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Initiatives “Takasago Hydrogen Park” to Create a Hydrogen Society

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Looking the global trend toward carbon neutrality, there is an urgent need to make GTCC power generation plant and steam power generation plant, which are among the main products of Mitsubishi Heavy Industries, Ltd. (MHI), carbon-neutral as well. In such an environment, the Takasago Hydrogen Park, the world's first integrated validation facility for technologies from hydrogen production to power generation, is being constructed at our Takasago Machinery Works, where we develop and manufacture hydrogen gas turbines. This report presents its construction status and a hydrogen production technology to be introduced. In addition, the Takasago Hydrogen Park is scheduled to expand its related facilities sequentially and is targeted at the commercialization of 30% co-firing large gas turbine products and 100% hydrogen-firing small-to-middle gas turbine products by 2025.

1. Introduction

Solving the problem of global warming is now an important issue for the world. In October 2020, the Japanese government declared its goal of "carbon neutrality" by reducing greenhouse gas emissions to net zero by 2050. The term "reducing emissions to net zero" means to reduce to practically zero the amount of carbon dioxide (CO_2) and other greenhouse gases emitted artificially minus the amount absorbed artificially through afforestation, forest management, and other means. To achieve carbon neutrality, it is essential to significantly expand the use of renewable energy. In parallel, it is also important to maintain economic efficiency and a 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 infrastructure.

Renewable energies such as photovoltaic and wind power generation contribute greatly to the achievement realization of a carbon-neutral society, but their output fluctuates widely and causes a decline in the reliability of the power grid because of their characteristics being easily affected by weather conditions. As a means of suppressing this decline in reliability, the gas turbine combined cycle (GTCC/natural gas-firing thermal power generation plants), which has the lowest CO_2 emissions among thermal power generation plants, is expected to remain an important power source due to its flexibility and high reliability. Furthermore, by mixing, or eventually substituting natural gas fuel with hydrogen or ammonia, which do not emit CO_2, it is possible to ensure power grid stability and significantly reduce CO_2 emissions from thermal power plants. **Figure 1** shows the background of hydrogen and ammonia utilization. Renewable energies such as photovoltaic and wind power generation are becoming increasingly popular worldwide. These power sources fluctuate greatly with time, weather and season, and the introduction of energy storage technology is necessary to expand their utilization. The left side of Figure 1 shows the gains and losses of energy storage technologies in terms of discharge number and discharge hours per year. For short-time storage, lithium batteries are advantageous. In contrast, for several-day storage or

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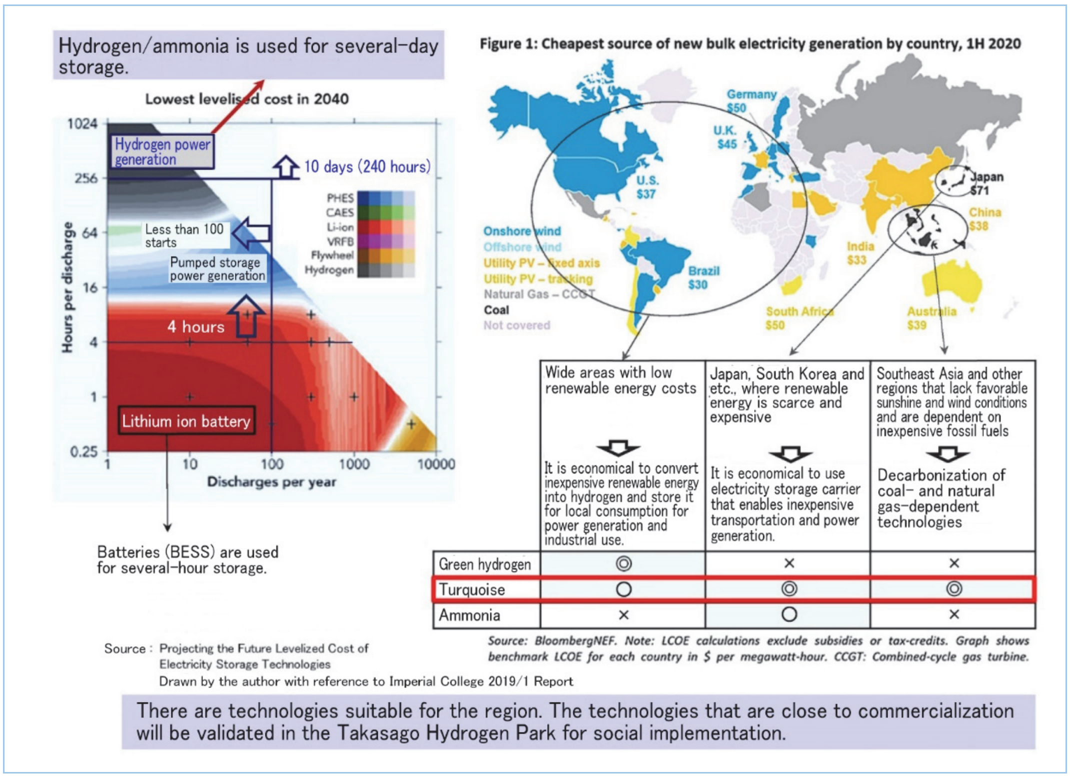
storage dozens of times per year, conversion to chemical energy such as hydrogen has an advantage. The right side of Figure 1 shows the regional characteristics of renewable energy reserves. In many regions of the world, renewable energies are becoming more widespread and hydrogen production by water electrolysis using surplus electricity of renewable energy (green electricity) is expected to become more widespread. On the other hand, in regions that are not blessed with renewable energy resources, such as Japan and South Korea, there are high expectations for the utilization of ammonia, which has high transportation efficiency, and turquoise hydrogen, which is hydrogen produced through methane pyrolysis into hydrogen and solid carbon, utilizing existing LNG infrastructure. Also in Southeast Asia and other regions that have no choice but to rely on inexpensive fossil fuel resources, expectations for turquoise hydrogen are growing. In this way, there is an urgent need to demonstrate and socially implement decarbonization technologies that meet the respective needs.



