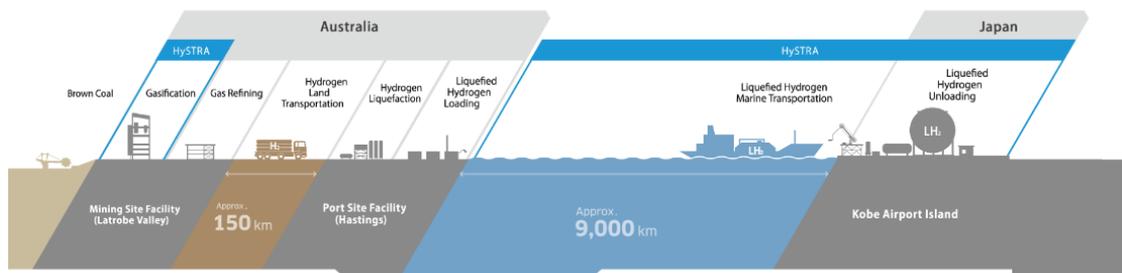
Its main disadvantages are the energy loss during the conversion, between 25% and 45%, the high cost of the infrastructure for cryogenic temperatures and its maintenance, and the daily loss between 0.5% and 1.0% due to boil-off, making LH₂ less efficient for long-term storage compared to other energy carriers [25]. For developers, the classification of LH₂ as a high-pressure industrial gas increases the compliance costs, including large space around fueling stations and high-grade material for facilities. The Japanese government is reviewing the regulation (Chapter 3.2.2).

Australia and Norway are on a race to supply Japan with liquid hydrogen. The Australian project, producing hydrogen from brown coal, was already included in the national Strategy and have several years of developing. Japan aims to establish basic technologies and develop a liquefied hydrogen supply chain through this project. However, Norway wants to produce it from renewable sources at a lower price, which could make the Japanese government change its priorities since it is a climate-friendly method aligned with its long-term goals¹²³.

From Australia’s brown coal

The Hydrogen Energy Supply Chain (HESC) is a world-first pilot project to establish an integrated commercial-scale hydrogen supply chain from Victoria’s Latrobe Valley in Australia to Japan (Figure 47). It will be developed in two phases, a pilot project over one year by 2021, and the decision to proceed to a commercial phase in the 2020s, with operations targeted in the 2030s, depending on the successful completion of the pilot phase, regulatory approvals, social license to operate and hydrogen demand. During the pilot phase, 160 tonnes of inexpensive lignite will be treated to produce 3 tonnes of hydrogen¹²⁴. The brown coal reserves in Australia have the potential to meet Japan’s electricity demand for several hundred years¹²⁵.

Figure 47: Hydrogen Energy Supply Chain Pilot Project between Australia and Japan



Source: CO₂-free Hydrogen Energy Supply-chain Technology Research Association (HySTRA)

Hydrogen will be produced from the gasification of brown coal at the newly constructed hydrogen production plant located at the AGL Loy Yang Complex in the Latrobe Valley. It will be transported by conventional high-pressure tube trailer trucks to a liquefaction and loading terminal at the Port of Hastings. A pipeline is envisaged for the commercial phase. There, hydrogen gas will be liquefied by cooling it to -253 °C. Finally, liquid hydrogen will be shipped to Kobe Airport Island, Japan, approximately once every three months using a world-first

¹²³ Reuters, 28 April 2017: <https://www.reuters.com/article/us-japan-hydrogen-race/norway-races-australia-to-fulfill-japans-hydrogen-society-dream-idUSKBN17U1QA>.

¹²⁴ HESC: <https://hydrogenenergysupplychain.com/about-hesc/>.

¹²⁵ HySTRA: <http://www.hystra.or.jp/en/project/>.

innovative carrier specifically developed for the task by Kawasaki Heavy Industries (KHI) with cryogenic tanks and vacuum insulation to contain the hydrogen and keep it at a very low temperature.

Because there are no established regulations for transporting liquefied hydrogen by sea, the International Maritime Organization adopted tentative safety standards proposed by Japan and Australia for liquefied hydrogen carrier ships in 2016. KHI and Japan will draft international standards to secure stable liquefied hydrogen transportation.

The total project cost was reported to be USD 496 million, spending about half of this investment in Victoria and the rest in infrastructure in Japan and shipping. The project is funding by:

- a Japanese portion, coordinated by HySTRA, established in February 2016 by KHI, Electric Power Development Co., Ltd. (J-POWER), Iwatani Corporation and Shell Japan Limited, which receive funds from the Japanese government. Marubeni Corporation is also a current member. HySTRA is implementing the Demonstration Project for Establishment of Mass Hydrogen Marine Transportation Supply Chain Derived from Unused Brown Coal by NEDO.
- an Australian portion, coordinated by Hydrogen Engineering Australia (HEA), a 100% subsidiary of KHI which comprised of several partners including KHI, J-POWER, Iwatani Corporation, Marubeni Corporation and AGL, and which receives USD 100 million in funds from the Australian and Victorian governments.

KHI estimates an import cost of around JPY 29.8 per Nm³ (about EUR 0.24 per Nm³), being the hydrogen production and liquefaction the two more expensive steps, while CCS cost will make up only 10% (Figure 48).

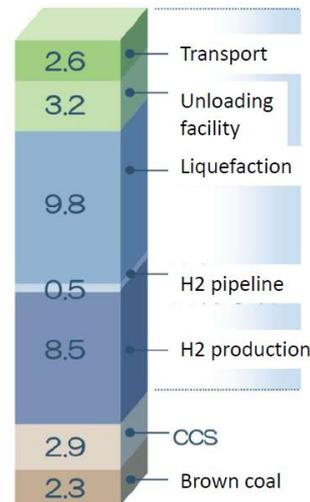
However, this project is being criticized because of the environmental implications and because of its huge cost. While CCS will be a key aspect of the commercial-scale phase, it will not feature during the pilot phase due to the small quantity of CO₂ emitted, around 100 tonnes, equivalent to annual emissions from approximately 20 cars. The related CarbonNet Project¹²⁶, which is jointly funded by the Australian and Victorian Governments, is investigating the potential for establishing a commercial-scale CCS network from the Latrobe Valley to offshore storage sites in the Gippsland Basin.

Without CCS, produce hydrogen from coal gasification is as polluting as the direct burning of coal for power generation, and experts claim that CCS technology will not be at a safe, affordable and usable stage by the time the pilot project concludes, what increases the risk to

¹²⁶ Earth Resources, Victoria State Government: <https://earthresources.vic.gov.au/projects/carbonnet-project>.

move towards the commercial scale¹²⁷. The Australian National Audit Office (ANAO) published a damning assessment of Australia’s CCS program, noting that more than USD 450 million were invested by the government over the past decade without achieving anything¹²⁸.

Figure 48: Cost of Imported Hydrogen from Australia



Source: Kawasaki Heavy Industries.

Additionally, this project was negotiated about ten years ago, before the dramatic cost reduction of solar PV, wind and Lithium-ion battery technologies. To spend USD 500 million to get only 3 tonnes of hydrogen plus 100 tonnes of CO₂ in one year looks no reasonable. Only in Australia, there are projects that will use renewable sources to produce more hydrogen, cheaper and completely clean. Even KHI is also investing in producing hydrogen in Norway from renewable sources.

For example, in the biggest one, the French renewable energy developer Neoen is building a 50 MW electrolyzer powered by a 150 MW wind and 150 MW solar complex at Crystal Brook, north of Adelaide, including also a 400 MWh battery storage. It will cost USD 600 million, and it will produce at least 20 tonnes of hydrogen per day¹²⁹.

Therefore, and although producing hydrogen from Victoria’s brown coal and importing it to Japan would be still cheaper than doing it locally, it seems that this project will have undeniable barriers from both sides to continue in the commercial phase. It looks environmentally and

¹²⁷ Environment Victoria, 13 July 2018: <https://environmentvictoria.org.au/2018/07/13/converting-brown-coal-to-hydrogen-the-dirty-details-on-another-coal-boondoggle/>.

¹²⁸ Renew Economy, 15 December 2017: <https://reneweconomy.com.au/audit-office-slams-australias-dud-investments-in-clean-coal-90953/>.

¹²⁹ Renew Economy, 7 March 2018: <https://reneweconomy.com.au/neoen-plans-worlds-biggest-solar-wind-powered-hydrogen-hub-in-s-a-53674/>.

economically more reasonable to continue with the demonstration of the conversion and transportation of liquefied hydrogen produced just from renewables.

About this, an important person working at NEDO told the author that all the current projects carrying out are in a research and development phase in which Japan will develop new knowledge, technologies, regulations, etc. for future energy systems. Therefore, he claimed that the total cost of all those projects is worth for securing new knowledge. Because Japan has limitations in renewables and CCS, it will need to import a huge amount of hydrogen in the future, taking care of the cost and the carbon footprint of that hydrogen. Australia will have the CCS part ready by 2030 when the commercial phase of this project could start operation.

From Norway's natural gas and renewable sources

In April 2016, it was announced a feasibility study of the potential for large scale hydrogen production in Norway for export to the European and Japanese markets. Hydrogen would be produced from natural gas including the CO₂ capture and store as well as surplus wind/hydropower. The project called HYPER has a budget of around EUR 2 million between 2016 and 2019¹³⁰ and counts with the collaboration of KHI, Mitsubishi Corporation, Nel and Shell, among others. SINTEF Energy Research is the host organization and the lead research partner. Nel aims to deliver liquefied hydrogen to Japan for a minimum JPY 24 per Nm³, cheaper than the hydrogen produced in Australia and mentioned before. If Norway's commercial production goes rapidly, it might be earlier than the Australian one¹³¹, what could make the Japanese government change its priorities since it is a climate-friendly method aligned with its long-term goals.

3.4.3. Organic Hydride – Methylcyclohexane (MCH)

MCH (C₇H₁₄) is the hydrogenated side of a chemical pair that can be used to store and transport hydrogen. Toluene (C₇H₈) is the dehydrogenated part. Therefore, their advantage is their reusability through repeated hydrogenation and dehydrogenation, though, on the other hand, their disadvantage is the additional heat required for dehydrogenation and the time needed to carry out both reactions. This pair is one of a number that has been proposed and studied under the rubric of “liquid organic hydrogen carriers” (LOHCs).

MCH is liquid at ambient temperature and pressure, being easy to handle and transport, and making it suitable for long-term storage. It can be compressed to 1/500 of its original volume.

¹³⁰ SINTEF, 10 June 2016: <https://www.sintef.no/en/projects/hyper/>.

¹³¹ Reuters, 28 April 2017: <https://www.reuters.com/article/us-japan-hydrogen-race/norway-races-australia-to-fulfill-japans-hydrogen-society-dream-idUSKBN17U1QA>.

Transportation, loading and unloading infrastructure, including tankers and tanks, is already established, though it is needed to develop technologies for hydrogenation and dehydrogenation facilities.

From Brunei's natural gas

In July 2017, four major Japanese infrastructure, shipping and trading companies, Chiyoda Corporation, Mitsubishi Corporation, Mitsui & Co. Ltd., and Nippon Yusen Kabushiki Kaisha, established the Advanced Hydrogen Energy Chain Association for Technology Development (AHEAD) and launched the world's first global full-scale hydrogen supply chain demonstration project, in collaboration with the Nation of Brunei¹³².

The project, a subsidized "Technology Development Project to establish Hydrogen Society/Technology Development for the Utilization of Large Scale Hydrogen Energy", is funded by NEDO, and demonstrates "The Hydrogen Supply Chain utilizing the Organic Chemical Hydride Method". With an investment of up to USD 100 million, the pilot project will run for a year to determine the commercial viability of the supply chain.

Hydrogen will be produced by steam reforming from the processed gas derived from the LNG plant of Brunei (Brunei LNG Sdn. Bhd.), and will be supplied as the fuel for the Keihin Refinery Thermal Power Plant, an affiliate of TOA OIL Co., Ltd., which is owned by Showa Shell Sekiyu K.K. It is expected a maximum supply of 210 tons of hydrogen in 2020, equivalent to filling 40,000 FCVs.

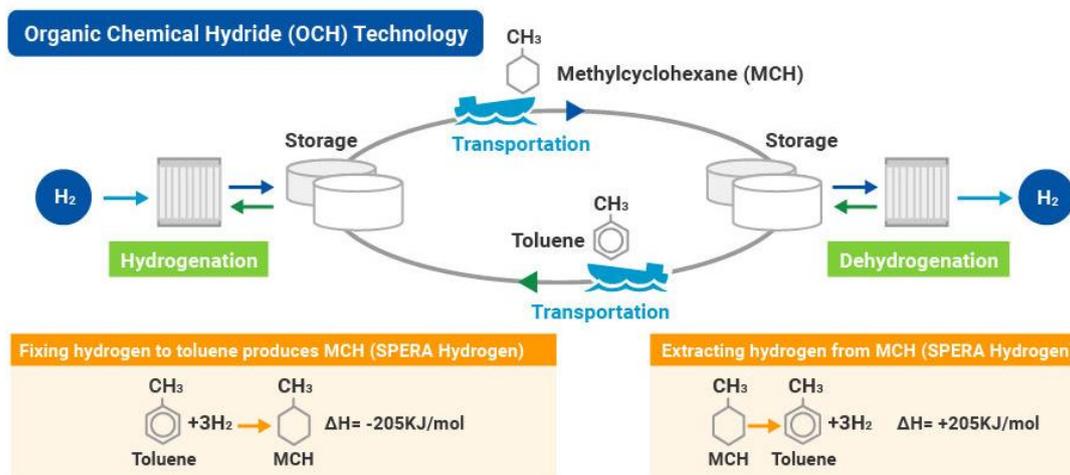
Chiyoda's SPERA Hydrogen technology shown in Figure 49 utilizes the organic chemical hydride method. In the supply country, hydrogen, chemically fixed to toluene, is converted into MCH by hydrogenation reaction for safely and economically storage and transport by ship. In the consumer country, gaseous hydrogen is catalytically extracted from MCH by dehydrogenation reaction and used as power generation fuel in another demonstration project. Toluene, a by-product of this process, is repeatedly recycled as a raw material for producing MCH.

Previously, and after obtaining continuous stable performance of the proprietary dehydrogenation catalyst at laboratory scale, several verification tests for commercial use, including catalyst life and catalyst durability tests, were conducted for around 10,000 hours at the demonstration plant at Chiyoda's Koyasu Office & Research Park in Yokohama. From the commercial-scale demonstration tests, it was confirmed that MCH could be hydrogenated with toluene with yields of over 99%, while hydrogen could be produced from the same MCH with yields of more than 98% through the dehydrogenation process¹³³.

¹³² NEDO, 27 July 2017: https://www.nedo.go.jp/english/news/AA5en_100278.html.

¹³³ Chiyoda Corporation: <https://www.chiyodacorp.com/en/service/spera-hydrogen/demo-plant/>.

Figure 49: Chiyoda's SPERA Hydrogen Technology



Source: Chiyoda Corporation¹³⁴.

The construction of both the hydrogenation plant in Negara Brunei Darussalam and the dehydrogenation plant in the Kawasaki's coastal region of Japan will be completed by 2019. The demonstration transport of liquid hydrogen procured in Brunei will be conducted in 2020¹³⁵.

SPERA Hydrogen can be inexpensively transported over long distances from any global location. It can be stored in mass quantities for extended periods of time without losses, making it well suited for strategic reserves. Therefore, Chiyoda expects that hydrogen produced from large renewable energy facilities in Russia, Australia, New Zealand and other countries in future projects will be converted into SPERA Hydrogen and transported to where it is needed.

Nevertheless, the concept of this project is wider since hydrogen could be produced from oil, coal and gas fields, but also from wind and solar farms through water electrolysis. In the first case, CO_2 generated would be captured and stored, using it to increase oil recovery and thus the production (Figure 50).

