"Hydrogen Park Takasago" and "Carbon Neutral Park Nagasaki" Initiative to Create Decarbonized World

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Gas turbine combined cycle (GTCC) and steam power generation systems are among the main products of Mitsubishi Heavy Industries, Ltd. (MHI). Looking at the accelerating global trend of energy transition, there is an urgent need to make these products carbon neutrality as well. The development of the key decarbonization technologies for thermal power generation is carried out in the Takasago and Nagasaki districts in Japan where our corporate machinery works and laboratories are located. In the former district's Hydrogen Park Takasago, we are working on the creation of an environment for long-term integrated demonstration of elemental technologies under actual operation conditions. On the other hand, the latter district, the Carbon Neutral Park Nagasaki, functions as the important area of our elemental technology development activities. This report introduces these parks, together with the summary of the technologies being developed therein such as hydrogen production.

1. Introduction

Addressing the issues of global warming is critical for the world. In October 2020, the Japanese government announced its intention of achieving carbon neutrality by reducing greenhouse gas emissions to net zero by 2050. The term "reducing emissions to net zero" means that the total amount of greenhouse gases including carbon dioxide (CO_2) becomes practically zero, when calculating the amount of "their (artificial) emissions" minus the amount of "their (artificial) absorption" through means such as afforestation and forest management, etc. To achieve such carbon neutrality, it is indispensable to significantly expand the use of renewable energy. Simultaneously, it is also important to maintain economic efficiency and stable energy supply. MHI aims to achieve a carbon-neutral society in a realistic and speedy manner, while minimizing social costs by promoting energy transition of existing thermal power generation facilities.

Renewable energies such as solar and wind greatly contribute to the achievement of a carbon neutral society. However, because of their weather-dependent nature, the output is quite variable, making it difficult to respond to the demand that changes every minute. As a means of absorbing such variability and dealing with the changing demand, natural gas-fired GTCCs, which emit the least amount of CO_2 among thermal power generation systems, are high in flexibility and reliability and are therefore expected to remain an important power source. Furthermore, by blending natural gas fuel with hydrogen and eventually substituting it with hydrogen or ammonia, neither of which emits CO_2, it becomes possible to ensure power grid stability and, at the same time, significantly reduce CO_2 emissions from thermal power plants.

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Figure 1 shows the background for hydrogen/ammonia utilization. When looking worldwide, the use of renewable energies such as solar and wind is getting increasingly widespread. As these power sources fluctuate greatly with time, weather and season, the expansion of their use requires the introduction of energy storage technologies. The left side of Figure 1 shows the gains/losses of energy storage technologies in terms of the number of electrical discharges and discharge hours per year. For short-time storage, lithium batteries are advantageous. However, for several-day storage or dozens of times of discharges per year, conversion to chemical energy such as hydrogen has an advantage.

The right side of Figure 1 shows the regional characteristics of renewable energy endowment. The use of renewable energies is expected to further progress in many regions of the world, thus enabling water electrolysis to be powered by surplus renewable electricity and this type of hydrogen product will be used more widely. On the other hand, in regions that are not rich in renewable energy resources such as Japan and South Korea, the application of ammonia with a high transportation efficiency will progress. There are also high expectations for turquoise hydrogen, which is produced by pyrolysis of methane to hydrogen and solid carbon, using existing LNG infrastructure. In the regions that have become unavoidably dependent on inexpensive fossil fuel resources such as Southeast Asia, turquoise hydrogen is also drawing attention, because the introduction of carbon capture utilization and storage (CCUS) entails issues such as cost. Therefore, the decarbonization technologies that can meet these respective needs should be urgently verified and implemented in society.

This report provides an overview of the progress in the development of hydrogen-fired gas turbines at the Hydrogen Park Takasago, and describes the development of decarbonization technologies including hydrogen production at the Carbon Neutral Park Nagasaki.

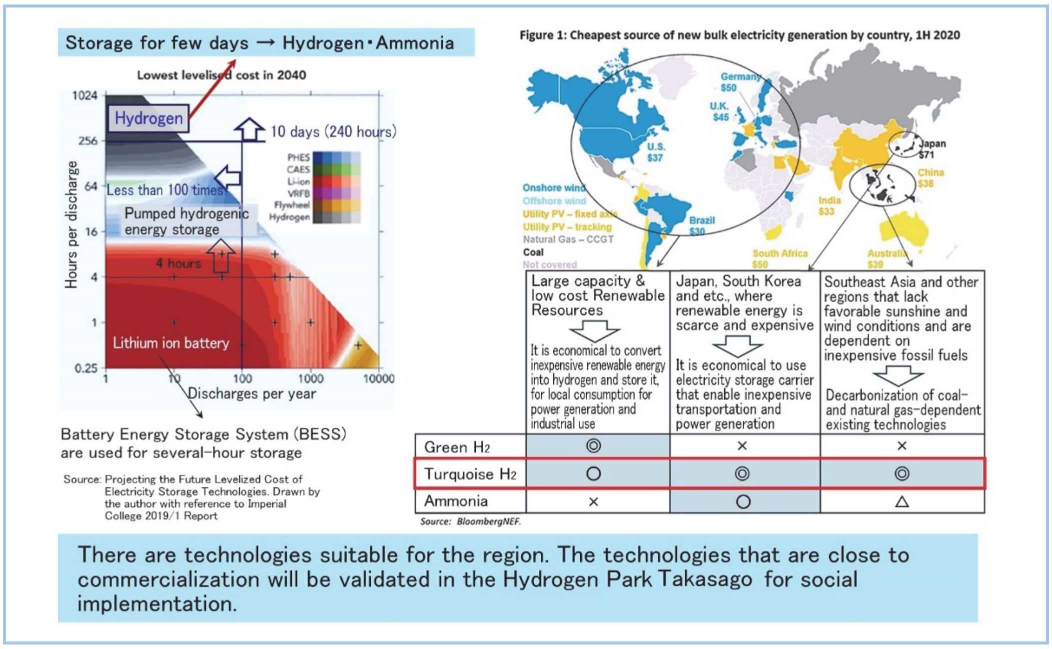

Figure 1　Background for hydrogen and ammonia utilization

2. MHI's road map for zero-emission power generation

MHI Group has declared "MISSION NET ZERO", we aim to achieve carbon neutrality by 2040. We offer products and technologies that enable customers to achieve carbon neutrality viable by 2050. Our major undertakings include the energy transition for low-carbonization and decarbonization of businesses/products, and the expansion of CCUS business including CO_2 capture. Among these, this report focuses on those in relation to power producers and industrial applications.