	Wide areas with low renewable energy costs It is economical to convert inexpensive renewable energy into hydrogen and store it for local consumption for power generation and industrial use.	Japan, South Korea and etc., where renewable energy is scarce and expensive It is economical to use electricity storage carrier that enables inexpensive transportation and power generation.	Southeast Asia and other regions that lack favorable sunshine and wind conditions and are dependent on inexpensive fossil fuels Decarbonization of coal– and natural gas–dependent technologies
Green hydrogen	◎	×	×
Turquoise	○	◎	◎
Ammonia	×	○	×

Source : Projecting the Future Levelized Cost of Electricity Storage Technologies
Drawn by the author with reference to Imperial College 2019/1 Report

Source: BloombergNEF. Note: LCOE calculations exclude subsidies or tax-credits. Graph shows benchmark LCOE for each country in $ per megawatt-hour. CCGT: Combined-cycle gas turbine.

There are technologies suitable for the region. The technologies that are close to commercialization will be validated in the Takasago Hydrogen Park for social implementation.

Figure 1 Background of hydrogen and ammonia utilization

While the early commercialization of hydrogen-firing gas turbines with hydrogen fuel is expected, they have issues such as the faster flame propagation velocity of hydrogen compared to natural gas, resulting in the high likelihood of flashback, in which the flame in the combustor returns to the fuel mixing area. However, MHI has developed a combustor suitable for hydrogen combustion based on the combustion technology it has cultivated so far and is currently developing a hydrogen-firing gas turbine. In addition, we are also developing technology for existing power generation plants that enable conversion into hydrogen-firing with minimal modifications.

In this way, the development of hydrogen utilization technology is progressing, there are few opportunities to secure hydrogen for power generation and to validate the operation of gas turbines. Therefore, MHI is currently constructing the Takasago Hydrogen Park, the world's first integrated validation facility for technologies from hydrogen production to power generation, at our Takasago Machinery Works, we develop and manufacture gas turbines, adjacent to a combined cycle power plant validation facility called T-Point 2. We are currently proceeding with the preparation, aiming at starting the operation of the park in fiscal 2023, so that we can begin testing and validation operations of hydrogen production/storage and hydrogen combustion technology in a gas turbine in the same year. Using the hydrogen production facility, we plan to test and validate next-generation hydrogen production technologies such as high-temperature steam electrolysis using solid oxide electrolysis cells (SOEC), integrated validation of turquoise hydrogen production, its storage, and power generation thereby, in addition to hydrogen production using an alkaline water electrolyzer.

This report introduces the development status of the hydrogen and ammonia power generation facility and the construction status of the Takasago Hydrogen Park as a validation facility and describes hydrogen production technologies.

2. MHI's Zero-Emission power generation roadmap

MHI Group has declared "MISSION NET ZERO," which aims to achieve carbon neutrality by 2040 concerning direct and indirect CO_2 emissions not only by our group but also by customers and suppliers related to our group business. The main initiatives include energy transitions for low-carbon or decarbonized businesses and products and expansion of the CCUS (Carbon Capture Utilization and Storage) business including CO_2 capture and storage. Among these, this report describes initiatives for the thermal power generation industry.

Specifically, our Energy Transition & Power Headquarters is working on "energy transition of thermal power generation", "efficient utilization of industrial energy" and "establishment of a hydrogen value chain" toward carbon neutrality by 2050. Among these, the promotion of carbon neutrality in thermal power generation by switching to non-fossil fuels is extremely important. **Figure 2** shows the roadmap for the development of power generation technologies.