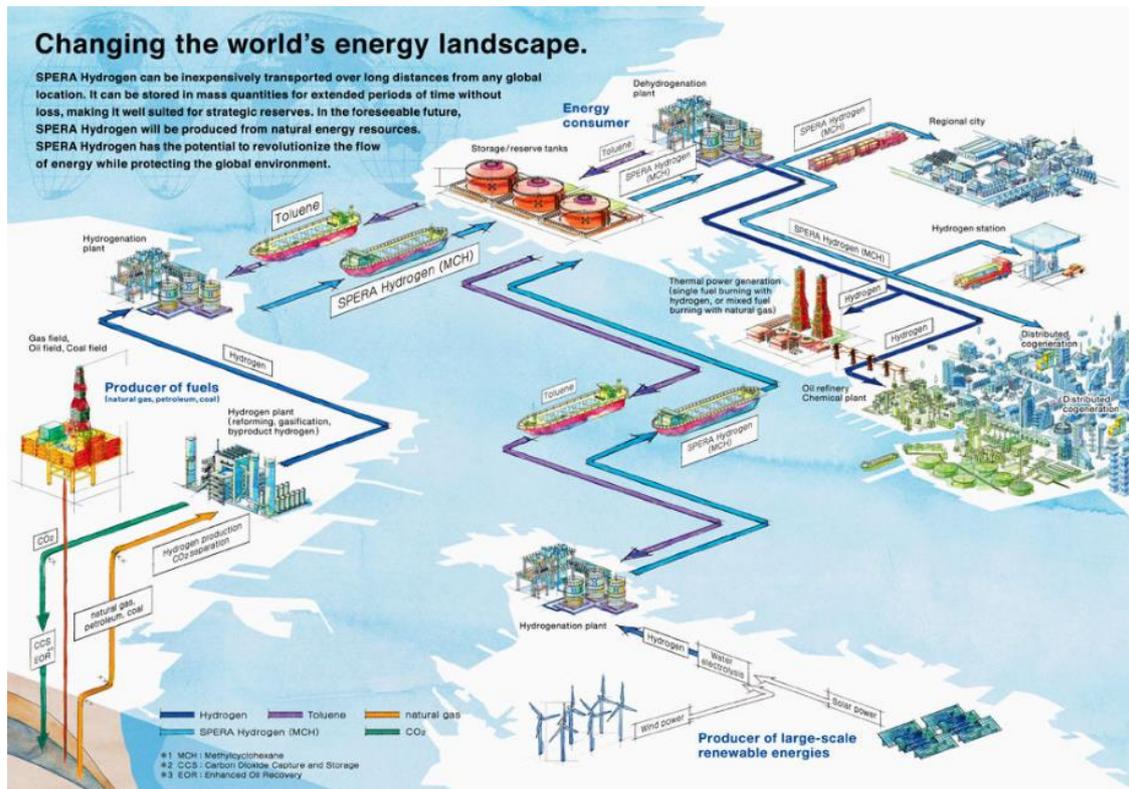
According to the Fire Defense Law in Japan, MCH and toluene are both designated as hazardous materials, the same as gasoline. Therefore, it is feasible to repurpose existing petroleum distribution infrastructure for SPERA Hydrogen, thereby lowering capital investment in realizing a hydrogen-based society.

Since the final goal is to use CO_2 -free for power generation, it can contribute to achieve the Japanese GHG emissions target. Power generation using a mix of hydrogen and natural gas can reduce CO_2 emissions by 6% compared with the use of natural gas alone (Chapter 3.3).

¹³⁴ Chiyoda Corporation: <https://www.chiyodacorp.com/en/service/spera-hydrogen/innovations/>.

¹³⁵ Chiyoda Corporation, 27 July 2017: https://www.chiyodacorp.com/meida/170727_e.pdf.

Figure 50: Chiyoda’s SPERA Hydrogen Supply Chain



Source: Chiyoda Corporation¹³⁶.

From Australia’s solar PV energy

In March 2019, JXTG Nippon Oil & Energy Corporation, Chiyoda Corporation, the University of Tokyo and Queensland University of Technology (QUT) announced the successful testing of the world's first production of CO₂-free hydrogen at low cost in Australia and its transportation to Japan¹³⁷. They plan to develop and scale up this method.

ARENA announced a fund of USD 3.35 million for this project in 2018, as part of its Research and Development Program – Renewable Hydrogen for Export¹³⁸. Therefore, this JXTG project is separate to but aligned with ARENA’s USD 7.5 million research project for extracting hydrogen from treated non-drinking water, such as seawater, using solar energy.

JXTG’s electrochemical synthesis of organic hydride technology simplifies the production process of MCH, with a potential of reducing 50% the cost of MCH production equipment, and

¹³⁶ Chiyoda Corporation: <https://www.chiyodacorp.com/en/service/spera-hydrogen/>.

¹³⁷ JXTG Nippon Oil & Energy, 15 March 2019 : https://www.no.jxtg-group.co.jp/english/newsrelease/2018/20190315_01.html

¹³⁸ QUT, 6 September 2018: <https://www.qut.edu.au/research/article?id=135488>.

thus, the cost of hydrogen. This project was also based on the technology of QUT, a high-efficiency tracking solar photovoltaic power generation system, and Chiyoda's dehydrogenation technology, and it was conducted in social collaborative research aimed at building the hydrogen supply chain in The University of Tokyo.

QUT's solar cell facility includes a concentrated photovoltaic array, tested in joint with Sumitomo Electric Industries, as well as a standard Si-PV array currently operating at Redlands Research Facility, in the south of Brisbane.

3.4.4. Ammonia

Ammonia (NH₃) has been manufactured using fossil fuels and distributed as a fertilizer or chemical raw material. Around 95% of ammonia is produced from fossil fuel hydrogen worldwide, emitting over 1% of energy-related CO₂ emissions. Recently, interest in manufacturing ammonia using renewable energies such as solar power is growing, which could make it become a carbon-free fuel with high hydrogen content but not carbon since burns without releasing CO₂. On the other hand, it is necessary to pay attention to NO_x emissions during NH₃ combustion, though it has been demonstrated that they can also be controlled.

It can be easily liquefied by compression at room temperature or by cooling to minus 30°C. In its liquid state, ammonia can carry large amounts of hydrogen energy since it has a volumetric hydrogen density 1.5 times higher than that of liquefied hydrogen. And it has a clear advantage compare to MCH since the energy density of ammonia is 2.5 times higher (18.6 MJ of energy per kilogram) than the effective energy density of the hydrogen carried by MCH (7.4 MJ per kilogram). This is because each molecule of MCH contains only six hydrogen atoms that can be detached and turned into diatomic H₂ molecules. This is, while the MCH molecule weighs 98 grams per mole, only six of these grams are composed of usable hydrogen. The result at scale is a ship loaded with 50,000 tonnes of liquid cargo which delivers only 3,100 tonnes of H₂, in contrast to the 8,900 tonnes of H₂ delivered by a ship loaded with 50,000 tonnes of ammonia¹³⁹. Besides, its transportation and storage infrastructure already exists (more than 18 million tons of NH₃ are traded per year globally), providing a big advantage for implementing in society early on with minimal capital investment. Therefore, it is expected to be an energy carrier suitable for mass transport of hydrogen.

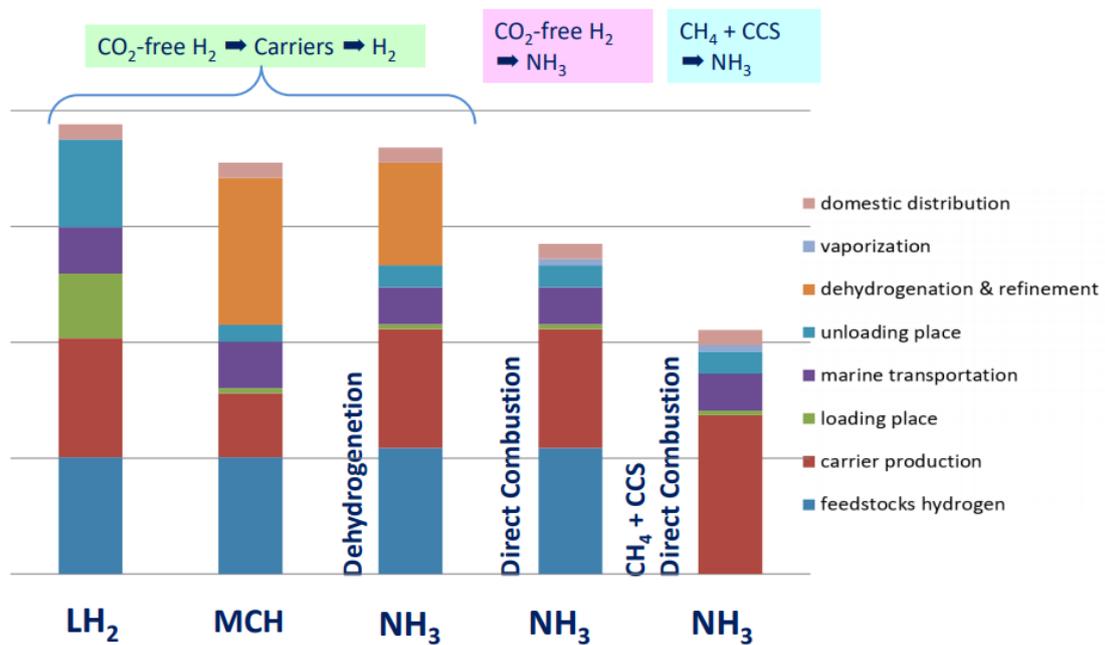
Ammonia can be used directly as a fuel for power generation without extracting hydrogen (dehydrogenation) from it, saving the energy that it requires. Ammonia has acute toxicity, strong smell and needs handling with care, but it has not chronic toxicity, it is easy to detect and safety measures are common practice. Furthermore, there is always an ammonia tank at thermal

¹³⁹ Ammonia Energy, 2 August 2017: <https://www.ammoniaenergy.org/japan-brunei-mch-energy-carrier-demonstration/>.

power plants (and workers are skilled in the handling of it) for using it in the de-nitration equipment, which removes nitrogen oxide by using ammonia with a catalyst. Finally, CCS from ammonia production plant is a feasible option, and, according to SIP's Energy Carriers [40], energy equivalent cost of ammonia is estimated to be the most feasible option among the energy carriers, as it is shown in

Figure 51.

Figure 51: Cost Comparison per Hydrogen Unit of Energy Carriers



Source: SIP's Energy Carriers [40].

Therefore, and given its properties, the technical maturity of its supply network and the wide range of end-use sectors, it looks that ammonia has a good chance to lead the beginning of the hydrogen society. In fact, the Hydrogen Strategy released in December 2017 seems to give ammonia the preference path in the race against LH₂ and MCH¹⁴⁰, calling for CO₂-free ammonia to come into use by the mid-2020s. Japan aims to co-fire ammonia and coal at coal power plants by around 2020 and use ammonia for gas turbines by around 2030. In contrast, the commercialization plan for MCH will start from 2025 onwards after completion of verification, and the commercialization of LH₂ around 2030.

¹⁴⁰ Ammonia Energy, 11 January 2018: <https://www.ammoniaenergy.org/ammonia-positioned-for-key-role-in-japans-new-hydrogen-strategy/>.

From Saudi Arabia's fossil fuels

Japan and Saudi Arabia are exploring the possibility of extracting hydrogen from Saudi fossil fuel through reforming, including CCS and enhanced oil recovery (EOR), and transport it to Japan in the form of ammonia¹⁴¹.

In September 2016, Prime Minister Shinzo Abe and Deputy Crown Prince Mohammed bin Salman established the Joint Group for Saudi-Japan Vision 2030, which includes nine themes, being energy one of those¹⁴². Saudi Arabia has been the largest and stable oil supplier for Japan, and Japan has been one of the largest customers for Saudi Arabia. Besides, it is the ninth-largest producer of ammonia.

In September 2017, The Institute of Energy Economics, Japan (IEEJ) and Saudi Aramco, a state-owned oil company that is responsible for approximately 10% of the world's petroleum production, co-hosted a workshop on "CCS and hydrogen in the framework of collaboration in studies on technologies toward a low carbon energy system in Saudi Japan Vision 2030" in Tokyo¹⁴³. It was part of the "Study of a master plan for creating a low-carbon energy system in Saudi Arabia" [34] adopted under METI's infrastructural development and study project for the acquisition of bilateral credits for FY2017 (Joint Crediting Mechanism¹⁴⁴ (JCM) supported by NEDO). METI pursues cooperation with oil-producing countries to promote the decarbonization of fossil fuels.

This study postulated a supply chain for carbon-free hydrogen and ammonia produced from Saudi Arabian fossil fuels and including CCS and EOR. The scope of evaluation includes the potential of greenhouse gas mitigation, commercial viability, types of financing options, and economic performance, and included a roadmap towards the establishment of a Japan-Saudi Arabia CO₂-free hydrogen/ammonia chain (Figure 52).

After that, IEEJ conducted a feasibility study about this supply chain [33], and after examining the different hydrogen carriers, Saudi Arabia expressed interest in ammonia given its maturity in production, transportation and use, and its cost advantage over the others.

In July 2019, Saudi Aramco and IEEJ signed an MoU for a pre-feasibility study of carbon-free ammonia production in the Kingdom of Saudi Arabia during the Saudi-Japan Vision 2030 Business Forum¹⁴⁵.

¹⁴¹ Ammonia Energy, 15 February 2018: <https://www.ammoniaenergy.org/japan-saudi-arabia-explore-trade-in-hydrogen-ammonia/>.

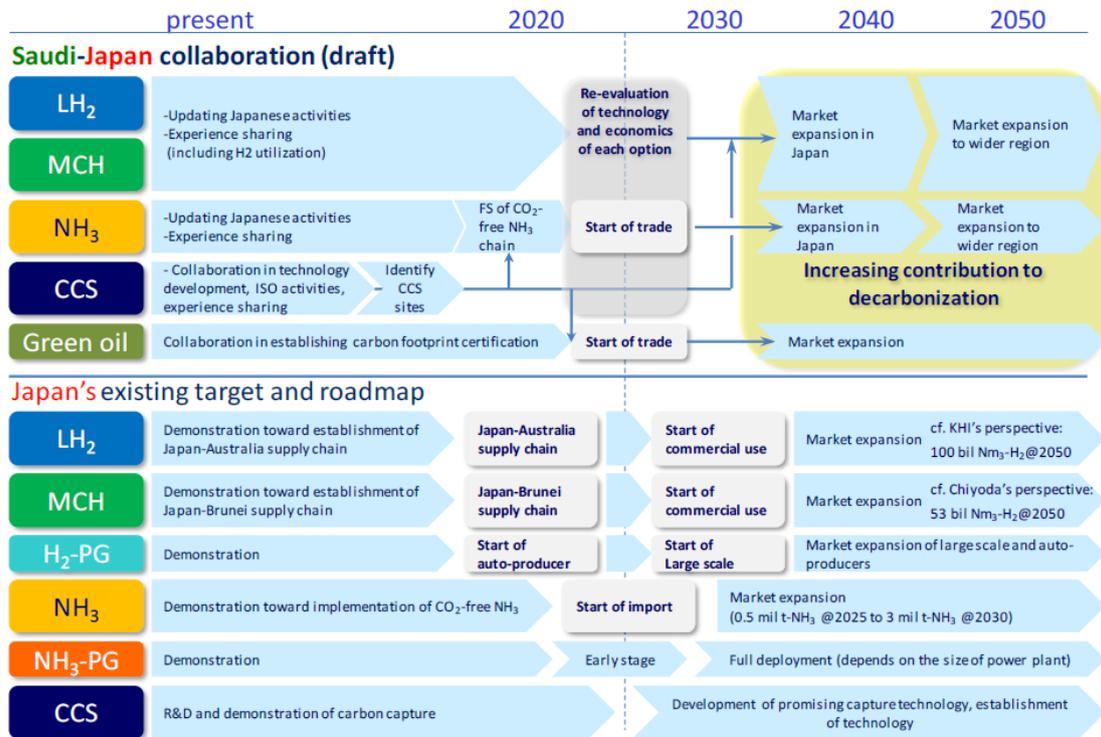
¹⁴² MOFA: <https://www.mofa.go.jp/mofaj/files/000237093.pdf>.

¹⁴³ IEEJ, 11 October 2017: <https://eneken.ieej.or.jp/en/jeb/171011.pdf>.

¹⁴⁴ The JCM was developed by the Japanese government to compliment the UN's Clean Development Mechanism (CDM). It allows Japan to account for its emission reductions by transferring low carbon technology, services and products to developing countries whilst contributing to their sustainable development (<https://www.jcm.go.jp/>).

¹⁴⁵ Aramco, 10 July 2019: <http://japan.aramco.com/en/home/news-and-media/news/ammonia.html>.

Figure 52: Roadmap for Establishment of CO₂-free Hydrogen/Ammonia Supply Chain between Japan and Saudi Arabia



Source: IEEJ [34]

3.4.5. Regional Renewable Hydrogen Supply Chains

The government aims to establish regional hydrogen supply chains using local unused resources, including renewable energy, waste plastics, sewage sludge, and by-product hydrogen using the achievements of Fukushima’s project (Chapter 3.5.2) as an example. The development of these regional supply chains will contribute not only to expanding the use of low-carbon hydrogen in the future but also to improving the regional energy self-sufficiency rates and creating new regional industries. However, hydrogen production from renewable sources was positioned in the long term in the national strategy and will not be implemented on a full scale until around 2040.

The barriers to regional hydrogen diffusion include the high cost of renewables, resources far from cities, better economics if directly using biogas/electricity, and low hydrogen demand even if the production is technically possible.

The combination of low solar and wind costs, continuously in a downward trend, and new developments in the electrolytic technology, with cheaper and more efficient products, are gradually making the large-scale renewable electrolysis a viable option in a near future. Therefore, further decline in the renewable generation cost is needed, as well as the development of new electrolyzers with higher efficiencies and durability. The government expect to reduce the system cost from JPY 200,000 per kW to JPY 50,000 kW by 2030, and the energy consumption from 5 kWh/Nm³ to 4.3 kWh/Nm³. To achieve that, Japan will promote sales also in overseas markets, including Europe where renewable energy expansion and cost reductions progressed faster than in Japan [9].