The more specific goals that MHI's Energy Systems has set for itself toward carbon neutrality by 2040 are as follows: "energy transition of thermal power generation", "efficient utilization of industrial energy" and "establishment of a hydrogen value chain". Extremely important among these is the promotion of carbon neutrality in thermal power generation by switching to non-fossil fuels. Figure 2 shows the roadmap for the development of power generation technologies.

Thermal power generation can be mainly divided into two types: steam power generation and GTCC. The mainstream of the former is the coal-fired thermal power generation system consisting of the boiler and the turbine, in which CO_2 reduction is under way through the already-established technology of high-ratio biomass co-firing. Further reduction of CO_2 emissions will be attempted by co-firing ammonia and increasing ammonia co-firing rate, the technology for which is being rapidly developed and demonstrated. The co-firing ratio of ammonia is expected to increase at later stages. Moreover, if coal-fired thermal power plants are replaced by high-efficiency GTCCs, CO_2 emissions can be reduced by about 65%. Even so, these thermal power generation systems are still in need of achieving further reduction of CO_2 emissions, which will be tried by co-firing hydrogen or ammonia. Our goal will be about a 90% reduction by CO_2 capture, and eventual zero emissions by single-fuel firing of non-fossil fuel such as hydrogen and ammonia.

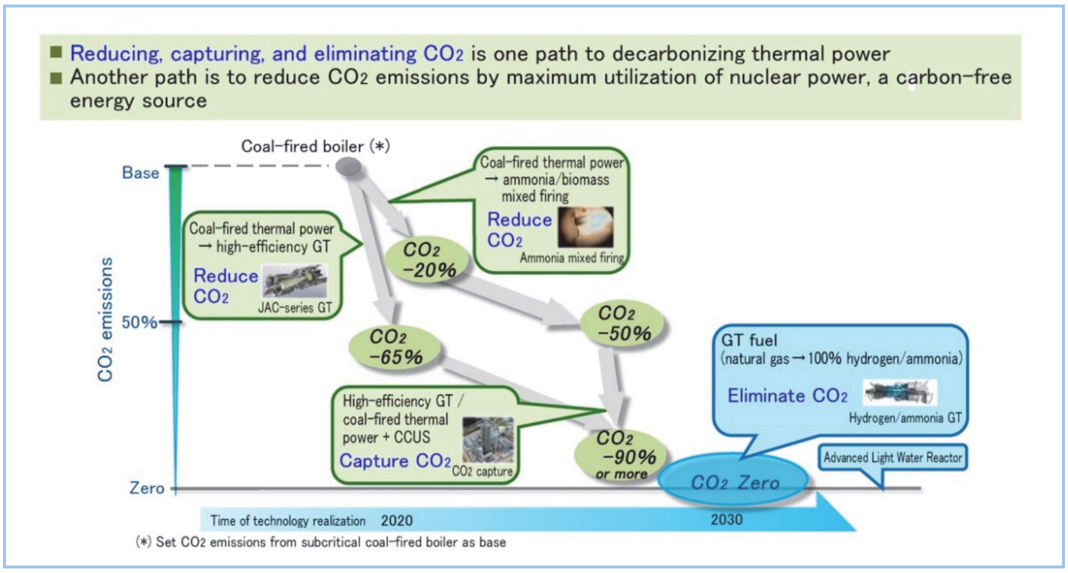

Figure 2 Road map for development of power generation technologies

3. Development status of hydrogen-fired gas turbines

Gas turbines, which are our flagship products, are being developed to meet European CO_2 emission standards – the strictest in the world. **Figure 3** gives the timeline and schedule of gas turbine development, together with the European CO_2 emission standards. Shown on the left side of the figure is the development status of hydrogen-fired gas turbines. For large gas turbines, with a view to making the co-firing system available commercially in 2025, a combustion test using a conventional combustor was performed, and stable combustion at the hydrogen co-firing ratio of 50% was confirmed. This indicates that the EU taxonomy's CO_2 emission standard of 270 g/kWh has been satisfied. We will develop a new combustor to realize 100% hydrogen firing in large gas turbines in 2030.

When it comes to the technological development for use of decarbonized fuel (such as hydrogen and ammonia) in small and medium-sized gas turbines, we have succeeded in testing 100% hydrogen firing in the combustor alone in 2022. The demonstration of these combustion technologies will be started this year at the Hydrogen Park Takasago, which is a full-scale power generation facility.

Furthermore, at the Hydrogen Park Takasago, the demonstration tests on our hydrogen production technologies under development will also be started one by one using the actual units, including alkaline water electrolysis, our originally developed solid oxide electrolysis cell (SOEC) and turquoise hydrogen by methane pyrolysis.

Figure 4 is a road map for ammonia power generation technology. As in the case of hydrogen, ammonia is expected to be a clean fuel that emits no CO_2 when burned. Furthermore, while gaseous hydrogen needs to be cooled to -253°C for liquefaction, ammonia can be transported as a liquid at -33.4°C. It is therefore expected to serve as a hydrogen carrier and energy source suitable for transportation and storage. With regard to 100% firing of ammonia in gas turbines, a combustor is in development with a view to conducting the demonstration test in 2025 or after. As for boilers, our plan is to conduct a demonstration test using the actual facility for co-firing of 50% or higher in the latter half of 2020.