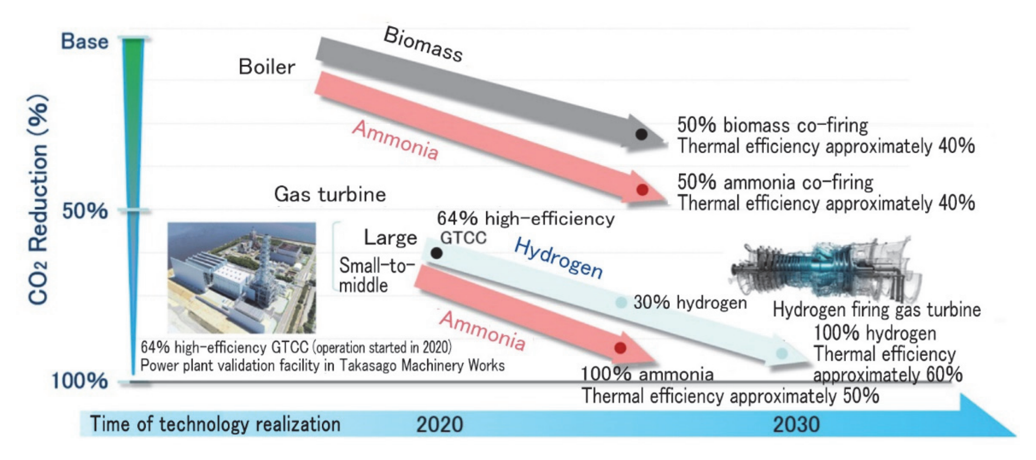


Figure 2 Roadmap for development of power generation technologies

Thermal power generation can be roughly divided into steam power generation system and gas turbine combined cycle. It consists of boilers, turbines, and other components that are the main of steam power generation, As for existing coal-firing thermal power generation which is the main stream of steam power generation system with boiler, turbine, etc., CO_2 emissions reduction is in progress through the use of high biomass co-firing, a technology that has already been established, and we aim at further reduction of CO_2 emissions by increasing the co-firing rate of ammonia, which is currently under rapid development and validation. On the other hand, as for gas turbine combined cycle, solid fuels such as coal are not utilized, further reduction of CO_2 emissions is required as well, and we aim to achieve zero CO_2 emissions by co-firing with hydrogen or ammonia, and in the future, hydrogen or ammonia single-fuel firing.

3. Development status of hydrogen-firing gas turbine

Carbon neutrality initiatives have been gaining momentum in recent years. As for gas turbine for power generation, the movement to realize social contributions by switching fuel from conventional natural gas to hydrogen and fuel ammonia to reduce or eliminate CO_2 emissions is growing.

Figure 3 shows the roadmap for validating and commercializing various combustors for hydrogen co-firing, single-fuel hydrogen firing, and single-fuel ammonia firing to realize the above. Combustion tests of 30% and 50% co-firing in a multi-nozzle combustor (premixed) have been completed, and the development of single-fuel hydrogen firing multi-cluster combustor (premixed) for a small-to-middle facility has reached the final stage. Both are expected to be commercialized by 2025 through validation with actual equipment at the Takasago Hydrogen Park described in Chapter 4.

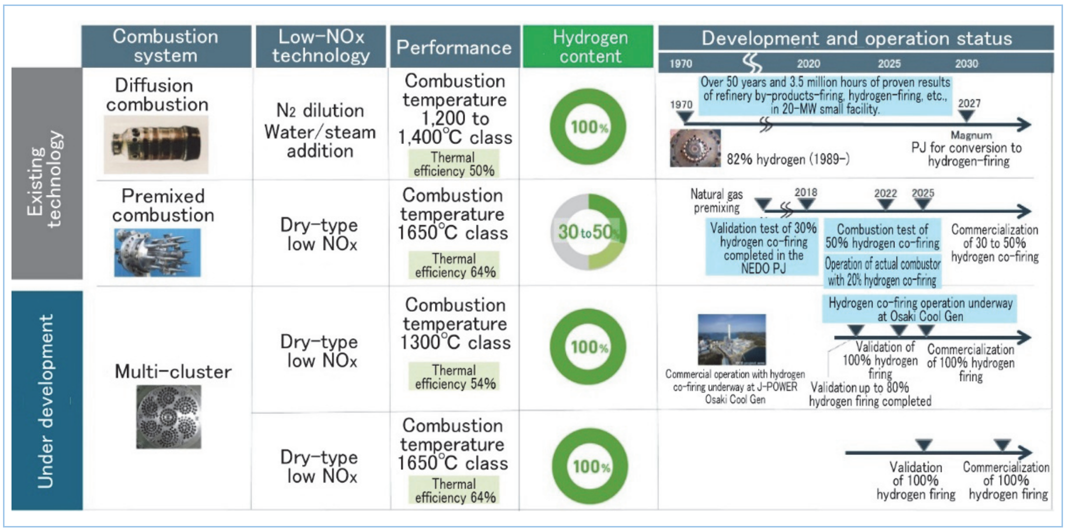


Figure 3 Roadmap for validation and commercialization of various combustors

In addition, the development of a 1,650°C class multi-cluster combustor (premixed) is underway to complete combustion tests by 2025 and commercialization by 2030, when hydrogen is expected to be in sufficient supply.

As a specific example of the commercialization, a project (Advanced Clean Energy Storage Project) to construct a hydrogen hub, the world's largest green hydrogen production and storage facility, in Utah, the United States through a U.S. subsidiary, and to supply the green hydrogen to the latest 840-MW-class hydrogen-firing gas turbine combined cycle (GTCC) power plant, which we supply equipment to, is already underway. According to the planning for this project, the plant will start operation in 2025 with 30% green hydrogen co-firing, the hydrogen rate will be gradually increased, and operation with single-fuel 100% green hydrogen firing will be finally achieved by 2045.

By achieving this commercialization roadmap, we will achieve the CO_2 emissions intensity required by the EU Taxonomy (270 g/kWh from 2023 to 2035 and 0 g/kWh after 2035) as shown in **Figure 4**. We will continue to develop our technology while keeping our eye on global trends and standards, and contribute to global efforts toward carbon neutrality.