Researchers from Japan's National Institute for Materials Science (NIMS), The University of Tokyo and Hiroshima University have conducted a techno-economic analysis for hydrogen production from photovoltaic power generation utilizing a battery-assisted electrolyzer (battery-assisted low-cost hydrogen production from solar energy: Rational target setting for future technology systems). With the use of the battery, the required capacity of electrolyzer is lowered and the operating ratio of electrolyzer increases, resulting also in a lower hydrogen production cost when the benefit of the two previous points exceeds the necessary investment for battery installation. The results showed a hydrogen cost between JPY 17 and 27 per Nm³ (about EUR 0.14 and 0.22 per Nm³, or EUR 1.5 and 2.4 per kilogram), less than the government target¹⁴⁶.

While METI is focusing on the large supply chains from overseas, MOE is supporting projects to construct low-carbon hydrogen supply chains in several regions through the use of renewable energy to promote decarbonization as part of its medium- to long-term global warming countermeasures. The following eight projects, some of them also considered power-to-gas (P2G) demonstration projects (Chapter 3.3), are part of its "Projects for the Creation of Hydrogen Society":

1. Introduction of fuel cell forklift at Keihin Coast Area and demonstration of clean hydrogen utilization model construction
Description: Hydrogen is produced by water electrolysis using wind power generated at Hama Wing, in Yokohama, Kanagawa. Stored in a tank and then compressed, it is delivered by a hydrogen fueling vehicle and supplied to FC forklifts used in distribution and refrigeration warehouses, and a fruit/vegetable market in the Keihin waterfront area.
Primary partner: Toyota Motor Corp.
Municipalities: Kanagawa Prefecture, Yokohama City, and Kawasaki City.
2. The hydrogen energy supply chain demonstration project from livestock manure
Description: Hydrogen is produced from biogas originating from livestock manure in Shikaoi, Hokkaido. After compression, it is delivered by pipelines or in gas tanks. The hydrogen is used to supply electricity and heat to dairy farming facilities, and as fuel for FCVs and FC forklifts.
Primary partner: Air Water Inc.

¹⁴⁶ Science Direct - International Journal of Hydrogen Energy, volume 44, 15 January 2019: <https://www.sciencedirect.com/science/article/pii/S0360319918337212>.

Strategic partners: Kajima Corp., Nippon Steel Pipeline & Engineering Co., Ltd., and Air Products Japan K.K.

Municipalities: Hokkaido Prefecture, Shikaoi Town, and Obihiro City.

3. Build a model of regional cooperation and local energy production/consumption using high purity waste hydrogen from caustic soda production

Description: High-purity by-product hydrogen produced at a caustic soda plant in Shunan, Yamaguchi, is supplied to pure hydrogen fuel cells through pipelines or compressed gas tanks to generate electricity and heat at a swimming club and a roadside station. Some of the gas is liquefied and delivered to a hydrogen fueling station for FCVs and FC forklifts. The liquefied hydrogen is also transported to pilot fueling facilities in Shimonoseki by tanker truck.

Primary partner: Tokuyama Corp.

Strategic partners: Tosoh Corp., Yamaguchi Prefecture, Shunan city, and Shimonoseki City.

4. Low-carbon hydrogen demonstration project of a waste plastic regional circular model

Description: Hydrogen is produced from plastic waste at the Showa Denko Kawasaki Plant. The hydrogen gas is carried to a hotel through dedicated pipelines to supply electricity and heat with a pure hydrogen fuel cell. It is also transported to a hydrogen fueling station for FCVs on a compressed hydrogen tube trailer (Chapter 3.1).

Primary partner: Showa Denko K.K.

Municipality: Kawasaki City.

5. Expanding the use of hydrogen produced from a small hydropower plant and establishing a hydrogen utilization model suitable for the local characteristic of Hokkaido

Description: Hydrogen is produced by electrolyzing water with electricity generated by a small-scale hydropower plant at Shoro Dam in Shiranuka, Hokkaido. Stored in a tank and then compressed, the hydrogen is delivered in high-pressure gas tanks to supply electricity and heat through pure hydrogen fuel cells at various facilities including dairy farms and a heated indoor swimming pool.

Primary partner: Toshiba ESS

Strategic partner: Iwatani Corporation.

Municipalities: Hokkaido Prefecture, Kushiro City, and Shiranuka Town.

6. Demonstrate a low-carbon hydrogen supply chain using fuel cells and the existing logistics network in Tomiya, Miyagi Prefecture

Description: Hydrogen is produced through electrolysis by solar power installed at the logistic center of Miyagi Coop., in Tomiya City, Miyagi, stored in a hydrogen-absorbing alloy cartridges, and delivered to supply electricity and heat through pure hydrogen fuel cells at a store, other facilities and several residential houses, by taking advantage of the existing logistics network of Miyagi Coop. This delivery also involves other goods.

Primary partner: Hitachi, Ltd.

Strategic partners: Marubeni Corp., Miyagi Coop., and Tomiya City.

7. Demonstrate the production of hydrogen from electrolysis using wind power and its energy storage, as well as the supply and use of hydrogen mixed with municipal natural gas

Description: Hydrogen is produced through electrolysis using wind power in Noshiro, Akita Prefecture, mixed with gas similar to municipal natural gas, temporarily stored in gas holders or tanks, and supplied through gas pipelines. The gas mixture is used in stoves and other commercially available gas devices to demonstrate their compatibility with this gas mixture.

Primary partner: NTT Data Institute of Management Consulting, Inc.

Strategic partner: Dainichi Machine and Engineering Co., Ltd.

Municipality: Noshiro City.

8. Demonstrate a low-pressure hydrogen delivery system to promote hydrogen use in buildings and city infrastructure

Description: Using electricity produced from wind power in Muroran, Hokkaido, water electrolysis produces hydrogen. It is then stored in a portable hydrogen-absorbing alloy tank and transported by a delivery vehicle. A pure hydrogen fuel cell at a hot spring facility supplies electricity and heat. To save energy, exhaust heat at the facility is used to heat up the alloy for extracting the hydrogen.

Primary partner: Taisei Corp.

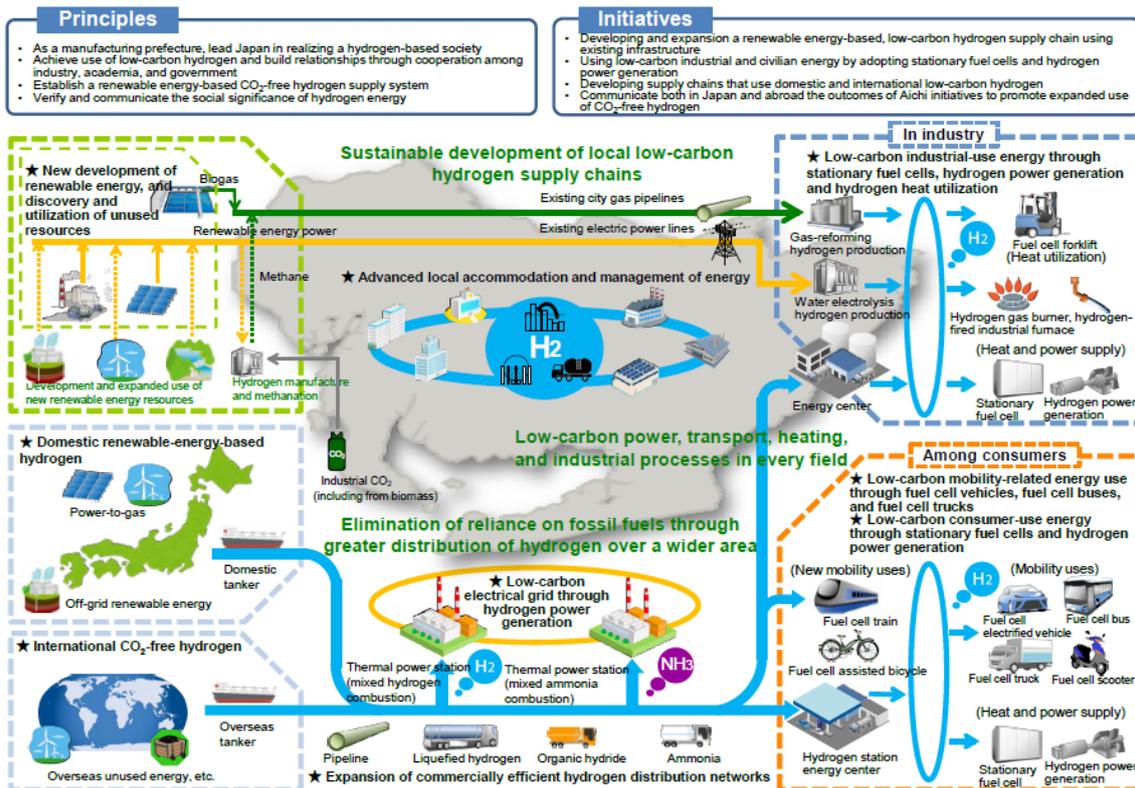
Strategic partners: Muroran City, Kyushu University, Muroran Institute of Technology, Tomoe Shokai Co., Ltd., The Japan Steel Works Ltd., and Kita Koudensha Corp.

In addition to these projects, other local governments are also working on initiatives toward creating a hydrogen society before the 2020 Tokyo Olympics and Paralympics. Some of them are the following:

- Tokyo Metropolitan: the Tokyo Hydrogen Promotion Team was launched in November 2017 in cooperation with industry and academia to increase the use of hydrogen among residents. It partnered with private sector companies and municipal bodies to promote the installation of hydrogen stations. TGM plans to have 6,000 FCVs, 100 FC buses and 35 HRSs by 2020, 100,000 FCVs and 80 HRSs by 2025, and 200,000 FCVs and 150 HRSs by 2030. At the end of July 2016, TMG opened an education centre to promote the spread of information about hydrogen energy. It also helps small and medium operators of hydrogen stations learn the skills necessary to operate their stations successfully and safely [26].
- Aichi Prefecture: the Aichi Low-carbon Hydrogen Supply Chain Promotion Association, a body established in October 2017 which includes the prefectural government, municipal governments and companies operating within the prefecture, developed the “Aichi Low-carbon Hydrogen Supply Chain 2030 Vision” (Figure 53) and the

corresponding roadmap to achieve it based on the national strategy. The three pillars of the 2030 Vision are a sustained development of a regional low-carbon hydrogen supply chain; carbon reduction in the various fields of electricity, transport, heating and industrial processes; and elimination of dependence on fossil fuels through the expansion of hydrogen distribution volumes over a wider area.

Figure 53: Aichi Low-carbon Hydrogen Supply Chain 2030 Vision



Source: Toyota.

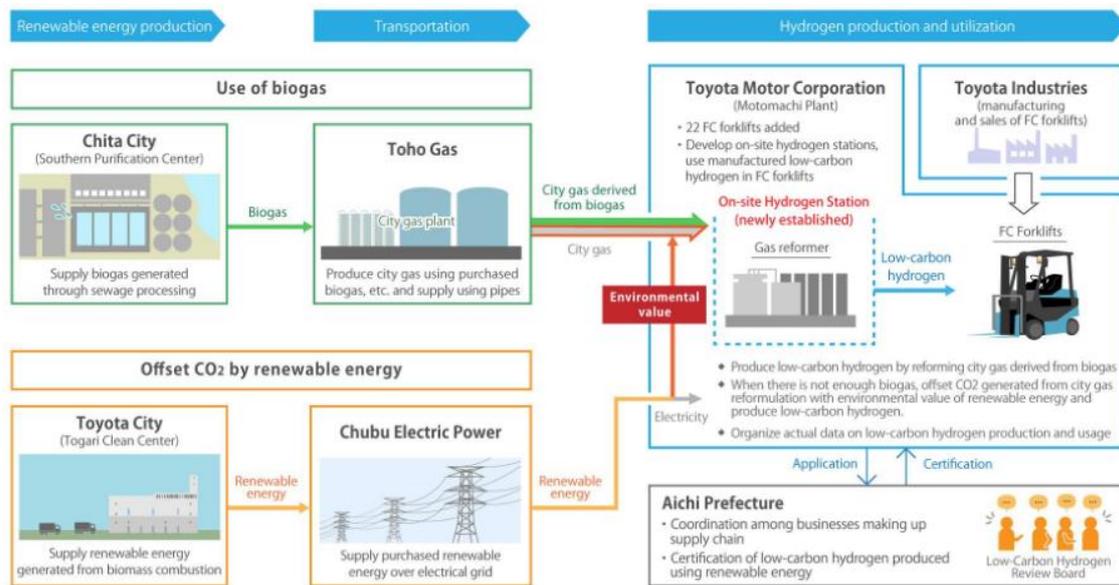
As a first step, in April 2018, Aichi Prefecture, Chita City, Toyota City, Chubu Electric Power Co., Inc., Toho Gas Co., Ltd., Toyota Motor Corporation, and Toyota Industries Corporation launched the Chita City and Toyota City Renewable Energy-use Low-carbon Hydrogen Project¹⁴⁷ (Figure 54). The project is designed to construct a subsistent low-carbon hydrogen supply chain to produce, supply, and use hydrogen generated from renewable resources within the prefecture.

In this project, Toho Gas is expected to produce city gas using biogas generated from sewage sludge at the Chita City Southern Sewage Treatment Center, which is then transported to Toyota's Motomachi Plant through existing city gas pipelines. The city

¹⁴⁷ Toyota, 25 April 2018: <https://global.toyota/en/newsroom/corporate/22312931.html>.

gas derived from biogas is passed through gas reformers at the Motomachi Plant, whereby low-carbon hydrogen, which is used to power the Toyota Industries fuel cell forklifts (FC forklifts) in the plant, is produced, compressed, and stored. Additionally, by supplying Toyota with renewable energy from Chubu Electric Power generated at the Toyota City Togari Clean Center through heat from waste incineration (biomass incineration heat), CO₂ emissions from city gas that would be used when there is a biogas shortage can be offset.

Figure 54: Chita City and Toyota City Renewable Energy-use Low-carbon Hydrogen Project



Source: Toyota.

The construction of hydrogen stations has progressed around the prefecture. From December 2017, the introduction of FC forklifts in the cargo area of Chubu Centrair International Airport is also subsidized.

- Yamaguchi Prefecture: based on the “Yamaguchi Next-Generation Industrial Cluster Concept”, it is promoting industrial development through the utilization of hydrogen with the aim to become a leading hydrogen prefecture (Chapter 3.5.3). To expand the range of hydrogen-related industries within the prefecture, it strengthened the support functions of the Yamaguchi Prefectural Industrial Technology Institute for hydrogen-related technologies, and provide support to Yamaguchi’s SMEs.
- Saitama Prefecture launched a project to produce sludge-derived CO₂-free hydrogen at its sewage treatment plants. This is part of a bigger plan to produce biomass power utilizing the sludge from sewage treatment plants. The prefecture plans to begin power generation by burning the methane gas produced from sludge in 2019 and expand

generation capacity by 2029 to a total of 25 million kWh, equivalent to the power consumption of 5,000 households, reducing up to 12,000 tons of greenhouse gas emissions annually.

The hydrogen will be supplied to FC forklifts working in distribution warehouses and FCVs. Hydrogen stations will be placed at the four sewage treatment plants planned to start biogas power generation. In preparation for the 2020 project start date, Saitama Prefecture is now conducting demonstrations using a model facility at the Nakagawa River Water Recycling Center. The prefecture aims to introduce 6,000 FCVs and 17 HRSs by 2020 and increase them to 60,000 FCVs and 30 stations by 2025. The number of stations to be established by 2025 may increase to 34 by adding the four stations to be constructed in the sewage treatment plants¹⁴⁸.

Fukuoka City is also carrying out a project to produce hydrogen with biogas extracted from sewage sludge, which will be used for FCVs (Chapter 3.5.1). With this methodology, sewage treatment plants across Japan have the potential to power up to 1.86 million FCVs¹⁴⁹.

- Toyama Prefecture: As part of a NEDO project, Alhytec Inc. started operations of a demonstration plant designed to separate the aluminium from waste composite materials and generate hydrogen to be used for fuel-cell power generation at Asahi Printing Co.'s Toyama Plant in April 2016. The demonstration plant has a production capacity of 2 kg/h, and the company plans to enhance the hydrogen generation to up to 5 kg/h. The technology is expected to find applications at printing, packaging and metals factories¹⁵⁰.
- Sendai City: In March 2017, Tohoku Electric Power Co. started a research project to produce and store hydrogen using electricity from a solar power system installed at its R&D Center in Aoba Ward, Sendai City, and use it as fuel to generate electricity for the Center¹⁵¹ (Figure 55). The purpose is to verify that hydrogen production technology can be applied as a countermeasure for output fluctuations accompanying the expansion of the VRE, similar to storage batteries, but for large scale and long-term storage (Figure 2). It installed a solar power generation system of 50 kW, a water electrolysis hydrogen production equipment with a capacity of 5 Nm³/h, a hydrogen storage alloy tank of 220 Nm³ (300 kWh), a hydrogen fuel cell of 9.9 kW, and a secondary battery of 50 kW (67 kWh).