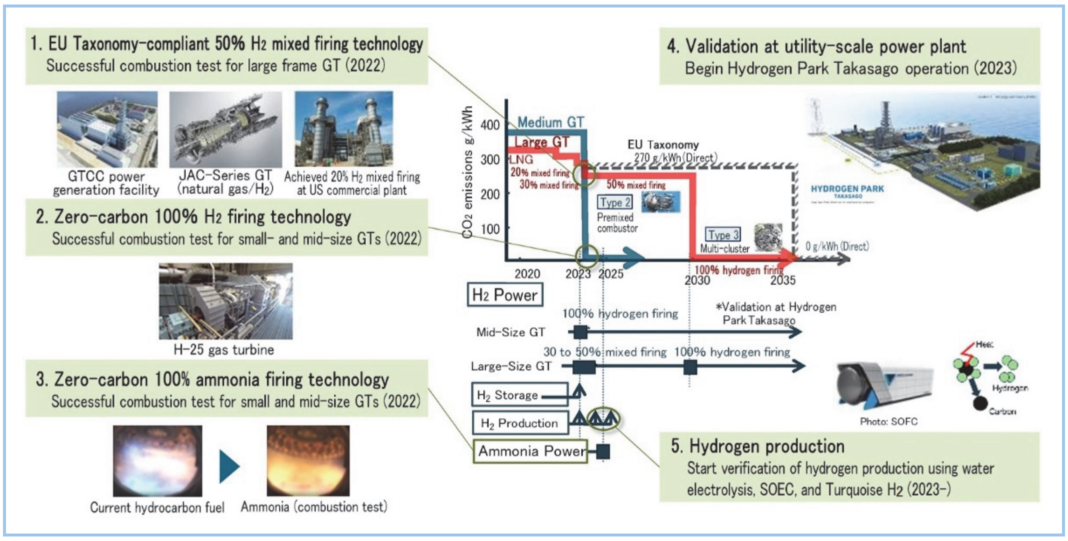

Figure 3 European CO_2 emission standards and schedule for gas turbine development

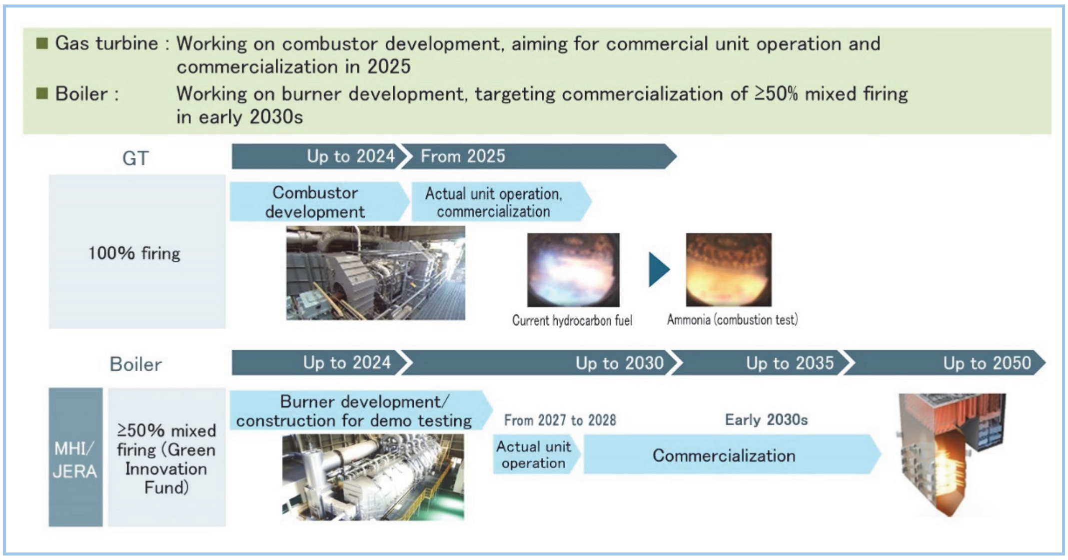

Figure 4 Road map for ammonia power generation technology

4. "Hydrogen Park Takasago" for demonstration of hydrogen power generation

Toward early commercialization of hydrogen gas turbines with hydrogen fuel, the Hydrogen Park Takasago is under construction to make it possible to perform the world's first integrated technological validation from hydrogen production to power generation on the premises of Takasago Machinery Works, which is our base for development, design, manufacturing and demonstration. Partial operation started in the Hydrogen Park Takasago in May 2023; preparation for full-scale operation is under way.

Besides the adoption of water electrolyzers, the next-generation hydrogen production technologies such as the production of turquoise hydrogen by pyrolysis of methane to hydrogen and solid carbon are planned to be tested and verified one by one. Overall concept of Hydrogen Park Takasago and its major facilities are shown in **Figure 5**. Regarding the gas turbine facility, the small-and-medium H-25 unit and the large M501JAC unit are already in operation. With the alkaline electrolyzer having been installed this spring, the installation of other facilities such as SOEC will start.

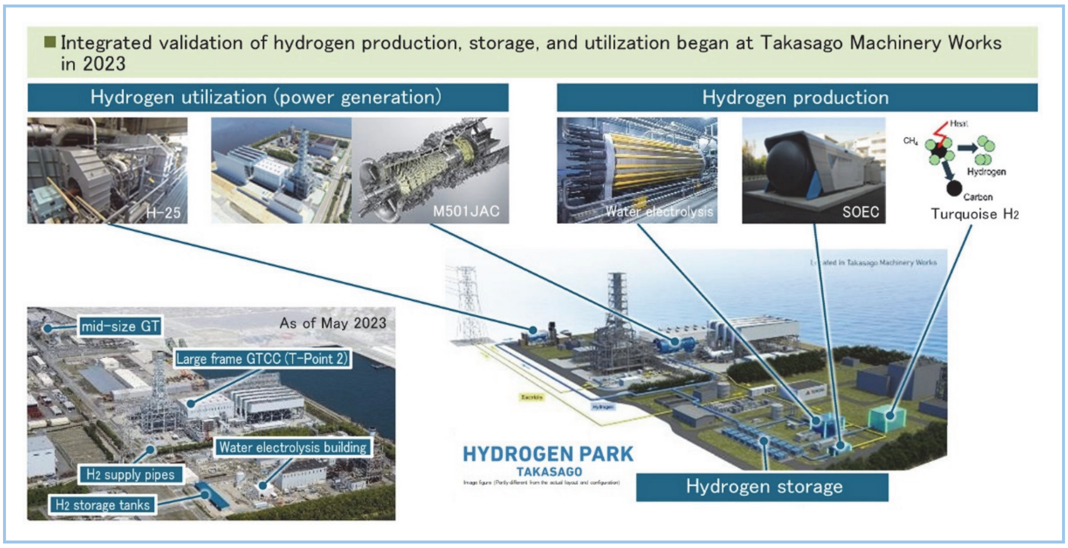

Figure 5 Overall concept of Hydrogen Park Takasago

Figure 6 is a configuration diagram of the Hydrogen Park Takasago. For hydrogen production, the electrolyzer is expected to be used for water or steam electrolysis with renewable energy, while the methane pyrolysis system involves thermal decomposition of natural gas (methane). Electrolytic hydrogen and turquoise hydrogen produced respectively are stored in the hydrogen storage facility. The stored hydrogen is used as fuel in the demonstration test facilities to generate electricity, which is then fed into the local power grid. The Hydrogen Park Takasago is not only a facility to conduct the integrated demonstration from hydrogen production to hydrogen power generation, but is also intended to become a facility by which the integrated demonstration of advanced energy management can be performed. Specifically, it means that, by combining with the secondary battery-based power storage system, surplus power is stored with electrolytic hydrogen and second batteries, and electricity can be supplied from the hydrogen gas turbines and the secondary batteries, when demand is high.