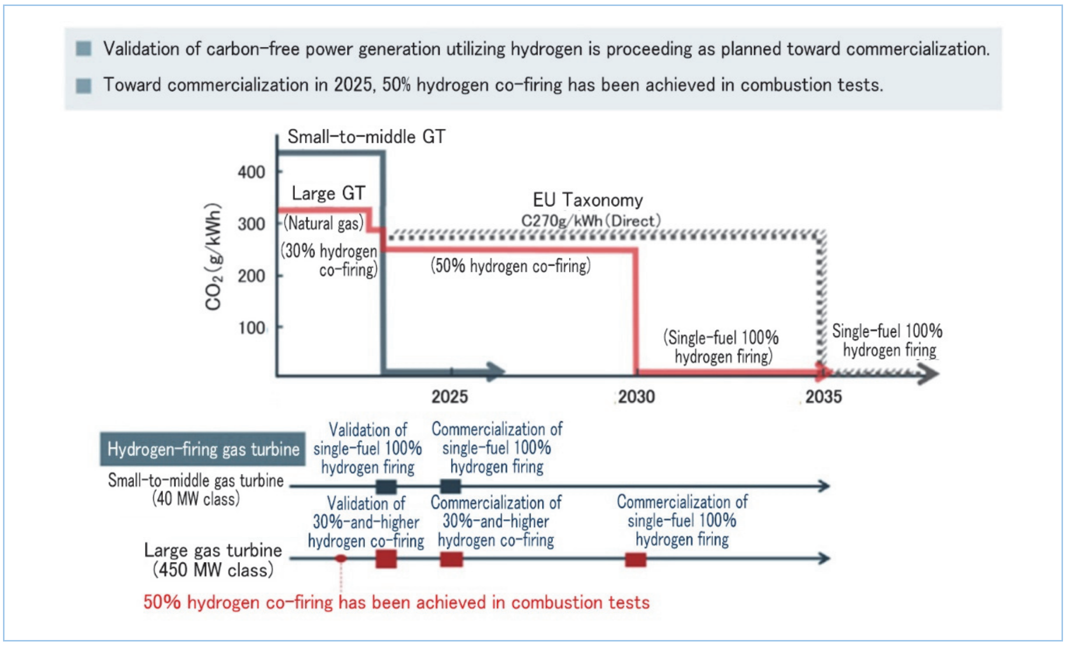
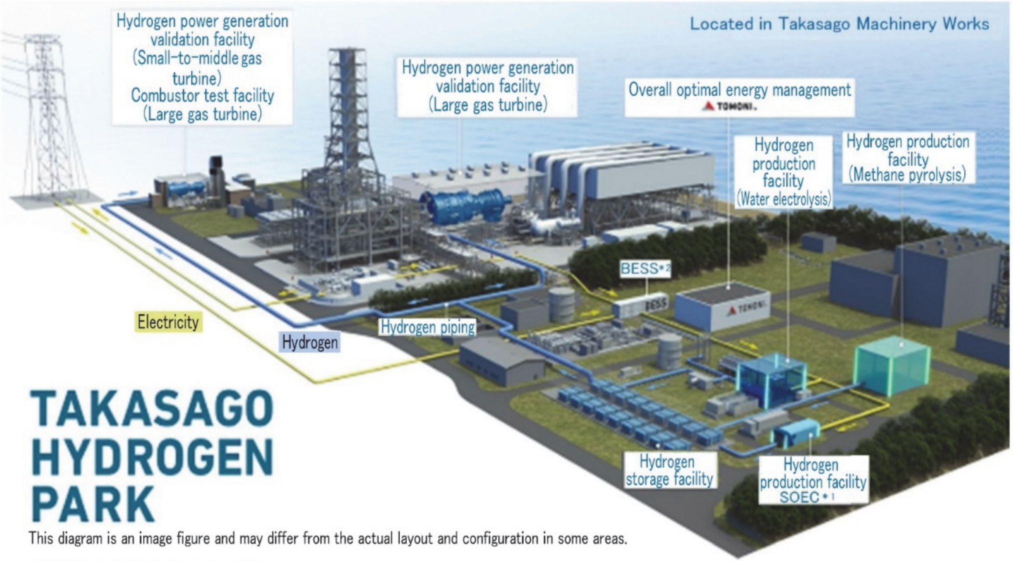


Figure 4 EU Taxonomy and gas turbine development schedule

4. Takasago Hydrogen Park, hydrogen power generation validation facility

MHI is currently constructing the Takasago Hydrogen Park, the world's first integrated validation facility for technologies from hydrogen production to power generation, at our Takasago Machinery Works, where we develop and manufacture gas turbines, adjacent to a combined cycle power plant validation facility called T-Point 2. **Figure 5** shows the overall concept of the Takasago Hydrogen Park, which consists of a hydrogen power generation validation facility consisting of a large gas turbine applied to the M501JAC model, small-to-middle gas turbines applied to the H25 model, and combustion test facilities. **Figure 6** shows the configuration of the Takasago Hydrogen Park. The electrolysis facility, which can be expected to be applied to water electrolysis and steam electrolysis using renewable energy, and methane pyrolysis facility, which performs thermal decomposition of natural gas (methane), produce green/turquoise hydrogen, which is then stored in a hydrogen storage facility. The validation facilities use hydrogen as fuel to generate electricity, which is then supplied to the power grid. We aim to establish a facility that allows integrated validation of green and turquoise hydrogen power generation, and of advanced energy management that combines secondary battery-based power storage and an overall optimal energy management system to store excess power with electrolytic hydrogen and the secondary batteries and to supply electricity from the hydrogen gas turbines and the secondary batteries during high demand periods.



This diagram is an image figure and may differ from the actual layout and configuration in some areas.