¹⁴⁸ Smart Japan, 15 September 2015:

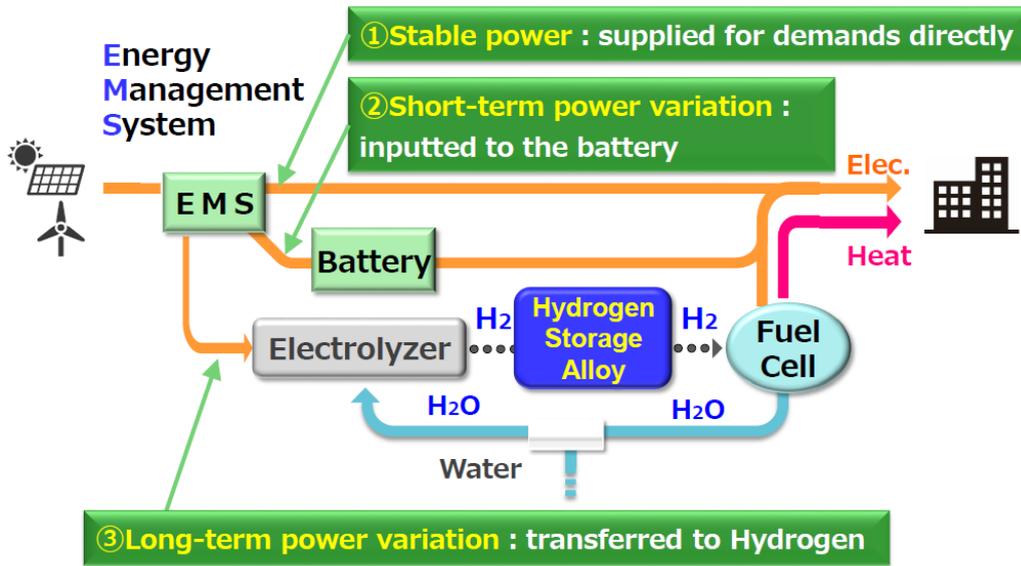
<https://www.itmedia.co.jp/smartjapan/articles/1509/15/news041.html>.

¹⁴⁹ Japan Times, 1 January 2019: https://www.japantimes.co.jp/news/2019/01/01/national/hydrogen-touted-clean-energy/?appsule=1#article_history.

¹⁵⁰ NEDO, 22 April 2016: https://www.nedo.go.jp/english/news/AA5en_100204.html.

¹⁵¹ Tohoku Electric Power Co., 31 March 2016: http://www.tohoku-epco.co.jp/news/normal/1191500_1049.html.

Figure 55: Hydrogen Energy System



Source: Tohoku University [41]

In October 2018, and under a NEDO project, Tohoku University and Maekawa Manufacturing Co., Ltd. also demonstrated the continuous operation for 72 hours (3 days) of a combined power and hydrogen energy storage system at the Moteiwa Water Treatment Plant in Sendai City. The combined system does not require fossil fuels, can stably supply high-quality power against long-term power outages in the event of a large-scale natural disaster, and enables the effective use of renewable energy even with irregular fluctuations in solar power output and power consumption¹⁵².

¹⁵² NEDO, 25 October 2018: https://www.nedo.go.jp/news/press/AA5_101036.html (only in Japanese).

3.5. MAIN HYDROGEN RESEARCH CLUSTERS

This chapter describes the three main clusters in Japan, which are in the Prefectures of Fukuoka, Fukushima and Yamanashi, and involved the collaboration of local and central governments, industry and academia. All of them pursue a local economic impact, developing new industries, human resources, etc., taking advantage of the regional characteristics to use local resources to produce hydrogen, and create a national and even international centre of excellence in research (Institute, University) [42].

3.5.1. Fukuoka Prefecture and Kyushu University

Fukuoka Prefecture established the collaborative government-industry-academia organization called the Fukuoka Strategy Conference for Hydrogen Energy¹⁵³ in August 2004 to take the initiative in creating an environmentally-compatible, sustainable society based on hydrogen energy. It is the largest in Japan with 795 members as of January 2017 (641 companies, 116 universities and 38 administrative, research and support organizations)¹⁵⁴. METI designated Fukuoka as the “hydrogen hub of Japan”. It promotes and supports the development of new local industries such as hydrogen gas impurity analyzer, hydrogen visualization stainless sheets, etc.

The prefectural government and the Conference launched the Fukuoka Hydrogen Strategy (Hy-Life Project), a unique initiative in Japan to build a world-leading hydrogen energy research centre (Figure 56). It promotes the dissemination of hydrogen with activities such as R&D, human resources development, promotion of new industries, builds an international hub for hydrogen knowledge, and community demonstrations, including the development of a Hydrogen Highway and Hydrogen Towns.

To aims to build an advanced base of FCVs society in Fukuoka, the Fukuoka FCV Club was also established in August 2014 by local businesses, industry organizations, universities and governments, to further the promotion of FCVs and the construction of hydrogen stations. The Fukuoka Fuel Cell Vehicle Implementation Plan is being carried out centring on the Fukuoka Strategy Conference for Hydrogen Energy for Fukuoka to continue playing a leading role in promoting the spread of FCVs and hydrogen supply infrastructures.

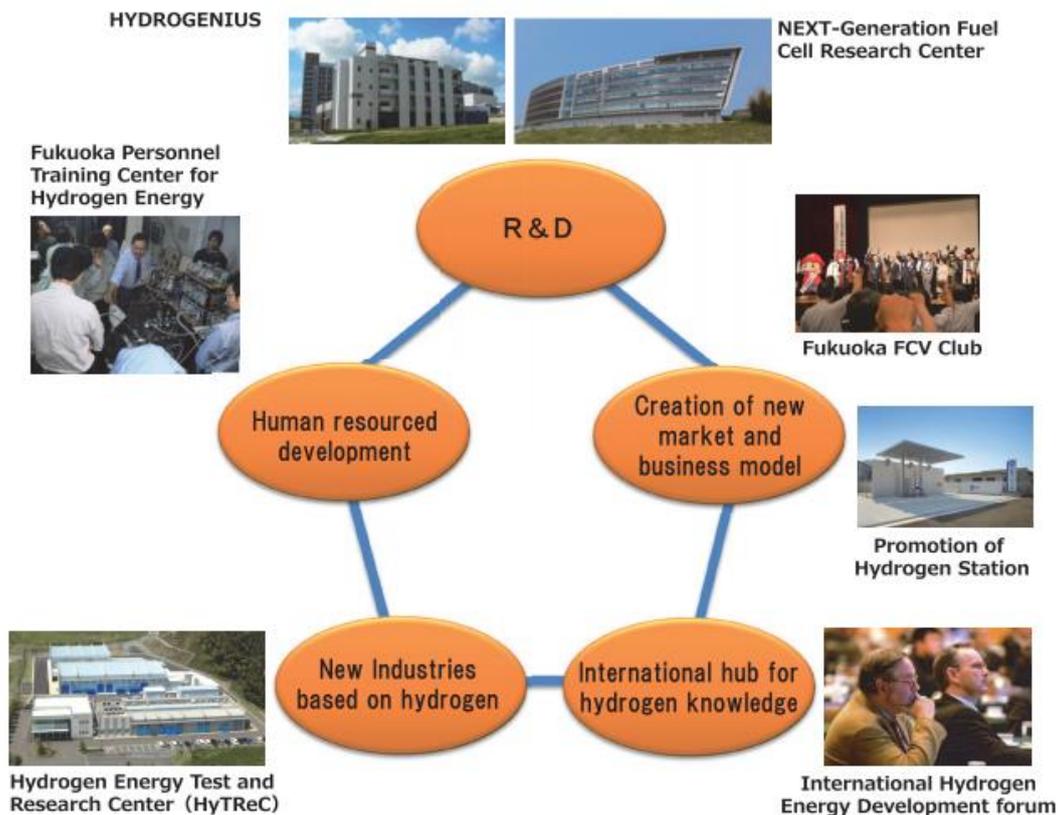
On the Kyushu University Ito Campus, the Hydrogen Technology Research Center (current International Research Center for Hydrogen Energy) was established in April 2004. Later, in July 2006, the Research Center for Hydrogen Industrial Use and Storage (HYDROGENIUS) was also established there by AIST as the national hydrogen materials research laboratory. It is

¹⁵³ Fukuoka Strategy Conference for Hydrogen Energy: <http://www.f-suiso.jp/>.

¹⁵⁴ Fukuoka Strategy Conference for Hydrogen Energy: [http://h2.kyushu-u.ac.jp/common/PDF/web18\(e\).pdf](http://h2.kyushu-u.ac.jp/common/PDF/web18(e).pdf).

the largest hydrogen-related research facility in the world and it is supported also by NEDO. It contributes to the development of safe and economical hydrogen systems through the establishment of design and evaluation methods, provision of data for standards and regulations, and data for risk assessment¹⁵⁵.

Figure 56: Overview of the Hy-Life Project



Source: Fukuoka Strategy Conference for Hydrogen Energy [43].

Also, as part of a commitment to forming a global hydrogen research base in cooperation with the Fukuoka Strategy Conference for Hydrogen Energy, the Hydrogen Energy Test and Research Center (HyTReC) was established in March 2009 to contribute to private sector development of hydrogen-related technologies and conduct product testing based on the research results of HYDROGENIUS. Furthermore, the addition of the CRADLE Building (Center for Research Activities and Development of Large-scale pressure vessel Equipment) in April 2014 has enabled testing of large-scale hydrogen storage tanks for hydrogen station applications, in addition to testing small components such as valves and pipes used for FCVs and other applications.

¹⁵⁵ Kyushu University, HYDROGENIUS: [http://h2.kyushu-u.ac.jp/common/PDF/web11\(e\).pdf](http://h2.kyushu-u.ac.jp/common/PDF/web11(e).pdf).

Other additional hydrogen-related facilities at Kyushu University are the following¹⁵⁶:

- The Fukuoka Personnel Training Center for Hydrogen Energy was established in October 2005 to support human resources development to the hydrogen industry through courses for engineers and business managers.
- The International Institute for Carbon-Neutral Energy Research (I²CNER), the world's leading laboratory in the field of low-carbon energy, was established in December 2010. Hydrogen manufacture, storage and use, and CO₂ capture and storage are among its areas of research.
- The Next-Generation Fuel Cell Research Center (NEXT-FC), the world's first industry-academia research hub focused on SOFC and other next-generation fuel cells, was established in January 2012 to improve their durability, reliability and performance.
- AIST-Kyushu University Hydrogen Materials Laboratory (HydroMate), for the elucidation of the phenomenon of embrittlement of hydrogen materials and development based on new materials, was established in January 2017.

All these activities are now organized under the “Energy Research Platform” (Q-PIT: Kyushu University Platform of Inter/Transdisciplinary Energy Research), established in October 2016. It is focused on water electrolysis hydrogen production and energy storage materials, being the first in the world to develop a hydrogen storage alloy material capable of safely and compactly storing a large amount of hydrogen, an important key to spreading its utilization.

The main four demonstration projects conducted in Fukuoka Prefecture were the following [43]:

- Build a “Hydrogen Highway” between Kitakyushu City and Fukuoka City by installing hydrogen stations at Higashida district (Kitakyushu; the first in Japan and based on by-product hydrogen supplied through a pipeline from steel plants) and Kyushu University Ito Campus (Fukuoka; based on water electrolysis using solar power), operational from September 2009. It also included the incorporation of FCVs for official cars of Fukuoka Prefectural Government and Kitakyushu City, being free for FCVs.

The Kyushu station was jointly established by Kyushu University, Kyushu Electric Power Co., Taiyo Nippon Sanso Co., and Kyuky Co. The Kitakyushu station was jointly built by Iwatani Co., Nippon Steel Co., and JXTG Nippon Oil & Energy.

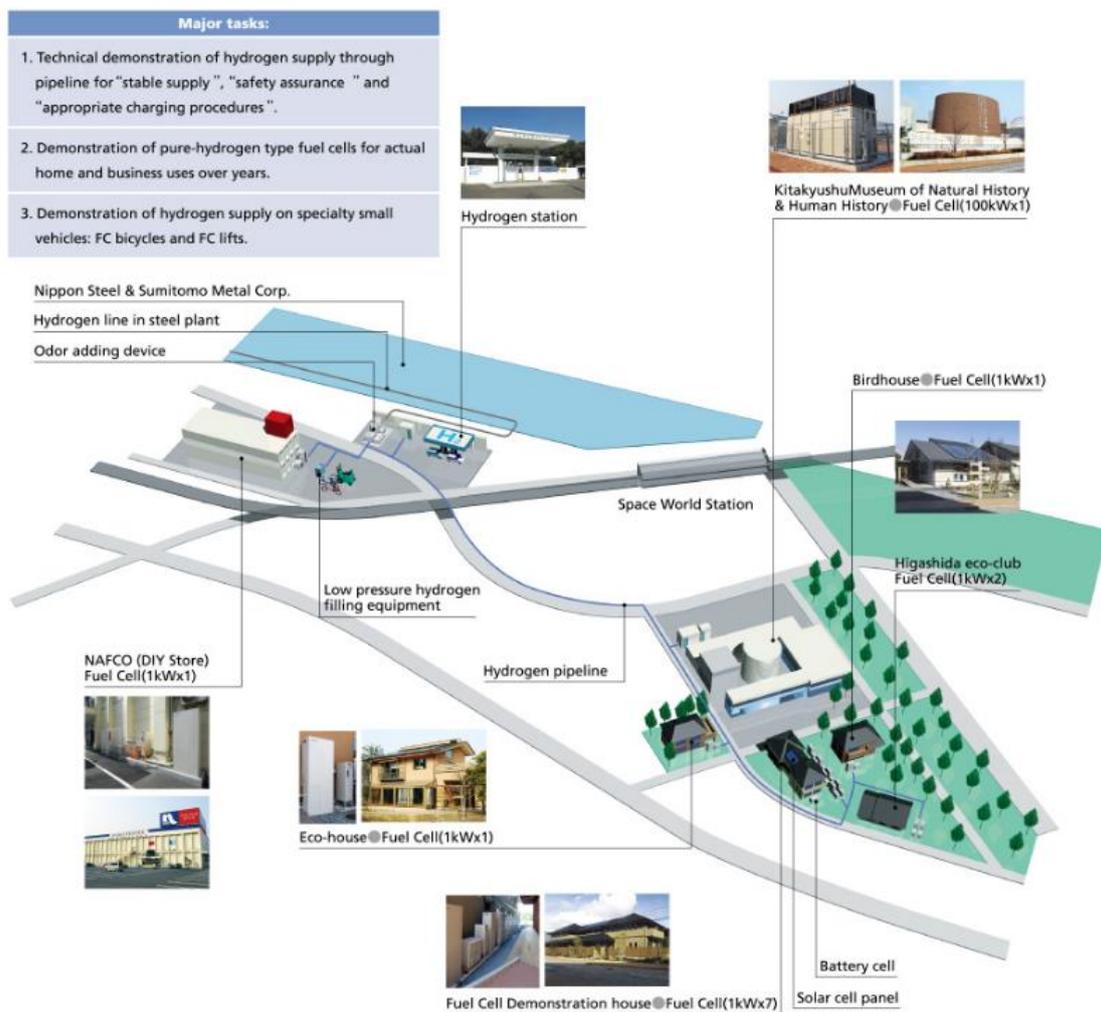
- Fukuoka Hydrogen Town, in the Minakazedai and Misakigaoka housing complexes in Itoshima City. It is the world's largest scale collective installation of 150 LPG-based 1 kW residential hydrogen fuel cells (ene-farms), that was completed in December 2009 as a showcase of a society based on hydrogen for a future full-scale usage [43]. It

¹⁵⁶ Kyushu University – International Research Centre for Hydrogen Energy: <http://h2.kyushu-u.ac.jp/english/index.html>.

counted with the collaboration of JXTG Nippon Oil & Energy and Saibu Gas Energy Co.

- Hydrogen Town in the Higashida district of Kitakyushu City, the world’s first demonstration of directly supplying by-product odour-mixed hydrogen produced in the Yawata Steel Works, owned by Nippon Steel & Sumitomo Metal, to the city through pipelines for a full-scale use in a region (Figure 57). It was implemented by HySUT, Fukuoka Prefecture and Kitakyushu City in January 2011, and was funded by METI through the “demonstration project for infrastructure in hydrogen-based society” [43].

Figure 57: Kitakyushu Hydrogen Town (2011-2014)



Source: HySUT¹⁵⁷.

¹⁵⁷ HySUT: <http://hysut.or.jp/en/projects/index.html>.

The project tested the hydrogen supply via a 1.2 kilometer long pipeline; the operability of 14 pure hydrogen fuel cells for multiple applications, installed in apartments, commercial facilities and hydrogen fueling stations; fuel cell-powered small vehicles, such as forklifts and bicycles; the electricity supply from FCVs to houses; and a smart community power-sharing in the Higashida home for the elderly.