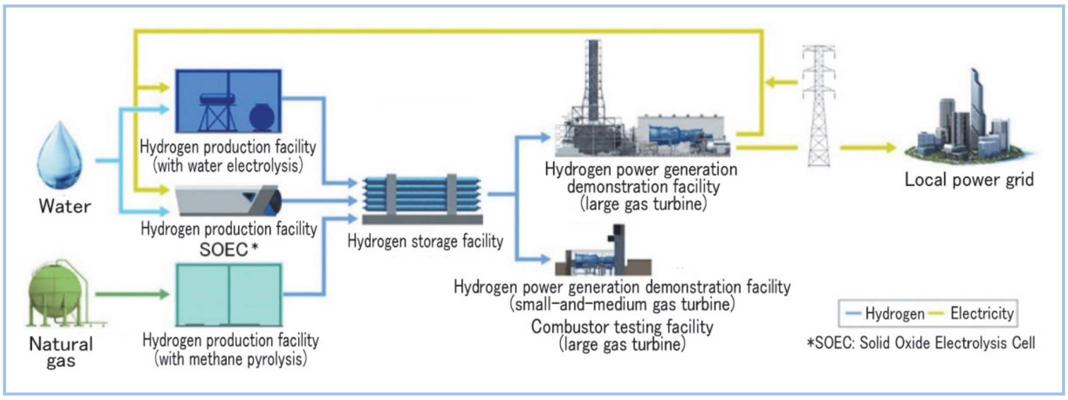

Figure 6 Configuration diagram of Hydrogen Park Takasago

Figure 7 is the latest construction status of the Hydrogen Park Takasago (taken in May 2023). With the installation of the hydrogen storage facility completed, the operation has partially started in the facility. The use of this demonstration facility is expected to greatly contribute to the widespread introduction of hydrogen and the implementation of hydrogen power generation into society.

Figure 8 shows an example of hydrogen projects in which we are taking part. The Advanced Clean Energy Storage is a US project to realize hydrogen production, storage and utilization, for which the demonstration test of a water electrolyzer will be conducted at the Hydrogen Park Takasago before being introduced to the actual units. As renewable sources of energy have been widely introduced in western US, there is a surplus of renewable electricity during spring when the demand is low. This project aims to level out the supply and demand of power across seasons, by utilizing the renewable electricity surplus.

Renewable electricity from the grid is used to produce green hydrogen by electrolysis. The produced hydrogen is stored as a gas in the underground rock salt cavern. The hydrogen is then sent in the pipeline to the power generation plant where it fuels our 840-MW hydrogen-fired GTCC. This GTCC power plant is planned to start operation with 30% co-firing of green hydrogen in 2025, and gradually increase the hydrogen ratio until finally reaching 100% by 2024.

Figure 7　Construction status of Hydrogen Park Takasago(taken in May 2023)

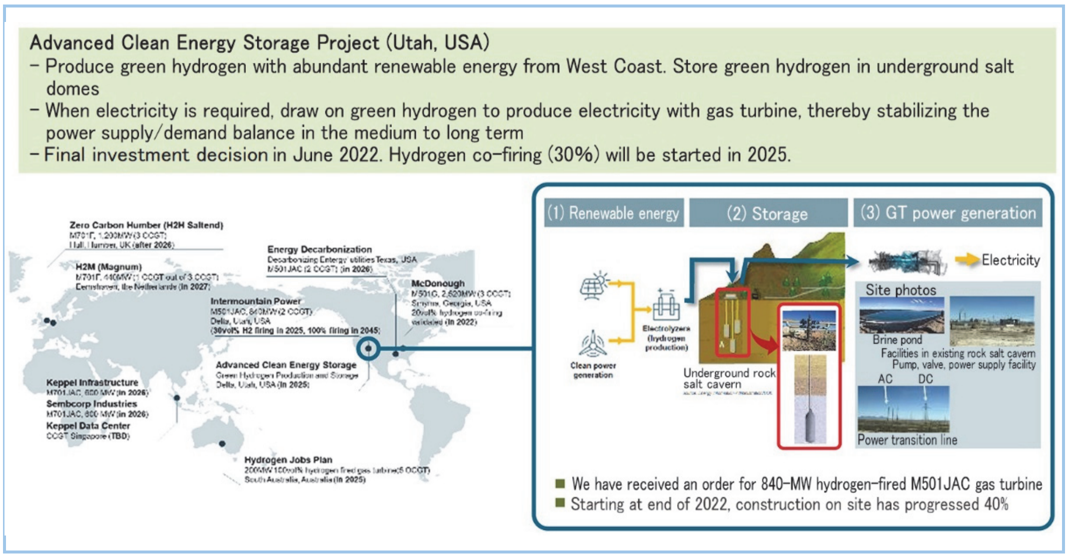

Figure 8　Example of hydrogen storage and gas turbine project in US

5. "Carbon Neutral Park Nagasaki" – main area of key technology development

In the Nagasaki District (the Nagasaki Shipyard & Machinery Works, and the Research and Innovation Center), the departments of design, manufacturing and development are united in working toward realizing the practical application of the latest product technologies for decarbonization. This district is called "Carbon Neutral Park Nagasaki" as shown in **Figure 9**, focuses on the development of key technologies to be tested for demonstration in the Takasago District. The Research and Innovation Center in Nagasaki, as shown in **Figure 10**, especially has the facilities for the development of key technologies that are closely related to the energy transition strategy of MHI Energy Systems. It has become the icon of aforementioned "Carbon Neutral Park Nagasaki".