*1 SOEC : Solid Oxide Electrolysis Cell
*2 BESS : Battery Energy Storage System

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Figure 5 Overall concept of Takasago Hydrogen Park

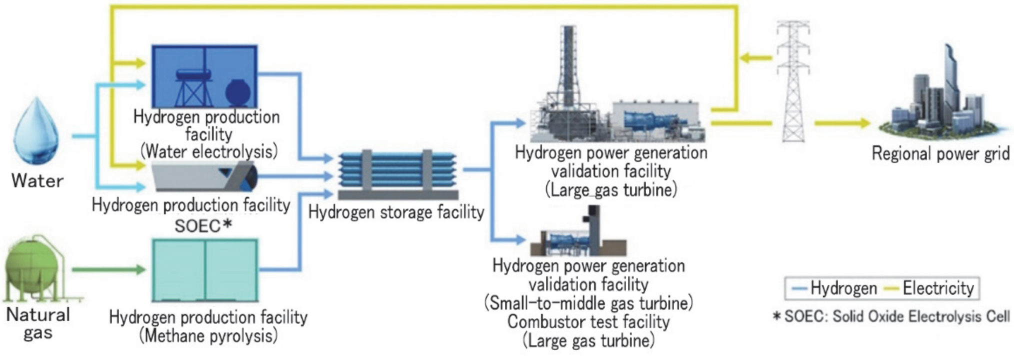


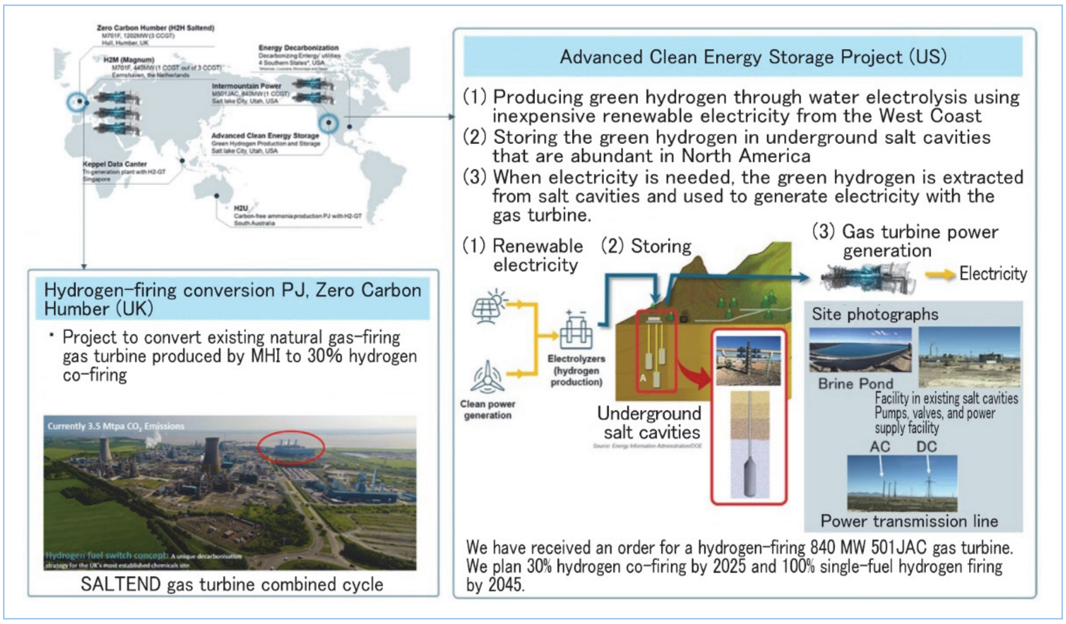
Figure 6 Configuration of Takasago Hydrogen Park

Currently, the storage facility is under construction (**Figure 7**) to start its operation in fiscal 2022, and the hydrogen production facility construction work is in progress, for which a 5.5-MW alkaline electrolyzer has been purchased from Hydrogen-Pro, to start its operation in fiscal 2023. After completion of the construction work, we will begin test and validation operations of hydrogen combustion technology in the gas turbine.

Figure 7 Construction status of Takasago Hydrogen Park (August 2022)

For the integrated validation of hydrogen power generation, we will first introduce alkaline water electrolysis, which is already in practical use, to the water electrolyzer, among other processes. Subsequently, we plan to install a SOEC as the high-temperature water electrolyzer under development, an anion exchange membrane (AEM) water electrolyzer as a low-temperature water electrolyzer, and a validation facility for turquoise hydrogen production, etc., in the park, and to conduct tests and validation of next-generation hydrogen production technologies.

Figure 8 shows example of hydrogen projects in which we are participating. The hydrogen hub (Advanced Clean Energy Storage project) to be a hydrogen production and storage facility in Utah, USA, is a project in which a cavity is constructed in the underground salt cavity and a hydrogen storage facility is prepared to store green hydrogen from renewable energy and generate electricity using a hydrogen gas turbine. The hydrogen production equipment to be used in this project will be manufactured by Hydrogen-Pro, the same equipment to be installed in "Takasago Hydrogen Park", and will be validated preliminarily at “Takasago Hydrogen Park”. In the U.K., a project to convert existing power plants from natural gas firing to hydrogen firing called Zero Carbon Humber is underway as Zero Carbon Humber.



Advanced Clean Energy Storage Project (US)

(1) Producing green hydrogen through water electrolysis using inexpensive renewable electricity from the West Coast
(2) Storing the green hydrogen in underground salt cavities that are abundant in North America
(3) When electricity is needed, the green hydrogen is extracted from salt cavities and used to generate electricity with the gas turbine.

We have received an order for a hydrogen-firing 840 MW 501JAC gas turbine. We plan 30% hydrogen co-firing by 2025 and 100% single-fuel hydrogen firing by 2045.

Hydrogen-firing conversion PJ, Zero Carbon Humber (UK)

- Project to convert existing natural gas-firing gas turbine produced by MHI to 30% hydrogen co-firing

SALTEND gas turbine combined cycle

Figure 8 Low-/Zero-carbon projects

5. Development status of hydrogen production technologies

Currently, our Energy Transition & Power Headquarters is developing several hydrogen production technologies. The following describes the development status of turquoise hydrogen production technology and next-generation AEM, a low-temperature water electrolyzer.