Although the test concluded in 2014, Fukuoka Prefecture and Kitakyushu City announced their intention to restart the project in 2016 to demonstrate a low-cost hydrogen supply. Later, the “Kitakyushu City Vision for Hydrogen Society” was announced in 2017 with the goal of creating a city hydrogen supply chain by 2030. In addition to the Higashida district, it designates the Hibikinada area as a leading area in which many energy-related facilities and port infrastructure are located. It aims to import hydrogen from overseas in that area, produce it through LNG reforming, and construct a storage and supply base for supplying hydrogen to Kyushu and other parts of Japan [18].

Kitakyushu’s initiatives have been recognized both in Japan and overseas, including its selection as the first Green Growth City in Asia by the OECD in June 2011, as well as an Eco-Model City, Future City, and SDGs Future City by the Japanese government.

- Hydrogen production from sewage sludge: In March 2015, Fukuoka City, Kyushu University, Mitsubishi Kakoki Kaisha, Ltd., and Toyota Tsusho Corporation Collaborative Research Body installed a station where the hydrogen is produced from biogas generated from the fermentation of sewage sludge at the Fukuoka City Chubu Wastewater Treatment Center, the first station of its kind in the world (Figure 58). The plant forces the biogas through a separation membrane to separate it into CH₄ and CO₂ and produces hydrogen via steam reforming in which this methane is made to react with steam. The purpose of this project is to verify the quality of the hydrogen produced and overall production capacity.

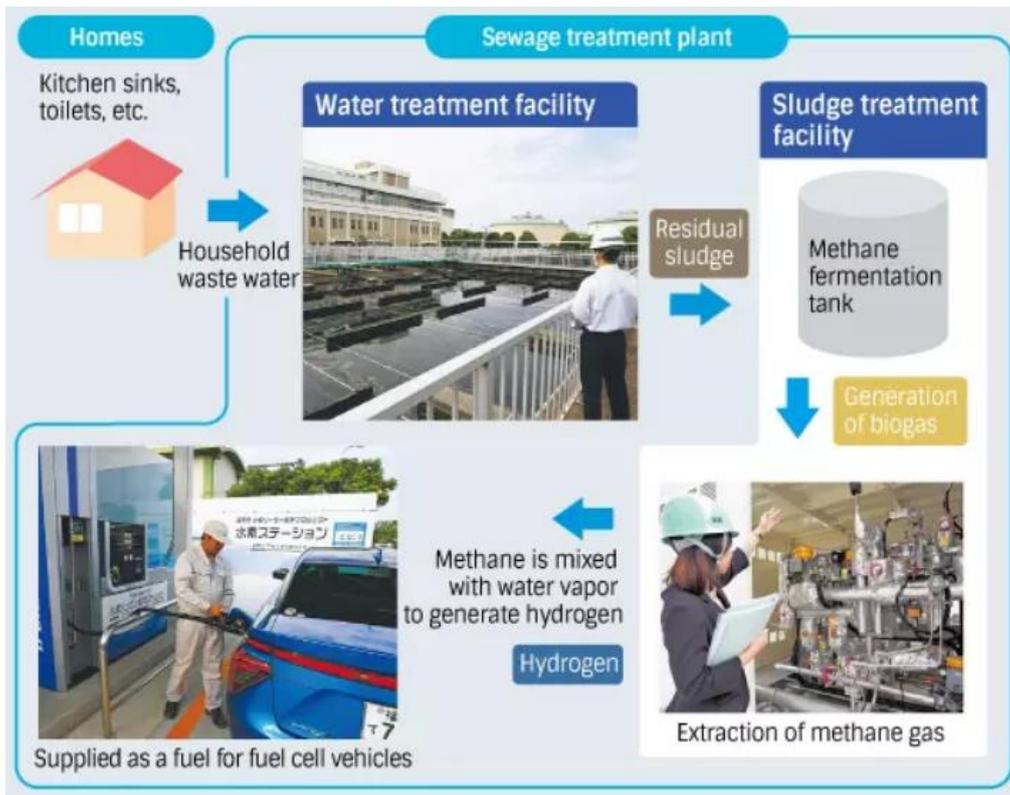
The Fukuoka plant produces 300 kilograms of hydrogen per day, enough to fill 65 Mirai vehicles, and it could grow to 600 vehicles if all the biogas at the plant is converted to hydrogen. According to MLIT, more than 11 million kilograms of hydrogen could be produced annually if all treatment plants across the country use this technology, enough to fill around 2 million FCVs. Nevertheless, this technology needs more R&D due to it was not an economically viable option without the government’s subsidy given that to produce a kilogram of hydrogen at the sewage plant costs around JPY 13,000 while selling it at the station costs around JPY 1,100¹⁵⁸.

This demonstration project, “Hydrogen Leader City Project - Demonstration of Hydrogen Generation from Sewage Biogas Source”, was adopted in FY 2014. It is part of the Breakthrough by Dynamic Approach in Sewage High Technology (B-DASH)

¹⁵⁸ Los Angeles Times, 31 July 2016: <https://www.latimes.com/world/asia/la-fg-japan-hydrogen-cars-sewage-snap-story.html>.

conducted by MLIT to accelerate the R&D, and commercialization of new technologies to substantially reduce sewage service costs, create renewable energy and support Japanese enterprises' overseas water business expansion¹⁵⁹. Researches are conducted by private companies and the NILIM.

Figure 58: Hydrogen Production from Sewage Sludge Demonstration Project



Source: Asia Nikkei¹⁶⁰.

3.5.2. Fukushima Prefecture and AIST, FREA

As an important component of the reconstruction and recovery efforts after the nuclear accident in 2011, Fukushima Prefecture remains committed to becoming a national and international center for renewable energy research, promoting its expansion, R&D, and clustering of related

¹⁵⁹ NILIM, Wastewater and Sludge Management Division: <http://www.nilim.go.jp/lab/ecg/english/bdash.htm>

¹⁶⁰ Nikkei Asian Review, 12 November 2015: <https://asia.nikkei.com/Business/Biotechnology/Sewage-sludge-gaining-attention-as-biomass-resource2>.

industries, and with the target of obtaining 100% of its energy demand through renewables by 2040.

The central government created the Fukushima Plan for a New Energy Society in September 2016 that meant additional support for maximizing renewables use in the Prefecture, and develop a model for realizing the new energy society of the future in Fukushima, where hydrogen is produced from renewable energy, stored, transported and used. The three main components of the plan were to expand the introduction of renewable energy, model construction for realizing a hydrogen-based society and building smart communities [44].

The Prefecture also hosts several organizations promoting renewable energy, including the Fukushima Renewable Energy Institute (FREA) in Koriyama, which is part of the National Institute of Advanced Industrial Science and Technology (AIST). AIST is one of the largest public research institutes in Japan and works to promote collaboration among industry, academia, and government. FREA promotes collaboration with domestic and overseas organizations, and the developed technologies at FREA are available for everyone. It has two teams working on hydrogen technology:

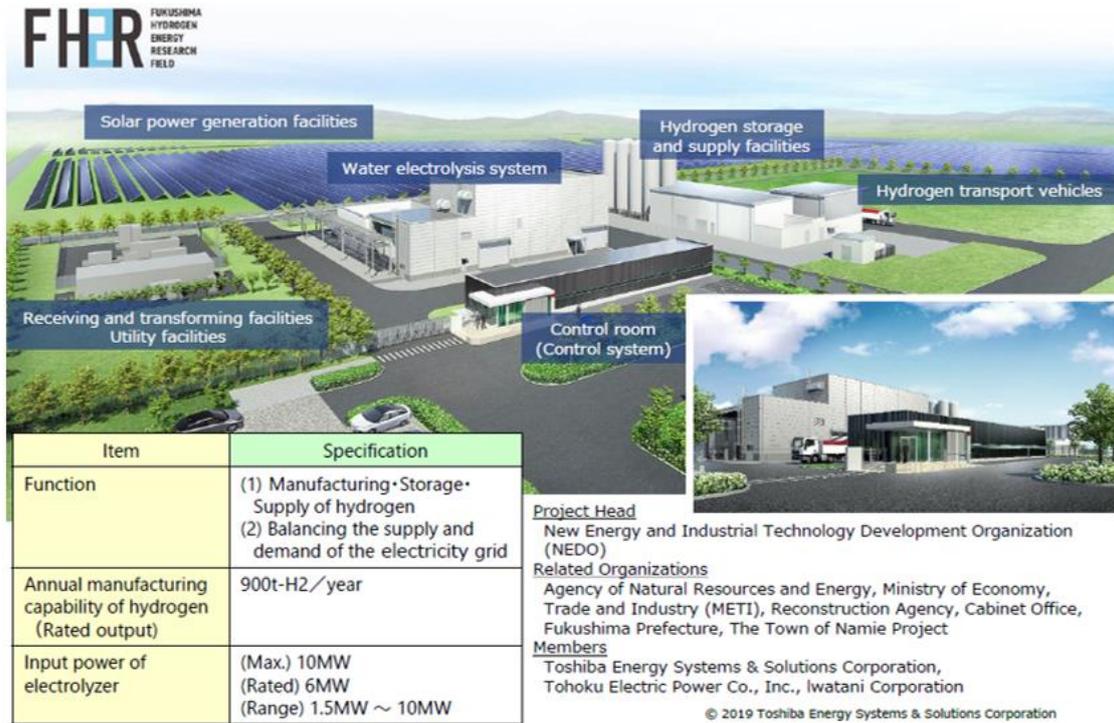
- Hydrogen energy carrier team, which has been developing technologies for converting renewable electricity into hydrogen or hydrogen energy carriers (organic chemical hydride, ammonia, formic acid), and technologies on the combustion of all these options for cogeneration engines and gas turbines.
- Hydrogen and heat utilization system team, which is developing a high-efficiency hydrogen production technology that directs direct current surplus power from photovoltaic systems to the water electrolyzer; and an inexpensive, safe, and large-scale hydrogen storage systems that is not subject to the High Pressure Gas Safety Act and Fire Service Act because it uses a metal hydride that has a pressure of 1 MPa or less and does not ignite.

In August 2018, Toshiba ESS, Tohoku Electric Power Co., Inc., Iwatani Corporation and NEDO announced the construction of Fukushima Hydrogen Energy Research Field (FH2R), a large-scale CO₂-free hydrogen production facility in Namie City, Fukushima Prefecture (Figure 59). It will start operation in 2020, after final tests to verify the technologies, and in time for burning the Olympic torch and flame during the Games with this hydrogen, and promoting the use of hydrogen internationally. This project represents the biggest P2G demonstration effort in Japan (Chapter 3.3).

The water electrolysis system will have 10 MW of maximum input power capacity, the largest in the world, being 6 MW the rated power and 1.5 MW the minimum. It will be powered mainly by a 20 MW solar plant, backed up by the grid. It will produce and store up to 900 tons of hydrogen a year, which will be used to power FCVs and FC buses, and to support factory

operations¹⁶¹. The hydrogen production per hour will be 1,200 Nm³, which means that in a day, it will be enough fuel for 560 FCVs or 150 households.

Figure 59: Fukushima Hydrogen Energy Research Field

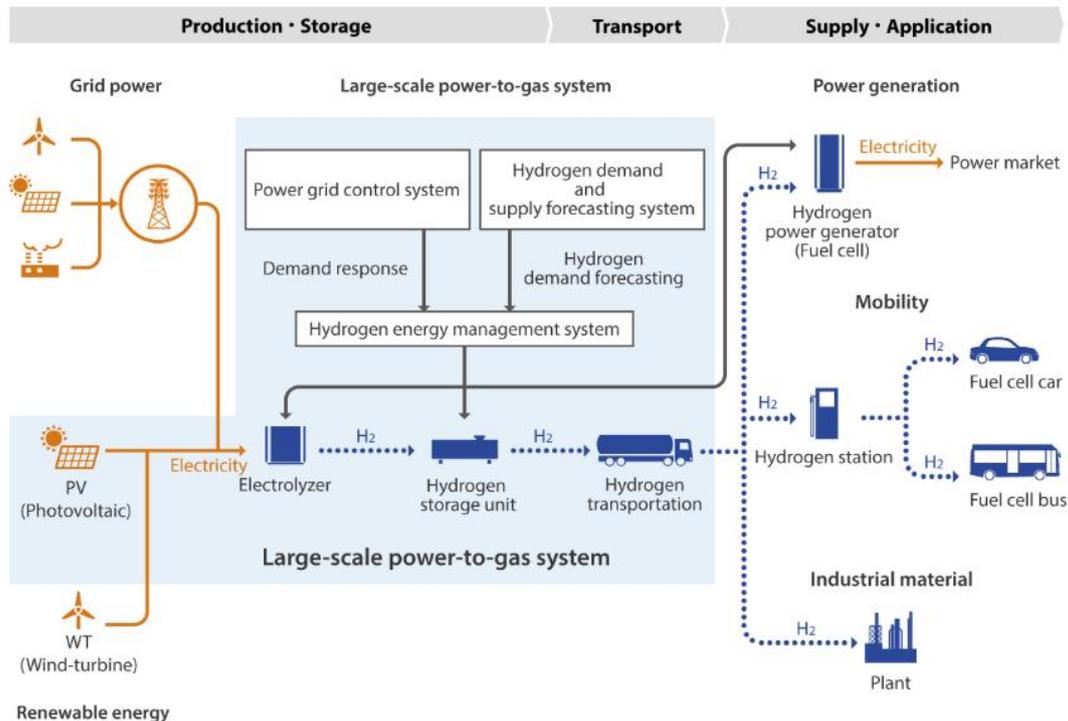


Source: Toshiba.

P2G utilizing hydrogen requires not only the grid balancing function to make the maximum use of fluctuating renewable energy, but also the optimal system operation function based on the forecasting of hydrogen supply and demand. FH2R will use a new control system to coordinate the overall operation of the hydrogen energy system, the power grid control system, and the hydrogen demand forecast system, so as to optimize hydrogen production, hydrogen electricity generation and hydrogen gas supply (Figure 60). Therefore, the project will seek to demonstrate also the advantages of hydrogen as a solution in grid balancing and as a hydrogen gas supply. For that purpose, it will be liquefied and transported in compressed hydrogen trailers to locations in Tohoku and beyond.

¹⁶¹ NEDO, 9 August 2018: https://www.nedo.go.jp/english/news/AA5en_100393.html.

Figure 60: FH2R System Structure



Source: NEDO.

3.5.3. Yamanashi Prefecture and the Yamanashi Fuel Cell Valley

Yamanashi Prefecture Government has been making efforts to become a national centre for both energy storage and hydrogen fuel cell development by attracting companies such as Panasonic Corp. or Toray Industries Inc.

In the Komekurayama Facilities of Kofu City (Table 12), a 1 MW solar power station (Electric Power Storage Technology Research Site) was built for being available for developers of storage devices who wish to conduct tests under closed conditions, in a joint venture with TEPCO. Also the Yume Solar Hall Yamanashi exhibition hall for TEPCO and operated by the Yamanashi Prefectural Public Enterprise Bureau was installed, and a 10 MW solar power plant [45].

One of the demonstration projects in the Komekurayama facilities is a P2G, which provides a wide adaptation to the grid needs. The excess energy generated by the 10 MW Komekurayama solar power plant, built nearby by TEPCO and the Prefecture in 2012, is used to produce pure hydrogen through a 1.5 MW PEM electrolysis system developed by Kobelco Eco-Solutions Co., a unit of Kobe Steel Ltd. Hydrogen is stored in a tank to be used by fuel cells installed by

Panasonic to produce electricity when the energy provided by the panels is not enough. Hydrogen can be also compressed for transporting for LPG customers or injected to near the customer pipelines for using in pure hydrogen fuel cells and boilers (Figure 61).