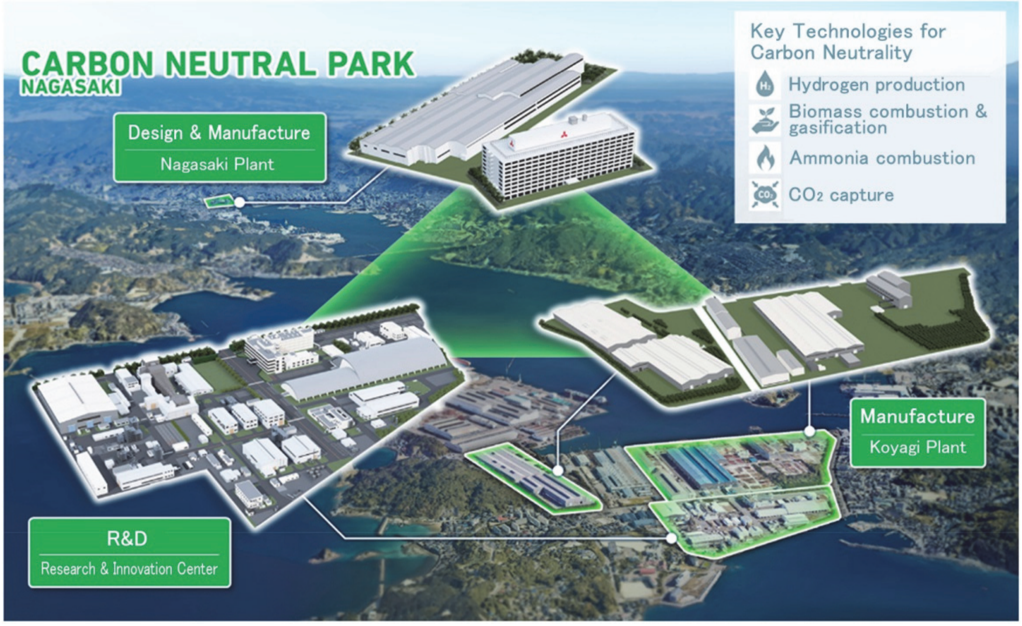

Figure 9　Carbon Neural Park Nagasaki

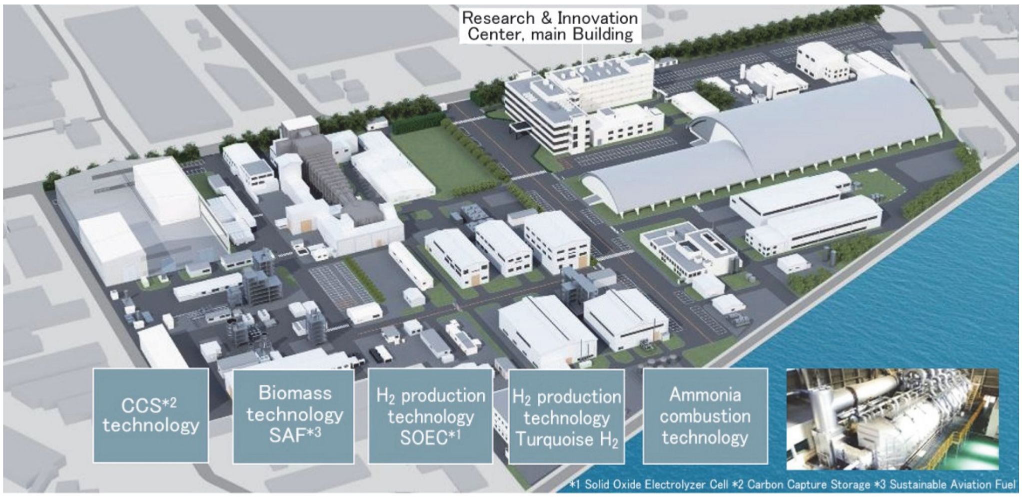

Figure 10　Our base for technological development at Carbon Neutral Park Nagasaki (Research and Innovation Center in Nagasaki)

The ongoing projects at the laboratories of the Research and Innovation Center in Nagasaki include the hydrogen production technologies such as turquoise hydrogen, SOEC and anion exchange membrane (AEM), the ammonia combustion technology for gas turbines, boilers and engines, and the production of sustainable aviation fuel (SAF) from biomass. The underlying technologies for CO_2 capture are also in development here.

Figure 11 shows some of the evaluation facilities related to hydrogen production. Methane and hydrogen can be readily used in the test environments created by these facilities, thanks to past projects such as long-term development of solid oxide fuel cell (SOFC). As the needs of society rapidly increase, more facilities become usable for carbon neutral technologies. Combustion testing, whose main test fuel was natural gas or coal, is now likewise able to be conducted for carbon neutral technologies, because an ammonia supply system has been installed while taking safety into consideration.

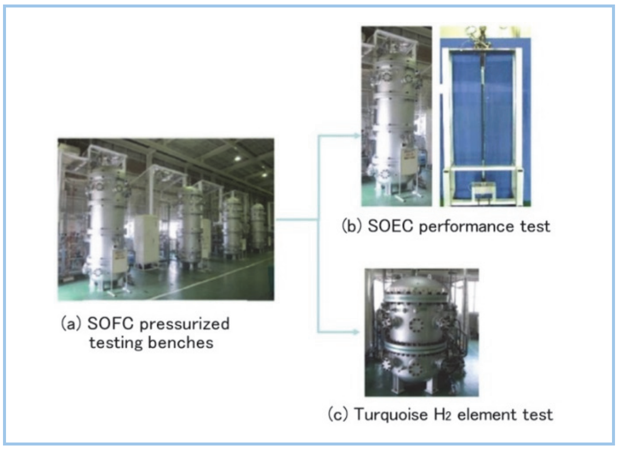

Figure 11 SOEC and turquoise H_2 test facilities

6. Development of elemental technologies at Carbon Neutral Park Nagasaki

This chapter presents some of the developments in carbon neutral technology related to MHI Energy Systems.