(1) Turquoise hydrogen production technology

As described in the previous chapter, methane pyrolysis is a technology for decomposing methane, the main component of natural gas, into solid carbon and hydrogen at high temperatures, which is a process conventionally used to produce carbon materials such as carbon black, a material used in industry. We focused on hydrogen produced in methane pyrolysis and found a reaction form that can efficiently produce hydrogen.

Figure 9 shows an overview of the turquoise hydrogen production technology. The natural gas infrastructure has already been established, and many natural gas-firing thermal power plants have been constructed. By simply installing a turquoise hydrogen plant additionally between the natural gas infrastructure supply line and the thermal power plants, etc., or power generation facilities of other natural gas power producers upstream of the consumer facility, dramatically lowering or even decarbonizing (Zero CO_2 emissions) in existing thermal power generation can be achieved. Because the byproduct carbon is solid, the byproduct carbon can be more easily fixed and stored than CO_2, which is a gas at ambient temperature and pressure. Currently, screening of reaction conditions and appropriate conditions is being conducted using an element test facility. We plan to take the reactors shown in **Figure 10** from our products and select appropriate reactors from these to accelerate the development. **Figure 11** shows a rough roadmap.

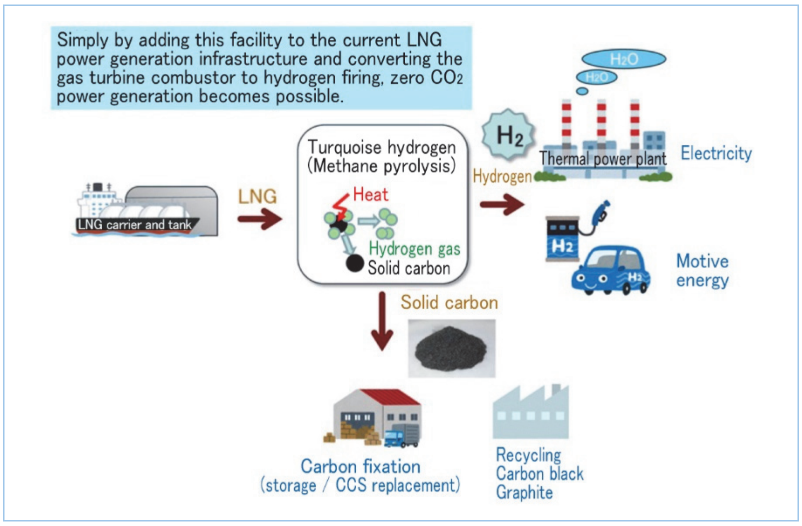


Figure 9 **Overview of turquoise hydrogen production technology**

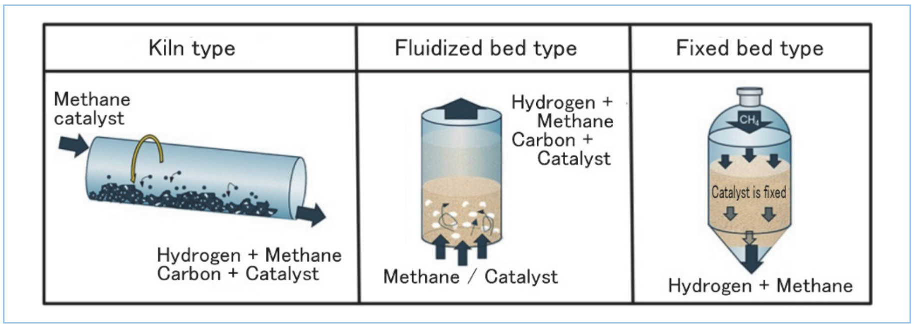


Figure 10 **Turquoise hydrogen reactors under development**

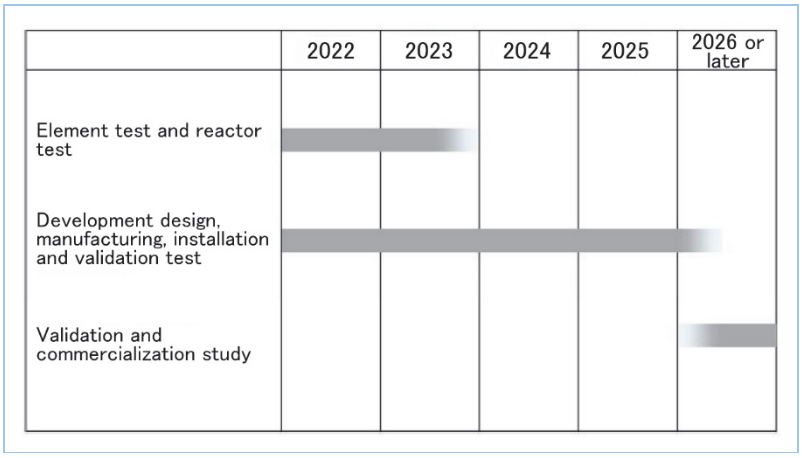


Figure 11 Roadmap for development of turquoise hydrogen

(2) Anion exchange membrane (AEM) water electrolysis hydrogen production

The mainstream of electrolysis technology using solid polymer electrolyte membranes is polymer exchange membrane (PEM) water electrolysis technology using hydrogen ion permeable membranes. However, compared to alkaline electrolysis, which is widely implemented, PEM water electrolysis technology, while capable of high current density operation and downsizing of the electrolyzer, requires highly pure water and needs extensive use of precious metals and Ti-based materials for catalysts and other wetted parts due to its acidic environment. On the other hand, AEM water electrolysis can be high current density-operated in the same manner as PEM water electrolysis, but it can be performed in an alkaline solution and thus stainless steel can be used, which can be expected to reduce the cost.