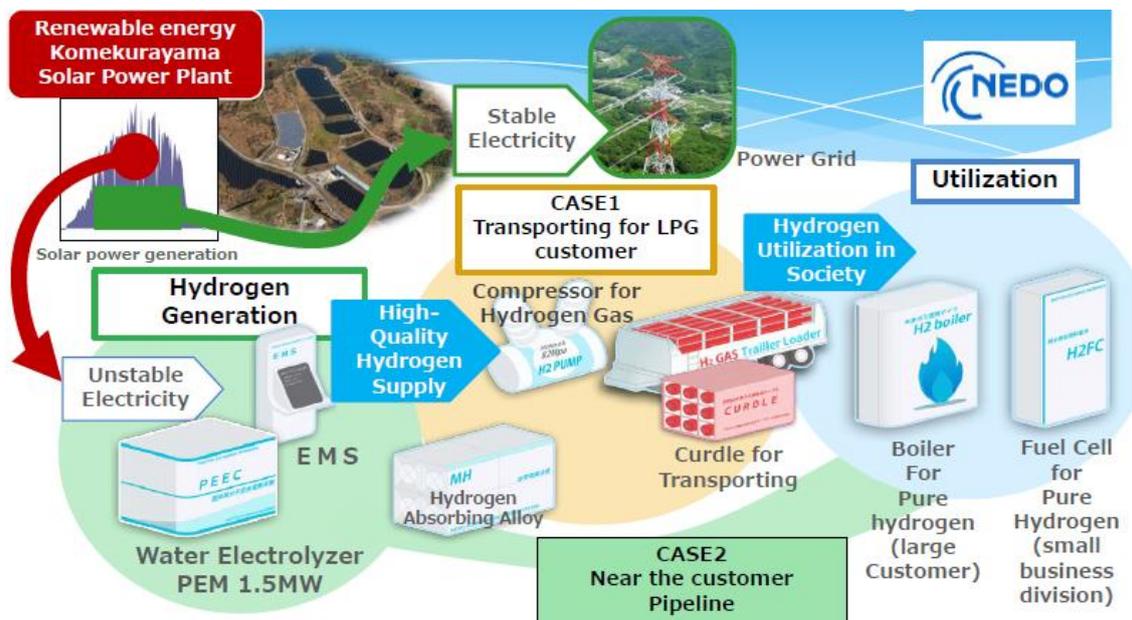
Table 12: Komekurayama Facilities

	Yume Solar Hall (from FY 2011)	Storage Research Site (from FY 2012)
Short-period (inertia, frequency)	Electric double-layer capacitor	Superconducting flywheel energy storage system
Medium-period (voltage, peak shift)	Lithium-ion battery	Hybrid hydrogen storage system
Long-period (electric energy amount)	Hydrogen electric power storage	Power-to-Gas system

Source: Author, with data from the Yamanashi Prefectural Enterprise Bureau [45].

Apart from NEDO, TEPCO, the Yamanashi Prefectural Enterprise Bureau, Panasonic and Kobelco, other firms and institutions involved in this project are Toray, Takaoka Toko Co. Ltd., HySUT, AIST, Nichicon, Miura, Hitz Hitachi Zosen, and JSW (The Japan Steel Works, Ltd.).

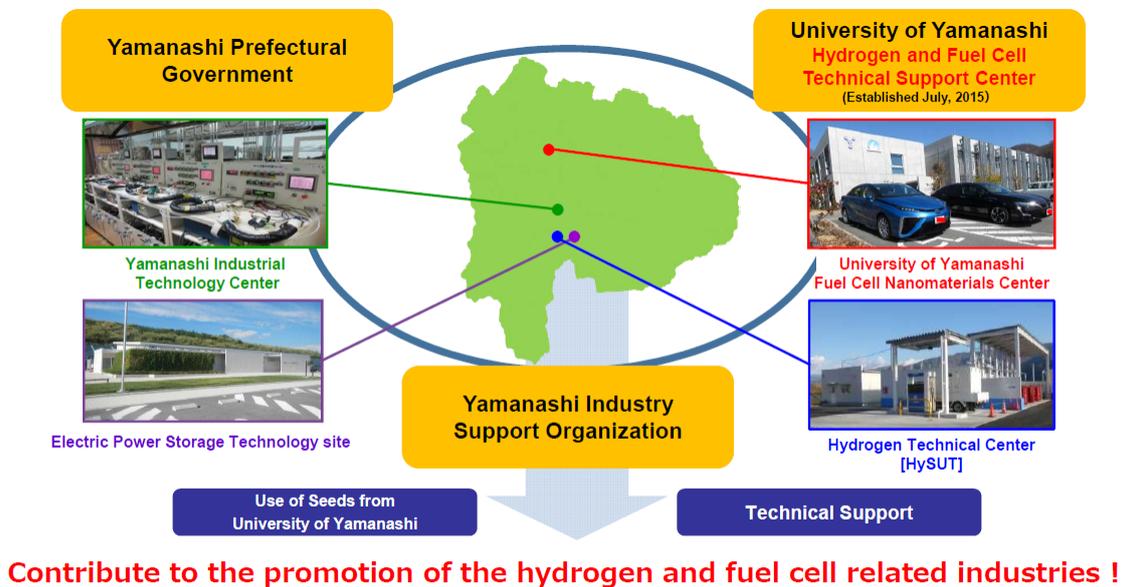
Figure 61: Power to Gas System. Long-term Electric Power Storage



Source: Yamanashi Prefectural Enterprise Bureau [45].

Therefore, the Yamanashi project is also boosting the prefecture’s efforts to become a “Fuel Cell Valley” and attract talent and investment (Figure 62). The Yamanashi Fuel Cell Valley is included in the Yamanashi Hydrogen Energy Society Realization Roadmap, making the best use of the regional characteristics such as one of the highest solar power potential in Japan, and a cluster of research institutes on hydrogen and fuel cells. The roadmap defines the following three approaches: the expansion of the use of hydrogen energy, with a target to have 1,300 FCVs, 10 FC buses, 2 HRSs and 34,000 ene-farms by 2030; the construction of a CO₂-free hydrogen supply chain, promoting the P2G from the solar generation; and the promotion of hydrogen and fuel cell-related industries. The regional government expects 200 enterprises entering, 5,000 employees and JPY 100 billion in sales by 2030 [42].

Figure 62: Key Characteristics of the Yamanashi Fuel Cell Valley



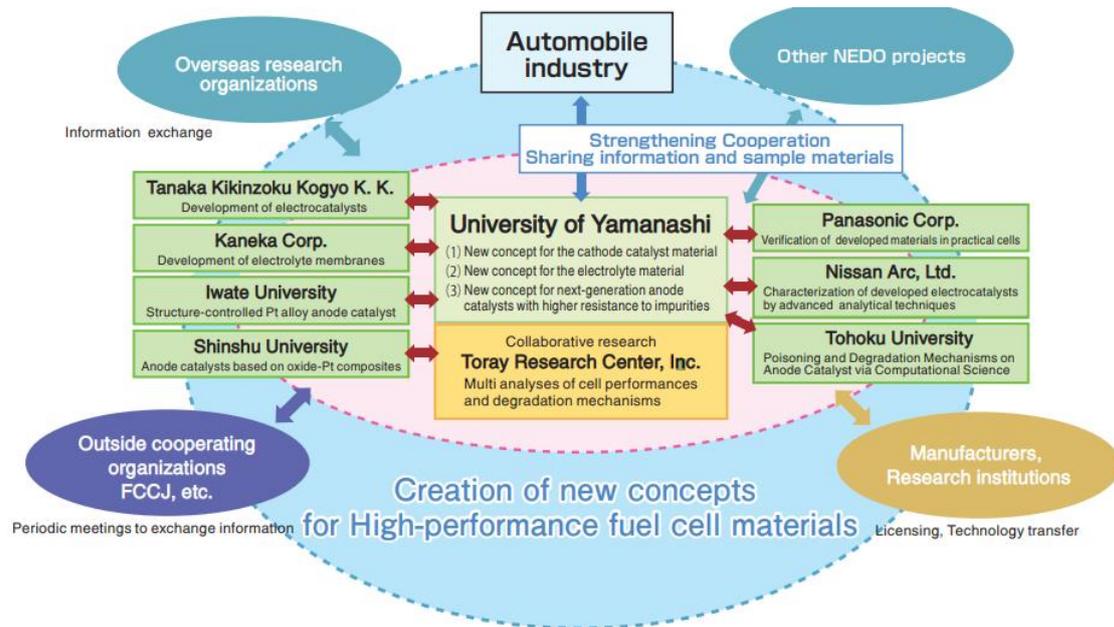
Source: NEDO [42].

As a Yamanashi University-affiliated facility, the Clean Energy Research Center was established in April 2001 to promote research related to clean energy and contribute to the resolution of energy and global environmental problems. It has two divisions, Fuel Cell Research, and Solar Cells and Environmental Science. The first one’s aim is to push forward R&D on fuel cells and contribute to their full, large-scale market penetration, especially residential fuel cells (ene-farms) and FCVs, in cooperation with the industry.

The Fuel Cell Nanomaterials Center was established in April 2008. The research was carried out under the NEDO project “HiPer-FC” (High-Performance Fuel Cell) from that date with the full use of nanotechnology to establish basic technologies for fuel cells (catalysts, electrolyte membranes, etc) that can simultaneously achieve higher performance, higher reliability, and

lower costs. From May 2015, “S-Per-FC” ((Superlative, Stable, and Scalable Performance Fuel Cell) project, also funded by NEDO, aims to contribute to the large-scale proliferation of FCVs based on these superior outcomes. Creation of a new concept for the cathode catalyst material, for the electrolyte material and for next-generation anode catalysts with higher resistance to impurities. As the project leader, the University of Yamanashi is collaborating with Tanaka Kikinzoku Kogyo K.K., Kaneka Corp., Panasonic Corp., Nissan Arc, Ltd., Toray Research Center, Inc., Iwate University, Shinshu University and Tohoku University¹⁶² (Figure 63).

Figure 63: Research and Development Organization



Source: Fuel Cell Nanomaterials Center.

The Fuel Cell Evaluation / Testing Facility at Yamanashi Industrial Technology Center was established in April 2016 with the support of NEDO to R&D on technological advance, price reduction and productivity improvement of fuel cells.

The Hydrogen Technology Center for HRs was established in December 2017 also in Kofu City. It was founded by NEDO and it is operated by HySUT. Its purpose is to develop new technologies to contribute to the further safety and security of hydrogen, to research on cost reduction of HRs, and to carry out tests in a real environment. Two examples are the increase of the maximum operating pressure to 87.5 MPa (cylinder bundle, compressor, pressure vessel and dispenser), and the standardization of equipment, individually designed by each contractor, and design specifications (Chapter 3.2.2).

¹⁶² Fuel Cell Nanomaterials Center, University of Yamanashi: http://fc-nano.yamanashi.ac.jp/english/img/nono_en2016.pdf.

Finally, some other universities and research institutes with research groups working on hydrogen, fuel cells and related materials are the following:

- Research Center for Advanced Science and Technology, The University of Tokyo.
- Tokyo Institute of Technology.
- Institute for Material Research, Tohoku University.
- Department of Energy and Hydrocarbon Chemistry, Kyoto University.
- Aichi Institute of Technology.
- Nagoya University.
- Hokkaido University.
- Osaka University.

3.6. ORGANIZATIONS AND ASSOCIATIONS

Government Organizations

Ministry of Economy, Trade and Industry (METI)

1-3-1, Kasumigaseki, Chiyoda-ku, Tokyo 100-8901

+81-(0)3-3501-1511

<http://www.meti.go.jp/english>

Agency for Natural Resources and Energy (ANRE)

1-3-1, Kasumigaseki, Chiyoda-ku, Tokyo 100-8901

+81-(0)3-3501-1511

<http://www.enecho.meti.go.jp/en/>

New Energy and Industrial Technology Development Organization (NEDO)

MUZA Kawasaki Central Tower, 16F-20F, 1310 Omiya-cho, Saiwai-ku,

Kawasaki, Kanagawa 212-8554

+81-(0)4-4520-5273

<http://www.nedo.go.jp/english/index.html>

Ministry of the Environment (MOE)

Godochosha No. 5, Kasumigaseki 1-2-2, Chiyoda-ku, Tokyo 100-8975

+81-(0)3-3581-3351

<http://www.env.go.jp/en/>

Ministry of Land, Infrastructure, Transport and Tourism (MLIT)

2-1-3 Kasumigaseki, Chiyoda-ku, Tokyo 100-8918

+81-(0)3-5253-8111

<http://www.mlit.go.jp/en/index.html>

Ministry of Foreign Affairs of Japan (MOFA)

2-2-1 Kasumigaseki, Chiyoda-ku, Tokyo 100-8919

+81-(0)3-3580-3311

<https://www.mofa.go.jp/>

Cabinet Office

1-6-1 Nagata-cho, Chiyoda-ku, Tokyo 100-8914

+81-(0)3-5253-2111

<https://www.cao.go.jp/index-e.html>

Related Associations

National Institute of Advanced Industrial Science and Technology (AIST)

1-3-1 Kasumigaseki, Chiyoda-ku, Tokyo 100-8921

+81-(0)3-5501-0900

https://www.aist.go.jp/index_en.html

The Institute of Applied Energy (IAE)

Shimbashi SY Building, 14-2 Nishi-Shimbashi 1-Chome, Minato-ku, Tokyo, 105-0003

03-3508-8891

<http://www.iae.or.jp/e/>

Japan Science and Technology Agency (JST)

Honcho 4-1-8 Kawaguchi Center, Kawaguchi City, Saitama Prefecture, 332-0012

+81-(0)4-8226-5601

<https://www.jst.go.jp/EN/>

Central Research Institute Electric Power Industry (CRIEPI)

Otemachi Bldg. 7F, 1-6-1 Otemachi, Chiyoda-ku, Tokyo 100-8126

+81-(0)3-3201-6601

<https://criepi.denken.or.jp/en/index.html>

The Association of Hydrogen Supply and Utilization Technology (HySUT)

2-10-5 Akasaka, Minato-ku, Tokyo 107-0052

+81-(0)3-3560-2802

<http://hysut.or.jp/en>

Japan H2 Mobility (JHyM)

3-18-2 Kudan-minami, Chiyoda-ku, Tokyo 102-0074

+81-(0)3-5214-6711

<https://www.jhym.co.jp/en>

Fuel Cell Commercialization Conference (FCCJ)

Immeuble Kojima 2F,3-13-2 Higashi-Ikebukuro, Toshima-ku, Tokyo 170-0013

+81-(0)3-5979-7355

<http://fccj.jp/eng>

Fuel Cell Association (FCA)

7F, SVAX TT Building, 3-11-15 Toranomom, Minato-ku , Tokyo 105-0001

+81-(0)3-6689-0331

<http://www.fca-enefarm.org/index.html>

Next Generation Vehicle Promotion Center (NeV)

Nihonbashi Kimura Building, 16-3, Nihonbashi, Chuo- ku, Tokyo 103-0027

+81-(0)3-3548-3231

<http://www.cev-pc.or.jp/english/>

Fuel Cell Development Information Center (FCDIC)

1-9-1 Kanda Awajicho, Chiyoda City, Tokyo 101-0063, Japón

+81-(0)3-6206-0231

<https://www.fcdic.com/?language=eng>

The Hydrogen Energy Systems Society of Japan (HESS)

1-8-14, Kanda-Surugadai, Chiyoda-Ku, Tokyo 101-8308

Nihon University (College of Science and Technology)

+81-(0)3-3259-0514

<http://www.hess.jp/en/index.html>

Fuel Cell Cutting-Edge Research Center Technology Research Association (FC-Cubic TRA)

AIST Tokyo Waterfront Main Building, 2F, 2-3-26 Aomi, Koto-ku, Tokyo 135-0064

(+81)-03-3599-2357

<http://www.fc-cubic.or.jp/en/>

The Japan Gas Association

Japan Gas Association Building, 9F, 1-15-12 Toranomom, Minato-ku, Tokyo 105-0001

+81-(0)3-3502-0111

<https://www.gas.or.jp/en/>

3.7. MAIN PRIVATE COMPANIES

The Japanese hydrogen and fuel cells market is dominated by a wide variety of domestic companies from different sectors including automakers, engineering, gas, power, manufacture, construction or distribution companies, among others, already mentioned on previous chapters and summarized in the following lines:

Stationary Fuel Cells

Panasonic	Aisin Seiki
Toshiba ESS	Miura
Denso	Hitachi Zosen
Mitsubishi Hitachi Power Systems	Fuji Electric
Bloom Energy Japan	NGK Spark Plug

Fuel Cell Vehicles

Toyota Motor	Hino Motors
Honda Motor	Nissan Motor
JR East	

Refueling Stations

- Infrastructure developers:

JXTG Nippon Energy	Iwatani Corporation
Air Liquide Japan	Seiryu Power Energy
Nippon Mobile Hydrogen Station Services	Idemitsu Kosan
Toho Gas	Tokyo Gas
Osaka Gas	Chubu Gas
Honda Motor	Toshiba ESS
Nemoto Tsusho	Tama Koun
Nangoku Corporation	Marui Transport
Toyama Hydrogen Energy Promotion Council	Fukuoka Oxygen

- Investors:

Toyota Tsusho	JA Mitsui Lease
Development Bank of Japan	Mirai Creation Fund
Sompo Japan Nipponkoa Insurance	NEC Capital Solutions Limited
Mitsui Sumitomo Finance & Leasing,	

Power Generation

Mitsubishi Hitachi Power Systems	Kawasaki Heavy Industries
Toyota Tsusho	NTT Facilities, Inc.
Hrein Energy Inc.	Technova Inc.
Muroran Institute of Technology	Obayashi Corporation
JGC Corporation	IHI Corporation

JGC Catalysts & Chemicals Ltd.
 Taiyo Nippon Sanso Corporation
 Chubu Electric Power
 Tohoku Electric Power

Toyota Energy Solutions
 Kansai Electric Power
 Chugoku Electric Power

Supply Chains

- Liquefied Hydrogen:

Kawasaki Heavy Industries	Iwatani Corporation
Electric Power Development Co., Ltd.	Shell Japan
Marubeni Corporation	

- Methylcyclohexane:

Chiyoda Corporation	Mitsubishi Corporation
Nippon Yusen Kabushiki Kaisha	Mitsui & Co. Ltd.
JXTG Nippon Oil & Energy Corporation	

- Regional Supply Chains:

Toyota Motor Corp.	Air Products Japan K.K.
Nippon Steel Pipeline & Engineering Co., Ltd.	Kajima Corp.,
Tokuyama Corp.	Tosoh Corp.,
Showa Denko K.K.	Toshiba ESS
Iwatani Corporation	Hitachi, Ltd.
Marubeni Corp.	Miyagi Coop.
NTT Data Institute of Management Consulting, Inc.	Taisei Corp.
Dainichi Machine and Engineering Co., Ltd.	Tomoe Shokai Co., Ltd.
The Japan Steel Works Ltd.	Kita Koudensha Corp.
Chubu Electric Power Co., Inc.,	Toho Gas
Toyota Motor	Toyota Industries Corporation
Alhytec Inc.	Tohoku Electric Power
Muroran Institute of Technology	

Nevertheless, there are several foreign firms that successfully accessed into the Japanese hydrogen market. Some examples are the following:

- Air Liquide Japan (France) is well established in Japan since 1907, and it was one of the eleven original members of JHyM (Chapter 3.2.2). It masters the entire hydrogen supply chain, from production to storage and from distribution to the development of applications for end-users. In October 2013, it signed a partnership agreement with Toyota Tsusho Corporation for a hydrogen supply business for FCVs, building two HRSs in the Aichi area. The two companies established a new joint venture company

called Toyota Tsusho Air Liquide Hydrogen Energy Corporation¹⁶³. Air Liquide also installed and operates other four stations in Saga, Fukuoka, Hyogo and Kawasaki¹⁶⁴.