(1) Turquoise hydrogen production technology

Turquoise hydrogen is produced using the pyrolysis reaction of methane, which is a technology of decomposing methane (one of the major components of natural gas) into solid carbon and hydrogen at a high temperature. It has conventionally been used to produce carbon materials such as carbon black for industrial application. Focusing on this by-product hydrogen, we found a reaction mechanism that enables efficient production of hydrogen.

Figure 12 summarizes the technology for turquoise hydrogen production and rough development road map. As the natural gas infrastructure has already been established, there are many natural gas-fired thermal power plants. These existing thermal power plants can achieve a considerable degree of low-carbonization or even decarbonization (zero CO_2 emissions), simply by replacing the gas turbine combustor with one for hydrogen firing in addition to the installation of a turquoise hydrogen plant between the supply line of natural gas infrastructure and the thermal power plant, or upstream of the power generation facilities of other natural gas power producers. As the by-product carbon is solid, it is easier to perform fixation and storage than for CO_2, which is gaseous at normal pressure and temperature. The element testing is under way to take it to the next step of verifying the developed technologies at the Hydrogen Park Takasago.

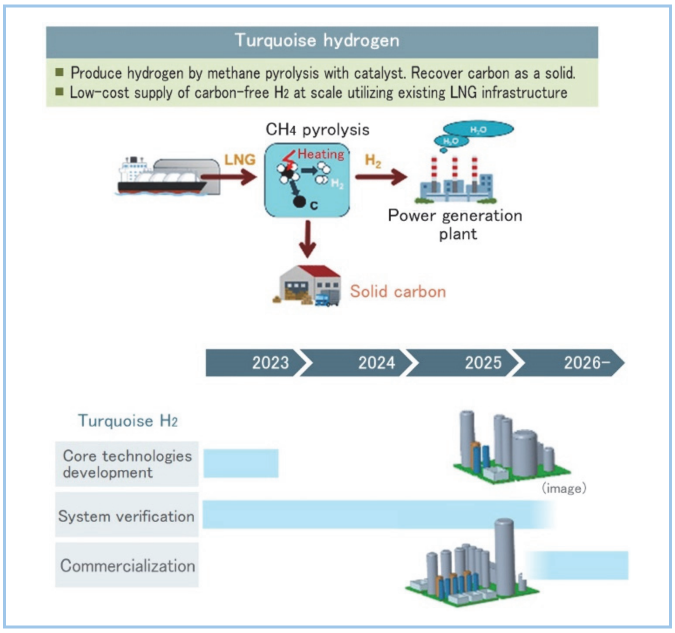

Figure 12 Turquoise hydrogen development status

(2) Hydrogen production technology using SOEC

SOEC is considered to be suitable for application to large-scale plants, because of its applicability for SOFC (which we already developed), advantageously high efficiency and relevance to our experience in high-pressure SOFC. **Figure 13** provides an outline of the SOEC development. Currently, we are determining the suitable SOEC operation conditions and are improving the specifications. As shown in the figure, we plan to start verifying the developed technologies using a several-hundred-kW-class SOEC module in 2024.

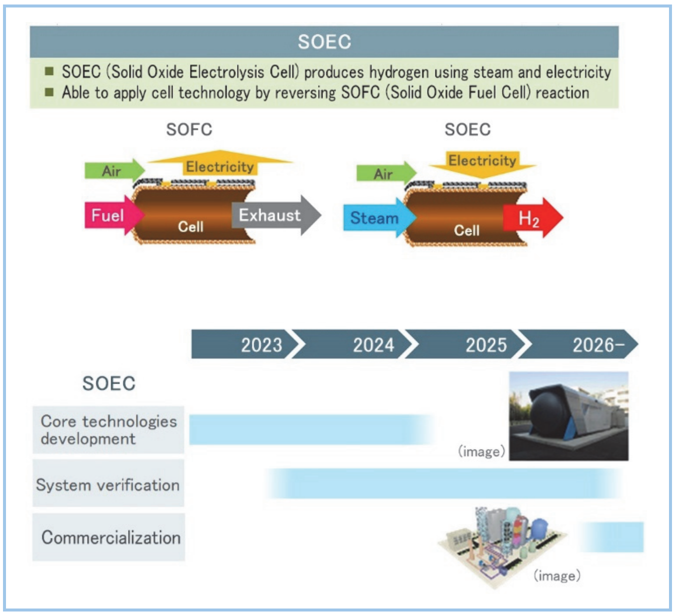

Figure 13 SOEC development status

Figure 14 shows our plan for SOEC development. In past projects, we developed and mass-produced SOFCs in which the reaction occurs backward, and combined many of these cells together to build a 200-kW-class module. Through further combining with high-temperature and high-pressure steam/gas handling technology in steam power generation, we aim for a large SOEC plant.

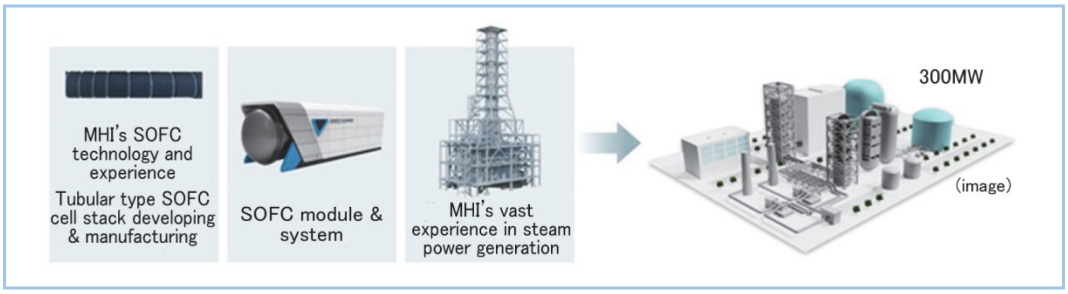

Figure 14 SOEC development plan

(3) Hydrogen production technology by AEM water electrolysis

The widely used electrolysis technology using a solid polymer electrolyte membrane is proton exchange membrane (PEM) water electrolysis using a hydrogen ion permeable membrane. When compared with the widely used alkaline electrolysis, PEM water electrolysis can be operated at higher current density with a smaller electrolytic cell. However, as the PEM containing many hydrogen ions is highly acidic, noble metals and Ti-based materials need to be extensively used for the adjacent catalysts and other liquid contact parts. It is also necessary to prevent impurities in the feed water from causing performance degradation, by controlling the purity by removing metal ions. When it comes to AEM water electrolysis, however, high current density operation similar to PEM water electrolysis is possible. It can also be expected to have low cost, because the electrolysis can take place in an alkaline aqueous solution in which materials such as stainless steel are usable.