Figure 12 shows the development status. Using a small element cell fabricated as a prototype, we are currently considering the appropriate manufacturing process and optimizing operating conditions. The evaluation results of the samples shown in the figure indicate that a significant increase in current density can be expected compared to general alkaline water electrolysis. As shown in **Figure 13**, we will continue the development, validate the technology with several MW class facility at the Takasago Hydrogen Park, and then commercialize the technology.

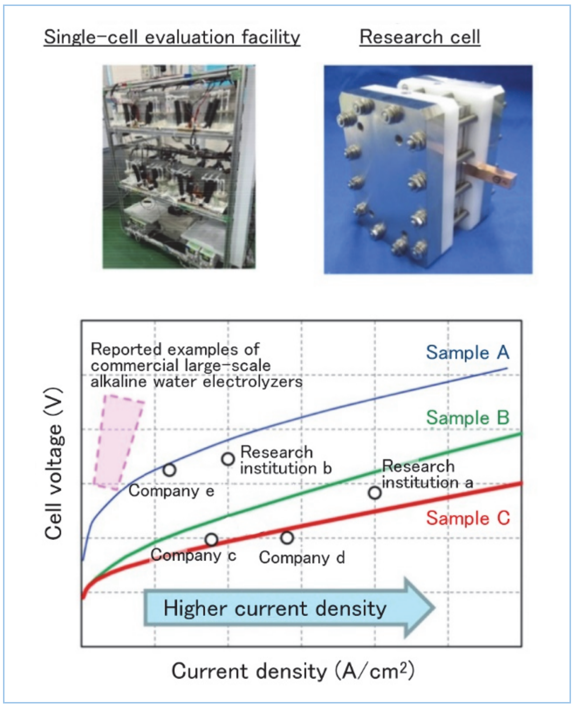


Figure 12 Development status of AEM water electrolysis

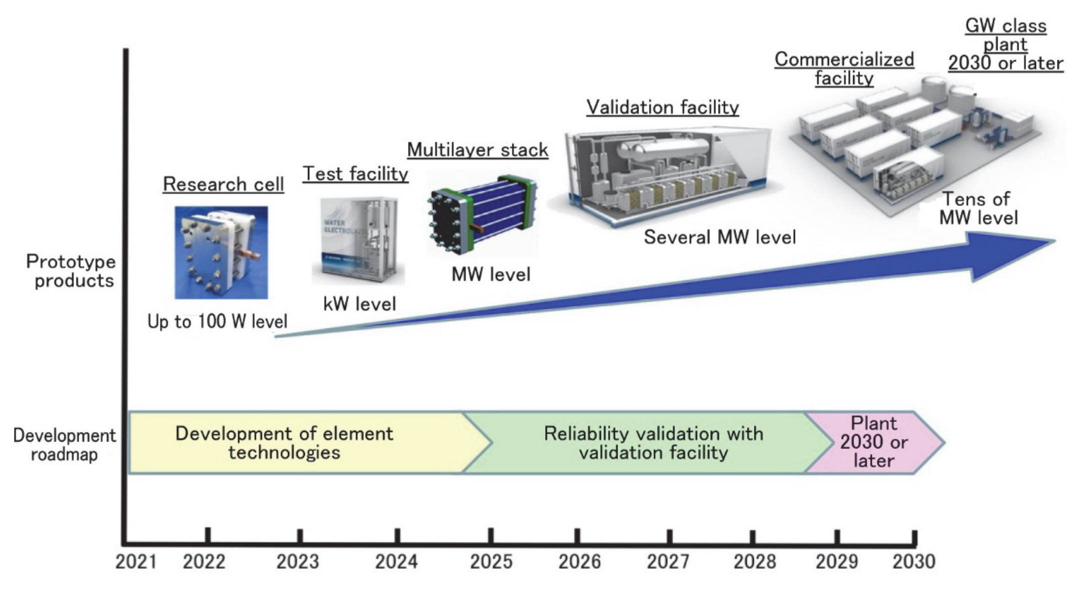


Figure 13 Roadmap of AEM water electrolysis

6. Development status of fuel ammonia utilization technology

Finally, we will describe the development status of ammonia utilization technology, which, along with hydrogen, plays an important role in the energy transition of thermal power generation. We have intensively installed a test facility in our Research & Innovation Center, Nagasaki District as shown in **Figure 14** (called the Nagasaki Carbon Neutral Park) to accelerate the development of ammonia utilization technology.