- Shell Japan (The Netherland) is involved in the transportation of liquefied hydrogen from Australia (Chapter 3.4.2).
- Wärtsilä (Finland) signed a business development agreement with Hitachi Zosen in March 2010 to develop and market fuel cell-based power plant solutions for distributed power generation applications in Japan. The combined heat and power applications, which can be run on either city gas or biogas, feature the use of Wärtsilä's SOFC technology¹⁶⁵.
- Bloom Energy (US) and SoftBank Group established a 50/50 joint venture called Bloom Energy Japan to deploy Bloom Energy's SOFC technology in Japan¹⁶⁶. In November 2013, they installed the first 200 kW unit at SoftBank's M-Tower in Fukuoka City, which provides 75% of the building's electricity consumption¹⁶⁷.
- Linde Group (Germany) signed a deal with Iwatani Corporation in July 2014 for the delivery of 28 HRSs with ionic compressors in Japan during the opening of the world's first small-series production facility for HRSs of Linde in Vienna¹⁶⁸.
- Air Products (US) signed an agreement with NIPPON STEEL & SUMIKIN Pipeline & Engineering Co. Ltd. in 2014 to work together on Japan's developing hydrogen fueling infrastructure market for automotive customers. In February 2015, it also signed an agreement with Suzuki Shokan, an industrial gas company, to work together on the design, construction and operation of hydrogen fueling stations for use in fueling the material handling vehicle market in Japan¹⁶⁹.
- H2 Logic (Norway), subsidiary of Nel, signed a binding technology transfer agreement with Mitsubishi Kakoki Kaisha, Ltd. in July 2015. The collaboration included the adaptation of the H2Station® CAR-100 product for the Japanese market with the aim to strengthen Mitsubishi's position in the supply and construction of HRSs and to provide H2 Logic access to the Japanese market¹⁷⁰.

¹⁶³ Air Liquide, 28 October 2013: <https://energies.airliquide.com/japan-air-liquide-signs-partnership-toyota-tsusho-hydrogen-supply-fuel-cell-electric-vehicles>.

¹⁶⁴ Air Liquide, 6 November 2017: <https://www.airliquide.com/japan/20171106kawasakihrs01e>.

¹⁶⁵ Wärtsilä, 2 March 2010: <https://www.wartsila.com/media/news/02-03-2010-wartsila-and-hitachi-zosen-sign-agreement-to-develop-and-market-fuel-cell-based-power-plant-solutions-in-japan>.

¹⁶⁶ SoftBank Group, 18 July 2013: https://group.softbank/en/corp/news/press/sb/2013/20130718_01/.

¹⁶⁷ SoftBank Group, 25 November 2013: https://group.softbank/en/corp/news/press/sb/2013/20131125_01/.

¹⁶⁸ Linde, 14 July 2014: https://www.linde.nl/en/news_and_media/press_releases/news_20140714.html.

¹⁶⁹ Air Products, 19 February 2015: <http://www.airproducts.com/Company/news-center/2015/02/0219-air-products-and-suzuki-shokan-to-develop-hydrogen-fueling-for-japan-material-handling-market.aspx>.

¹⁷⁰ Nel, 10 July 2015: <https://nelhydrogen.com/press-release/h2-logic-as-and-mitsubishi-kakoki-kaisha-ltd-to-collaborate-on-hydrogen-fueling-for-japan/>.

- Ceres Power (UK) signed a second two years joint development agreement with Honda in January 2016 to jointly develop SOFC stacks using Ceres Power's unique metal-supported Steel Cell technology based on the use of low-cost metal sheets for a range of potential power equipment applications. It included a third party who will consider the future mass-production scale-up of the Steel Cell technology¹⁷¹. It also developed SOFCs in partnership with Miura Co. Ltd.¹⁷² (Chapter 3.1). Ceres Power set up a representative office in Osaka.
- Ballard Power Systems (Canada) signed a distribution agreement for fuel cell products in Japan with Toyota Tsusho Corporation in August 2016¹⁷³. In April 2018, Toyota Tsusho sold five Ballard's hydrogen fuel cells to be used as part of a renewable emergency power system installed in Soma City, Fukushima Prefecture. The purpose of the project led by IHI Corporation is to produce hydrogen for storage through excess solar power generation¹⁷⁴. Ballard also collaborated with Nisshinbo Holdings, an environmental and energy company, to develop a non-precious metal catalyst (NPMC) for use in the world's first commercialized NPMC-based PEMFC product¹⁷⁵. They have jointly collaborated on the development of NPMC since 2013.
- ITM Power (UK) signed a strategic partnership agreement with Sumitomo Corporation in July 2018 for the CO₂-free hydrogen production in Japan through the introduction of the ITM's multi-megawatt PEM electrolyzers¹⁷⁶.
- Energy Solutions and PDC Machines (US) jointly manufactured SimpleFuel™ to Toyota, a simplified hydrogen station that uses electricity from solar panels at the plant site to produce and store hydrogen through the electrolysis of water (Chapter 3.2.2).

In previous chapters, it was mentioned collaborations between Japanese and European corporations also for the European market, such as Panasonic with Viessmann (Germany) and Engie (France), Toshiba with BAXI Innotech GmbH (Germany), Aisi Seiki with Bosch (Germany), Kawasaki Heavy Industries with Nel (Norway) and Shell (The Netherland), or Nissan with Ceres Power (UK).

¹⁷¹ Ceres Power, 18 January 2016: <https://www.cerespower.com/news/latest-news/new-joint-development-agreement-with-honda/>.

¹⁷² Ceres Power, 20 June 2019: <https://www.cerespower.com/news/latest-news/miura-to-launch-new-chp-fuel-cell-product-for-the-commercial-building-sector-in-japan/>.

¹⁷³ Ballard Power System, 18 August 2016: <https://www.ballard.com/about-ballard/newsroom/news-releases/2016/08/18/ballard-and-toyota-tsusho-sign-distribution-agreement-for-fuel-cell-products-in-japan>.

¹⁷⁴ Toyota Tsusho Corporation, 5 April 2018: https://www.toyota-tsusho.com/english/press/detail/180405_004158.html.

¹⁷⁵ Ballard Power System, 12 September 2017: <https://www.ballard.com/about-ballard/newsroom/news-releases/2017/09/13/ballard-to-offer-world-s-first-pem-fuel-cell-product-using-non-precious-metal-catalyst>.

¹⁷⁶ ITM, 9 July 2018: <http://www.itm-power.com/news-item/sumitomo-and-itm-power-announce-strategic-partnership-agreement>.

3.7.1. Potential Opportunities and Recommendations for European Firms

Japanese hydrogen and fuel cells market will have great growth in the next decades, which also represents increasing business chances for foreign companies with advanced products and technologies, or with expertise in these areas. According to NEDO's estimation, the hydrogen market will reach JPY 1 trillion (about EUR 8 billion) by 2030 and JPY 8 trillion (around EUR 65 billion) by 2050. Foreign research institutions will also have good opportunities for collaborating with Japanese institutions and universities that are looking for partners and foreign researchers.

Japan has a leading position in some of the hydrogen and fuel cell technologies. The government awaits the results of several demonstration projects around 2020 to start the operation of large-scale infrastructures, though some technologies will not be commercialized until around 2030. Japan will continue investing in and developing technologies for the production, transportation, storage and use of hydrogen, aligned with the ten technological development items in three main areas (fuel cell technology, supply chain and water electrolysis) that were announced in the Hydrogen and Fuel Cell Technology Development Strategy in September 2019 (Chapter 3). European technology has advanced faster during the last years making European firms to be well-positioned for entering into the Japanese market.

Foreign companies have already entered into the refueling station business, with JHyM offering easy procedures and lower costs. Since Japan needs to build a larger network of HRSs across the country, this sector still offers opportunities for European companies with innovative and cheaper solutions. For example, polymer materials for gas seals and dispensing hoses, life-extension methods of ground storage pressure vessels, or a new type of compressors, such as an electro-chemical compressor. Also low-cost equipment and parts for the next generation of ultra-high pressure hydrogen stations, such as high-pressure hydrogen-compatible polymer technology, electrochemical pumps, new large-sized, thin-walled high-pressure hydrogen tanks, or ultra-high pressure hydrogen trailers equipped with lightweight containers for the large-scale and efficient hydrogen transport.

The increasing importance of SOFCs for residential and commercial buildings represents another opportunity for European companies. Indeed, some of them are already active in this segment as it was mentioned before. SOFC technologies with higher electrical efficiencies, durability and lower costs, PEFC technologies with higher durability and lower costs, and pure hydrogen fuel cells technologies will be very welcome in Japan.

New materials and technologies for increasing the performance of membranes, membrane electrode assemblies, electrodes and catalysts used in the fuel cells will have opportunities. For example, alternative platinum catalysts with a lower amount of platinum. Also lighter materials and more compact materials used in high-pressure storage tanks that allow increasing the compression ratios of the gas, and technologies for reducing the amount of carbon fibre used in the hydrogen storage systems.

Develop efficient technologies to produce low-cost CO₂-free hydrogen through renewable sources is a priority for Japan. Therefore, innovative water electrolysis technologies with higher efficiencies, durability and lower costs will have great opportunities.

Another priority is to develop highly efficient energy carriers and technologies for long-distance mass transportation and storage.

Finally, to enter the Japanese market, there are several important points to take into account:

- Long-term commitment. There is no easy and quick way to succeed in Japan.

Research the Japanese market. There are significant differences between doing business in Japan and in Europe. Japan presents challenges uniquely distinct from many other markets, so it is important to be familiar with the Japanese concept of business negotiation and corporate decision-making.

- Understand regulatory requirements. There are three levels of government (national, prefecture and local), and sometimes lack coordination between Ministries, that makes difficult to understand what regulations are applicable to each case. Additionally, the Japanese government is reviewing different regulations about hydrogen and fuel cells technologies. Language is also a barrier.

On the other hand, the European Union and Japan recently signed the Economic Partnership Agreement (EPA), a free trade agreement for goods and services which will contribute to facilitating the access of European companies to Japan.

- Develop the right market entry strategy. Business partnerships, joint-ventures or distribution agreement with Japanese firms can make business easier at the beginning (see examples above), while direct presence through a subsidiary may be the best long-term strategy.
- Showing presence in Japan through industry fairs (Annex B) and conferences, and meeting with potential partners. Now is a good time for positioning in the Japanese market, so it is advisable to strengthen business relations with relevant public and private organizations. Build networks may take some time, meaning that the strategy should follow a mid to long-term strategy.
- Adapt products to local needs, emphasizing the unique features and advantages of the technology, and the previous proven success in other markets. Japan is a highly developed and industrially advanced market, and with similar offers, Japanese customers tend to choose local suppliers, who are culturally and geographically closer and have no language barrier. Therefore, those companies that want to address it must do so with innovative concepts and competitive technologies. The international experience of the company is a key factor for success.

- Offer high quality and extensive customer support and after-sales service system, usually more demanding and expensive than in Europe. Serving the customer is part of the Japanese business culture.

4. CONCLUSIONS

Since the Great East Japan Earthquake, the necessity of suppressing power consumption on the demand side rose in Japan, and the government has been promoting a low-carbon society through energy efficiency measures and the development of a stable and reliable supply of renewable energy, reducing electricity costs and CO₂ emissions.

The Japanese government is also promoting the use of the hydrogen as a clean and alternative energy vector. It is the key for reducing energy procurement and supply risks since it can be produced from various energy resources, and for decarbonizing the Japanese energy supply and demand structure, transport, heating (buildings), industry and power sectors. The fast growth of variable renewable energy capacity provides an opportunity to complement solar and wind installations with the production of hydrogen using the surplus that would otherwise be wasted, keeping power systems flexible and helping to balance the grid. Hydrogen, in contrast to storage batteries, can be stored on a large scale and for the long term.

But its widespread adoption faces challenges, especially a high cost. Realize a hydrogen society in Japan implies the necessity of both expanding hydrogen demand and the construction of reliable supply chains to meet that demand at a low cost, and reaching the cost parity with traditional fossil fuels, which will depend also on the application of a carbon price for those emitting CO₂. The Japanese government has been supporting demonstration projects for building supply chains from overseas to produce green hydrogen from renewable sources or from fossil fuels plus the carbon capture and storage.

Liquid hydrogen, methylcyclohexane (organic hydride) and ammonia are regarded as the most promising hydrogen carriers. Ammonia has the highest potential to lead the transition towards a hydrogen society due to its properties, the technical maturity of its supply network, it can be used directly as a fuel for power generation and its energy equivalent cost is estimated to be the most feasible option.

The government aims to establish also regional hydrogen supply chains using local unused resources, including renewable energy, waste plastics, sewage sludge, and by-product hydrogen, which will contribute to improving the regional energy self-sufficiency rates and creating new regional industries. The combination of low solar and wind costs, continuously in a downward trend, and more efficient and cheaper electrolysis technologies are gradually making the large-scale renewable electrolysis a viable option in the near future.

Therefore, hydrogen production, transportation and storage are potential areas for foreign companies with innovative technologies. Especially the water electrolysis market offers opportunities for European companies with more efficient and cheaper solutions.

Power generation accounts for 40% of total national CO₂ emissions, so the use of hydrogen in this sector will greatly contribute to reducing them and will directly lead to massive hydrogen consumption, which will contribute to cost reduction. Power-to-gas is expected to be one of the countermeasures against problems related to grid stability and reliability due to the higher penetration of renewables in Japan.

The three main technologies for hydrogen gas turbine power generation that are being developed in Japan are the co-combustion of hydrogen and natural gas, the hydrogen firing power generation, and the direct combustion of ammonia. Co-firing 20% ammonia in all the Japanese coal power plants would reduce around 3% the national CO₂ emissions, about 40 million tons per year, though it would increase the coal energy generation cost by 30%, still cheaper than the nuclear and natural gas generation. European technologies in the hydrogen power generation market will have a lot of opportunities in Japan.

In 2030, the government aims to reduce emissions by 39% in the residential sector and by 40% in the commercial sector compared to the emissions in 2013. Stationary fuel cell systems, which generate electricity and heat, are contributing to that goal, with around 300,000 units deployed across the country. Large-scale SOFC systems for commercial centres and other buildings are growing in importance. However, the national strategy set a target of 1.4 million units by 2020 that will not be met, and thus, the Japanese government should continue subsidized them even after reaching their target prices. Pure hydrogen fuel cells are the next step. Fuel cell systems market including components and material offers opportunities to foreign companies.

The transportation sector contributed with 19% to entire CO₂ emissions in Japan in 2015, and the government's target is to reduce it by 25% by 2030 increasing the popularization of the next-generation vehicles and reaching a share in the new car sales between 50% and 70% by 2030. Fuel cell vehicles offer a low emission driving performance, overcome electric vehicles' weight, range and charging limitations, and can be also used for power supply in case of disasters. However, compared to electric vehicles, the deployment of FCVs is being slower because they are more difficult to produce, they are much expensive, and there are not enough refueling stations. The national target of 40,000 units by 2020 will not be met, and thus, at this stage, policy support from the government is still indispensable in Japan.

The main issues for the dissemination of HRSs are the high construction and operation costs and the strict regulations. METI is reviewing the regulation that affects to HRSs and working on the standardization of equipment to achieve lower costs. To address the financing problem, Japan H₂ Mobility (JHyM) was established by several private companies. Some European companies are already active in this segment, but the necessity of increasing the number of stations across the country offers business opportunities for other firms.