Figure 15 shows the development status of AEM water electrolysis. At present, while observing properties using small element cells, we have prototyped a stack with an electrode area of several hundred cm^2, determining the appropriate manufacturing process and optimizing the operation conditions. As indicated by the results of the evaluation using small element cells, a marked increase in current density can be expected, when compared with alkaline water electrolysis in general. Further proceeding with the development as shown in **Figure 16**, we will conduct a demonstration test on a several-MW-class unit at the Hydrogen Park Takasago before applying it to the commercial units.

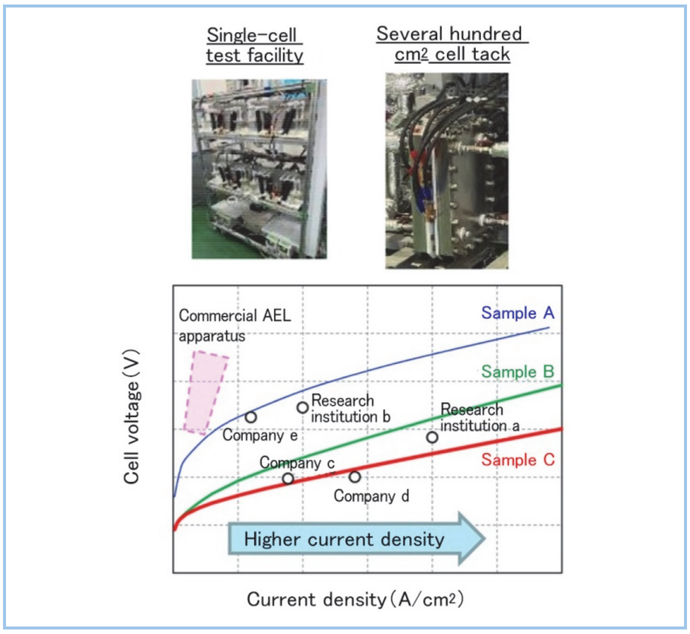

Figure 15 Development status of AEM water electrolysis

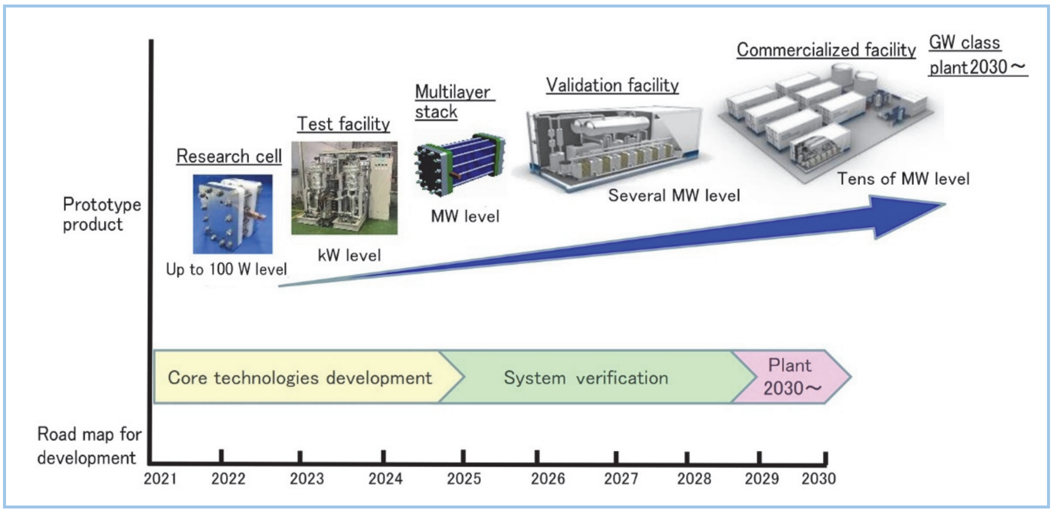

Figure 16 Road map for AEM water electrolysis

(4) SAF production technology by biomass gasification

SAF is an alternative aircraft fuel made from sustainable material such as biomass, whose introduction is under consideration to reduce CO_2 emissions. We have worked on the production of liquid fuel from biomass since around 2000. The production of SAF by biomass gasification was commenced in 2012. Under the sponsorship of the New Energy and Industrial Technology Development Organization (NEDO), a pilot plant was operated from 2016 to 2020 in cooperation with JERA Co., Inc., Toyo Engineering Corporation, and Japan Aerospace Exploration Agency (JAXA). The SAF produced at the pilot plant, which was built on the premises of JERA Co., Inc.'s Shin-Nagoya Thermal Power Station, was used in commercial flights by Japan Airlines Co., Ltd. in June 2021. **Figure 17** shows the situation in the development. In addition to scaling up for commercialization, we are working to improve SAF production by adding further value. This result was obtained as a result of the consignment business (JPNP17005) of NEDO.

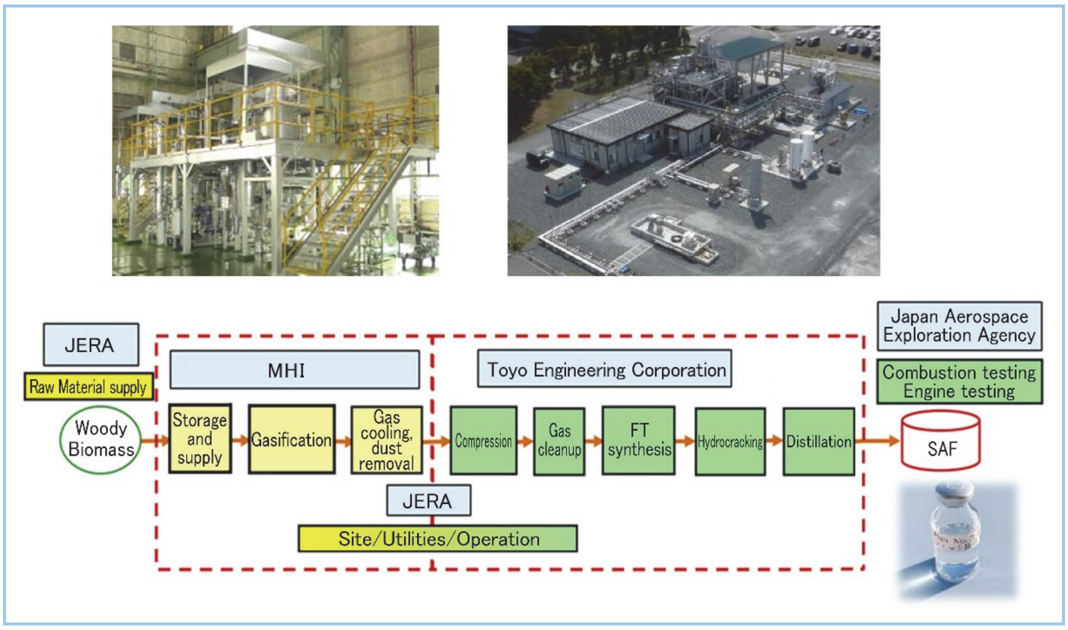

Figure 17 Technology of SAF production by biomass gasification

(5) Ammonia co-firing technology in coal-fired boilers

With regard to the use of ammonia in boiler/turbine plants, we are developing a burner that enables high-ratio co-firing of ammonia in pulverized coal-fired boilers. When compared with hydrocarbon fuels such as LPG, ammonia burns at a slower rate making it difficult to maintain the flame in the burner. Another issue is that, because of its high nitrogen (N) content, ammonia generates a large amount of NOx if the fuel concentration during combustion is not appropriate.

In 2021, a small combustion test furnace was used to conduct the testing for co-firing and single-fuel firing of ammonia. It was conducted on multiple burner types, based on our accumulated experience in burner design for various fuels and the results of basic combustion tests, with a view to providing burners for ammonia single-fuel firing in commercial and industrial boilers in Japan and overseas. While confirming that the flame was extremely stable during combustion, we also verified that NOx emissions were in line with the results of the basic combustion tests carried out in advance, and that there was no residual ammonia. With the aim of co-firing ammonia at a higher ratio, we are working to develop and demonstrate high-ratio co-firing of ammonia in coal-fired boilers as part of NEDO's Green Innovation Fund Project/Fuel Ammonia Supply Chain Establishment. As shown in **Figure 18**, we plan to develop a burner for ammonia single-fuel firing through combustion tests using a full-scale burner by 2024. Figure 18 (b) is an exterior view of our 0.5 t/h furnace with which we started the combustion testing, while Figure 18 (c) is the ammonia supply facility introduced in a project commissioned by NEDO. Together with JERA Co., Inc., we are also formulating a basic facility plan to demonstrate an ammonia co-fired boiler in an actual unit, and are conducting a feasibility study. During this demonstration operation in an actual unit, we will verify 50% or more ammonia co-firing with two different firing systems (circular and opposed firing).

Figure 18 (c) is the ammonia supply facility introduced in a project commissioned by NEDO. Together with JERA Co., Inc., we are also making the basic facility plan for demonstration of an ammonia co-fired boiler in an actual unit and are conducting the feasibility study. During this demonstration operation in an actual unit, we will verify 50% or more ammonia co-firing with two different firing systems (circular firing and opposed firing).

The development described in this section is being carried out as part of NEDO's "JPNP 21020 Green Innovation Fund Projects: Fuel Ammonia Supply Chain Establishment /High-ratio co-firing and single-fuel firing needed for ammonia power generation/ Development and demonstration of high-ratio ammonia co-firing technology (including single-fuel firing technology) in coal-fired boilers/Demonstration project of high-ratio ammonia co-firing in the commercial coal-fired power plants utilizing ammonia single-fuel burners".

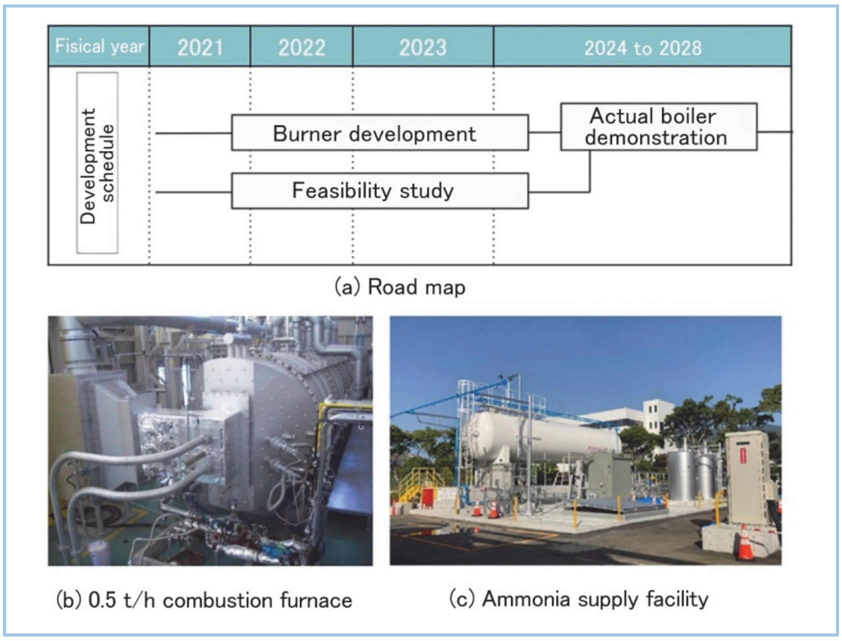

Figure 18　Overview of development of high-ratio ammonia co-firing technology funded by Green Innovation Fund

7. Conclusion

Centering on the technologies to be demonstrated at the Hydrogen Park Takasago whose operation partially started in the park in 2023, this report presents our initiatives toward achieving carbon neutrality in the thermal power generation industry. While these technologies have yet to be verified, the development of MHI's elemental technologies at the Carbon Neutral Park Nagasaki was summarized.

Making use of the technologies for energy transition in this report, we contribute to the achievement of a carbon-neutral society, while aiming to fulfil MHI Group's declared "MISSION NET ZERO" for 2040.

"Hydrogen is Not the Future, This is Real."