The government awaits the results of several demonstration projects around 2020 to start the operation of hydrogen large-scale infrastructures. Demonstration projects must reveal the deficiencies of the different technologies and allow to focus on the most technical and cost-effective areas, taking into account their applicability in real operating conditions.

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ANNEXES

A. STRATEGIC ROAD MAP FOR HYDROGEN AND FUEL CELLS. SUMMARY.

The Strategic Road Map for Hydrogen and Fuel Cells ~ Industry-academia-government action plan to realize "Hydrogen Society" ~ (overall)

- In order to achieve goals set in the Basic Hydrogen Strategy,
- ① **Set of new targets to achieve (Specs for basic technologies and cost breakdown goals), establish approach to achieving target**
- ② **Establish expert committee to evaluate and conduct follow-up for each field.**

		Goals in the Basic Hydrogen Strategy	Set of targets to achieve	Approach to achieving target						
Use	Mobility	FCV 200k by 2025 800k by 2030	2025 <ul style="list-style-type: none"> ● Price difference between FCV and HV (¥3m → ¥0.7m) ● Cost of main FCV system <table border="0"> <tr> <td>FC</td> <td>¥20k/kW → ¥5k/kW</td> </tr> <tr> <td>Hydrogen Storage</td> <td>¥0.7m → ¥0.3m</td> </tr> </table> 	FC	¥20k/kW → ¥5k/kW	Hydrogen Storage	¥0.7m → ¥0.3m	<ul style="list-style-type: none"> • Regulatory reform and developing technology 		
		FC	¥20k/kW → ¥5k/kW							
		Hydrogen Storage	¥0.7m → ¥0.3m							
HRS 320 by 2025 900 by 2030	2025 <ul style="list-style-type: none"> ● Construction and operating costs <table border="0"> <tr> <td>Construction cost</td> <td>¥350m → ¥200m</td> </tr> <tr> <td>Operating cost</td> <td>¥34m → ¥15m</td> </tr> </table> ● Costs of components for HRS <table border="0"> <tr> <td>Compressor</td> <td>¥90m → ¥50m</td> </tr> <tr> <td>Accumulator</td> <td>¥50m → ¥10m</td> </tr> </table> 	Construction cost	¥350m → ¥200m	Operating cost	¥34m → ¥15m	Compressor	¥90m → ¥50m	Accumulator	¥50m → ¥10m	<ul style="list-style-type: none"> • Consideration for creating nation wide network of HRS • Extending hours of operation
Construction cost	¥350m → ¥200m									
Operating cost	¥34m → ¥15m									
Compressor	¥90m → ¥50m									
Accumulator	¥50m → ¥10m									
Bus 1,200 by 2030	Early 2020s <ul style="list-style-type: none"> ● Vehicle cost of FC bus (¥105m → ¥52.5m) 	<ul style="list-style-type: none"> • Increasing HRS for FC bus 								
<small>※In addition, promote development of guidelines and technology development for expansion of hydrogen use in the field of FC trucks, ships and trains.</small>										
	Power	Commercialize by 2030	2020 <ul style="list-style-type: none"> ● Efficiency of hydrogen power generation (26%→27%) ※1MW scale 	<ul style="list-style-type: none"> • Developing of high efficiency combustor etc. 						
	FC	Early realization of grid parity	2025 <ul style="list-style-type: none"> ● Realization of grid parity in commercial and industrial use 	<ul style="list-style-type: none"> • Developing FC cell/stack technology 						
Supply	Fossil Fuel + CCS	Hydrogen Cost ¥30/Nm3 by 2030 ¥20/Nm3 in future	Early 2020s <ul style="list-style-type: none"> ● Production: Production cost from brown coal gasification (¥several hundred/Nm3 → ¥12/Nm3) ● Storage/Transport : Scale-up of Liquefied hydrogen tank (thousands m³ → 50,000m³) Higher efficiency of Liquefaction (13.6kWh/kg → 6kWh/kg) 	<ul style="list-style-type: none"> • Scaling-up and improving efficiency of brown coal gasifier • Scaling-up and improving thermal insulation properties 						
	Green H2	System cost of water electrolysis ¥50,000/kW in future	2030 <ul style="list-style-type: none"> ● Cost of electrolyzer (¥200,000m/kW → ¥50,000/kW) ● Efficiency of water electrolysis (5kWh/Nm3 → 4.3kWh/Nm3) 	<ul style="list-style-type: none"> • Designated regions for public deployment demonstration tests utilizing the outcomes of the demonstration test in Namie, Fukushima • Development of electrolyzer with higher efficiency and durability 						

Action Plan (key point) ① <Hydrogen Use (Mobility) >

Red : New target

In order to reduce cost for full-scale implementation period, thorough establishment of mass production technology and implementation of regulatory reform

	Target to achieve	Approach to achieving target
Hydrogen Use (Mobility)	FCV <ul style="list-style-type: none"> ● 200k by FY2025, 800k by FY2030 ● Achieving a cost reduction of FCV to the level of HV around 2025 (Price difference ¥3m → ¥0.7m) ● Reducing cost of main elemental technologies around 2025 <ul style="list-style-type: none"> 〔 Fuel cell system around ¥20k/kW→¥5k/kW Hydrogen storage system around ¥0.7m → ¥0.3m 〕 Expansion of vehicle types for volume zones in FY2025	<ul style="list-style-type: none"> • Sharing technical information and problems in a cooperation area among stakeholders • Developing technology for <u>reducing the amount of platinum used.</u> • Developing technology for <u>reducing of amount of carbon fiber in hydrogen storage systems</u>
	HRS <ul style="list-style-type: none"> ● 320 by FY2025, some 900 by FY2030 ● Making HRS independent by the second half of the 2020s ● Reduction of cost for construction and operation by FY2025 (construction cost ¥350m→¥200m, operation cost ¥34m/year→¥15m/year) ● Setting of cost target for each component <ul style="list-style-type: none"> 〔 Compressor ¥90m→¥50m High pressure vessels ¥50m→¥10m 〕 	<ul style="list-style-type: none"> • <u>Thoroughly integrate promotion of regulatory reform and technological development</u> (Realization of self-service HRS, use of inexpensive steel material etc.) • <u>Consideration for nation wide networking of HRS</u> • Extending opening hours • Increasing of the number of HRS with gasoline station/convenience store
	Bus <ul style="list-style-type: none"> ● 1,200 FC buses by 2030 ● Expansion of regions where FC buses run ● Reducing FC bus's price by half (¥105m→¥52.5m) ● Independent FC bus by FY2030 	<ul style="list-style-type: none"> • Developing technology for enhancing the fuel efficiency and durability of such vehicles • <u>Expansion of types other than city buses</u> • <u>Promotion of deployment of HRS for FC buses</u>
	Forklift <ul style="list-style-type: none"> ● 10k FC forklifts by 2030 ● Expansion to an overseas markets 	<ul style="list-style-type: none"> • <u>Versatile deployment</u> of fuel cell units • <u>Promotion of maintenance of simple and easy to operate filling equipment</u>

※In addition, promote development of guidelines and technology development for expansion of hydrogen use in the field of FC trucks, ships and train.

Key points of the Action plan ② (hydrogen supply chain)

Red: New Target

Acceleration of RD&D to establish technologies for future hydrogen mass-consuming society

Goals of hydrogen supply chain

- H2 CIF cost : ¥30/Nm3 in 2030, ¥20/Nm3 in the future
 - The future reduction of the H2 cost to the same level as conventional energy sources (e.g. LNG) will be necessary .
- Hydrogen cost that matches the LNG cost 10\$/MMBtu is **¥13.3/Nm3** (calorie equivalent)
- ※without consideration of the environmental value.



- Expansion of hydrogen supply network by building government-level relationships with resource-rich countries
- The development of the basic technologies to reduce hydrogen cost, targeting all processes, from hydrogen production to hydrogen transport

Targets

- Hydrogen supply chain
- Fossil fuel +CCS
- Toward realization of hydrogen supply cost of 30/Nm3 around 2030, **Targets by the first half of 2020 are set assuming the success of Japan-Australia Brown Coal-to-Hydrogen project.**
- <Hydrogen production>

 - ✓ Cost reduction of hydrogen production through brown coal gasification
(¥several hundred/Nm3 during brown coal-hydrogen project → ¥12/Nm3)

<Hydrogen storage and transportation>

 - ✓ Improvement of the efficiency of liquification
(13.6kWh/kg during brown coal-hydrogen project → 6kWh/kg)
 - ✓ Scaling-up of liquefied hydrogen tank
(several thousand m³ during brown coal-hydrogen project → 50,000m³)

<CCS>

 - ✓ Cost reduction of CO2 separation
(about ¥4,200/t-CO2 in Japan → ¥2,000 level/t-CO2)

Action to achieving the targets

- Green Hydrogen
- **Establishment of the technology of hydrogen production from Renewable energy**
- System cost of electrolyzer: ¥200,000/kW → **¥50,000/kW by 2030**

Energy consumption: 5kWh/Nm3 → **4.3kWh/Nm3 by 2030**
- Technological development for scaling-up and higher efficiency of brown coal gasifier
 - Development of an innovative liquefier structure (non-contact bearing) enables highly efficient hydrogen liquefaction
 - Development of technologies capable of manufacturing LNG-like large tanks with high insulation properties
 - Development of low-cost CO2 capture technologies (e.g. physical absorption)
 - Expansion of the demonstration in model regions for social deployment utilizing the achievement in the demonstration in Namie, Fukushima
 - Development of electrolyzer with higher efficiency and durability
 - Development of supply chain utilizing local resources

Key points of the Action plan ③ <other applications for a global “Hydrogen Society” >

Red: New Target

**Developing and deepening the market to expand the application of hydrogen
International cooperation led by Japan for realizing a Global “Hydrogen Society”**

		Targets	Action to achieving the targets
Hydrogen utilization	Power	<ul style="list-style-type: none"> ● Establishment of the technology for commercialization of hydrogen power generation in about 2030 ✓ Clarify conditions for hydrogen co-firing at existing power plants ✓ Achieve higher efficiency of hydrogen mono-combustion by 2020 (26%→27%) ※1MW class gas turbine 	<ul style="list-style-type: none"> • <u>FS on limit mixture co-firing rate, feasibility etc.</u> • <u>Development of highly efficient combustor</u>
	Industry	<ul style="list-style-type: none"> ● Utilizing CO2-free hydrogen in the future ● Considering the introduction of the various processes for using CO2-free Hydrogen in a sequential manner as the processes achieve economic rationality 	<ul style="list-style-type: none"> • <u>Investigation on utilization and supply potential of CO2-free hydrogen in each industrial process</u> • Study for practical application of carbon recycling technology
	Stationary fuel cell	<p>Ene-farm</p> <ul style="list-style-type: none"> ● Economic independence in about 2020, 5.3 million cumulative sales by 2030 ● Cost reduction to ¥800 thousand (PEFC) ¥1 million (SOFC) by 2020 ● Achieve 5 years as a period to recover investment by about 2030 <p>Commercial and industrial use</p> <ul style="list-style-type: none"> ● Realize grid-parity combining the utilization of exhaust heat in about 2025 <ul style="list-style-type: none"> Low voltage : CAPEX ¥500,000/kW, power generation cost ¥25/kWh high voltage : CAPEX ¥300,000/kW, power generation cost ¥17/kWh ● Realize higher efficiency and durability <ul style="list-style-type: none"> efficiency : over 55% in about 2025 → over 65% in the future durability : 90,000 hours → 130,000 hours in about 2025 	<ul style="list-style-type: none"> • Development of markets such as existing housing and condominium. • Review of regulations for <u>simplification of electrical work</u> • Development of fuel cell stack technologies for higher efficiency and higher power density • Development of fuel cell stack technologies to <u>eliminate the cause of degradation</u>
Global Hydrogen society/ social acceptance	<ul style="list-style-type: none"> ● Realize “Tokyo Statement” announced in Hydrogen Energy Ministerial Meeting ✓ Coordination on harmonization of regulation, codes and standards ✓ Promotion of information sharing, international joint research ✓ Study and evaluation of hydrogen’s potential ✓ Communication, education and outreach 	<ul style="list-style-type: none"> • Comparison of regulations with U.S., Europe, etc., sharing information on accidents • Involvement of resource-rich countries by sharing the outcome of Japan's supply chain demonstration • Take advantage of all opportunities such as Olympic and Paralympic in 2020, Osaka World Expo in 2025, and publicize the cutting-edge hydrogen technology • Implement innovative technology development 	

B. RELEVANT EXHIBITIONS IN JAPAN

The most relevant exhibitions related to the hydrogen and fuel cells market in Japan in 2019 are list below:

11th Automotive World 2019, Tokyo edition

The world's largest exhibition for the advanced automotive technologies, consisting in the following six shows:

- CAR-ELE JAPAN – 11th Int'l Automotive Electronics Technology Expo
- EV JAPAN – 10th EV & HEV Drive System Technology Expo
- 9th Automotive Lightweight Technology Expo
- 7th Connected Car JAPAN
- CAR-MECHA JAPAN - 5th Automotive Components & Processing Technology Expo
- 2nd Autonomous Driving Technology Expo

Tokyo Big Sight, Tokyo

January 16 - 18

<http://www.automotiveworld.jp/en/>

World Smart Energy Week 2019 – Tokyo Edition, consisting of the following nice shows:

- PV EXPO 2019 – 12th Int'l Photovoltaic Power Generation Expo
- 10th PV SYSTEM EXPO
- BATTERY JAPAN 2019 – 10th Int'l Rechargeable Battery Expo
- 9th INT'L SMART GRID EXPO
- FC EXPO 2019 – 15th Int'l Hydrogen & Fuel Cell Expo
- 4th INT'L BIOMASS EXPO
- THERMAL POWER EXPO 2019 – 3rd Next-generation Thermal Power Generation Expo
- WIND EXPO 2019 – 7th Int'l Wind Energy Expo
- 1st RESOURCE RECYCLING EXPO – Recycling technologies & Services for Renewable Energy Resources Gather

Tokyo Big Sight, Tokyo

February 27 – March 1

<https://www.wsew.jp/en-gb.html>

World Hydrogen Technologies Convention - WHTC 2019

Tokyo International Forum, Tokyo

June 2 – 7

<http://whtc2019.jp/>

Renewable Energy 2019

Pacifico Yokohama, Yokohama

July 10 – 12

<http://www.renewableenergy.jp/2019/english/>

International Congress on Advanced Materials Sciences and Engineering 2019 - AMSE

Ana Crowne Plaza Osaka, Osaka

July 22-24

<http://www.istci.org/ICAMSE2019/index.asp>

Advanced Materials Japan 2019 - 8th Annual World Congress

Session 3-4: Advanced Materials for Batteries Fuel Cells and Electrolyzer Technologies

Hyatt Regency Osaka, Osaka

July 22-24

<http://www.bitcongress.com/wcam2019/default.asp>

16th International Symposium on Solid Oxide Fuel Cells

Kyoto Terrsa, Kyoto

September 8 - 13

http://www.eguchi-lab.ehcc.kyoto-u.ac.jp/SOFC_XVI/

2st Automotive World Nagoya 2019 – Nagoya edition, consisting in the following 5 shows:

- CAR-ELE JAPAN Nagoya - 2nd Int'l Automotive Electronics Technology Expo Nagoya
- EV JAPAN Nagoya - 2nd EV/HEV Drive System Technology Expo Nagoya
- 2nd Automotive Lightweight Technology Expo Nagoya
- CAR-MECHA JAPAN Nagoya - 2nd Automotive Components & Processing Technology Expo Nagoya
- 2nd Autonomous Driving Technology Expo Nagoya

Portmesse Nagoya, Nagoya

September 18 - 20

<http://www.automotiveworld-nagoya.jp/en/>

World Smart Energy Week 2019 – Osaka Edition, consisting in the following five shows:

- PV EXPO OSAKA 2019 – 7th Int'l Photovoltaic Power Generation Expo Osaka
- BATTERY OSAKA 2019 – 6th Int'l Rechargeable Battery Expo Osaka
- 9th INT'L SMART GRID EXPO OSAKA
- 4th INT'L BIOMASS EXPO OSAKA
- THERMAL POWER EXPO OSAKA 2019 – 3rd Next-generation Thermal Power Generation Expo Osaka

INTEX Osaka, Osaka

September 25 – 27

<https://www.wsew.jp/en-gb.html>

REIF Fukushima (Renewable Energy Industry Fair)

Three main themes: expanded introduction of renewable energy, model construction of hydrogen-based society, and building smart communities.

Big Palette Fukushima, Fukushima

October 30 - 31

<http://reif-fukushima.jp/english/index.php>

The 13th Pacific Rim Conference of Ceramic Societies

Symposium 2: Solid Oxide Fuel Cells and Hydrogen Technologies

Okinawa Convention Center, Okinawa

October 27 – November 1

<http://www.ceramic.or.jp/pacrim13/>

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