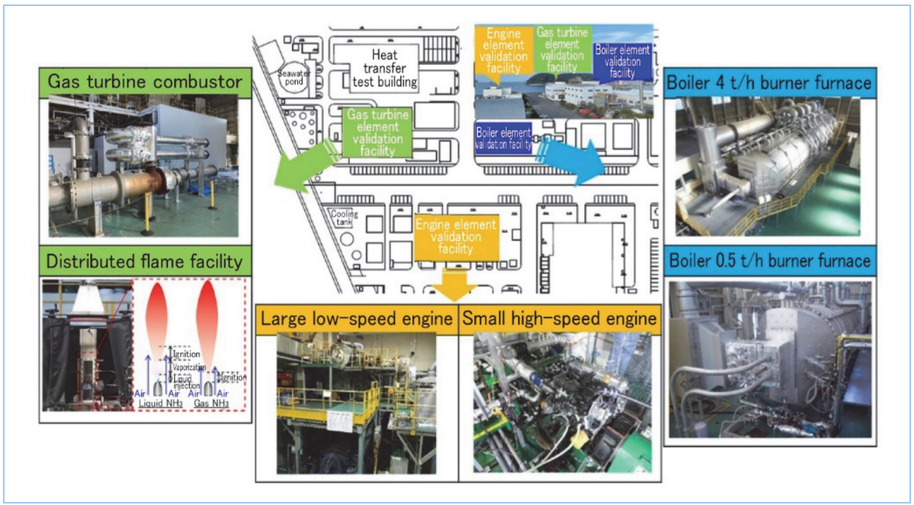


Figure 14 Nagasaki Carbon Neutral Park Ammonia-related facility in Research & Innovation Center, Nagasaki District

(1) Ammonia co-firing boiler

We are developing a burner that enables high-ratio ammonia co-firing in pulverized coal-firing boilers. There are issues in ammonia combustion: compared to hydrocarbon combustion such as LPG, ammonia burns at a slower rate, making it difficult to maintain a flame in the burner; and the large amount of N contained in ammonia causes a large amount of NOx to be generated if the combustion is not at the appropriate fuel concentration. We conducted ammonia co-firing and single-fuel ammonia firing tests using a small combustion test furnace in 2021. These tests were conducted for several burner types based on our accumulated experience in burner design for various fuels and the results of basic combustion tests, to provide single-fuel ammonia burners for commercial and industrial boilers in Japan and overseas. As a result, we confirmed that the flame was extremely stable during combustion, that NOx emissions were in line with the results of the basic combustion test conducted beforehand,

and that the residual ammonia was zero. At present, with the aim of high ammonia co-firing, we are working on the development and demonstration of high-ratio ammonia co-firing technology in coal-fired boilers under the Green Innovation Fund Project/Fuel Ammonia Supply Chain Establishment of the New Energy and Industrial Technology Development Organization (NEDO). As shown in **Figure 15**, by FY 2024, an Ammonia single-fuel burner will be developed through combustion tests with a full-scale burner equivalent to actual equipment. In addition, we are working on the basic equipment plan and feasibility study for the demonstration of an ammonia co-firing boiler in an actual plant in cooperation with JERA Co., Inc., aiming at the validation of more than 50% ammonia co-firing in two units, a circular firing system and an opposed firing system in the demonstration operation in the actual plant.

The development shown in this section is carried out in the "JPNP 21020 Green Innovation Fund Project/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" of the New Energy and Industrial Technology Development Organization (NEDO).

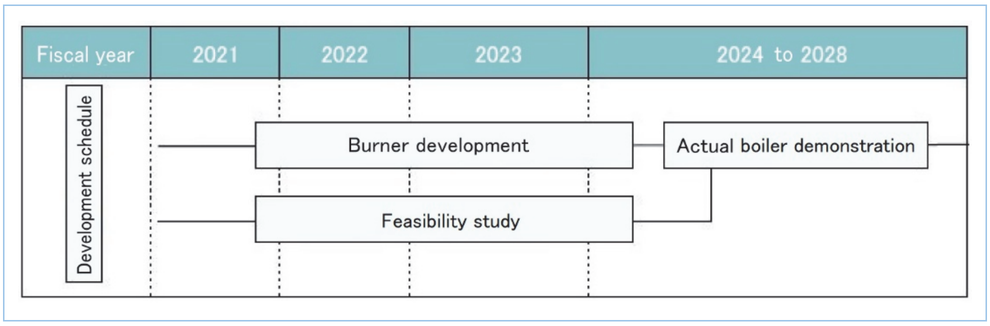
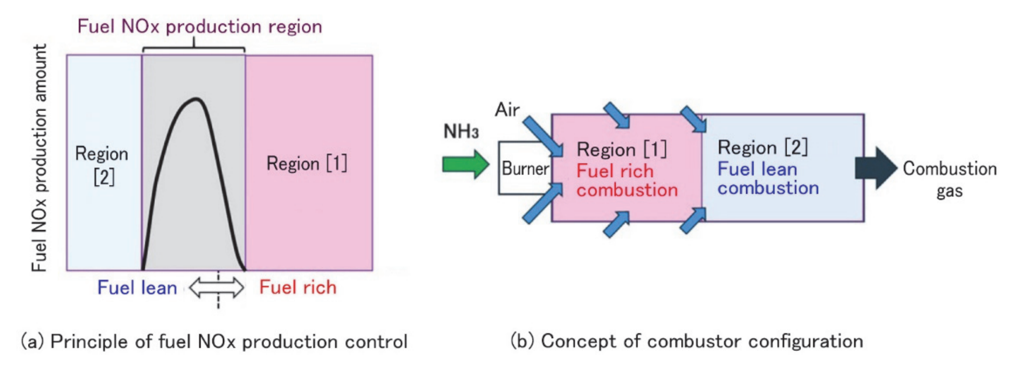


Figure 15 Overview of development of high-ratio ammonia co-firing technology funded by Green Innovation Fund

(2) Gas turbine utilizing ammonia

We have also started the development of a single-fuel ammonia combustor for gas turbine power generation. Since ammonia fuel contains nitrogen, a large amount of NOx called fuel NOx is produced during combustion. The principle is shown in **Figure 16**(a). It is known that the NOx emissions can be kept relatively low under fuel-rich and fuel-lean conditions. We are developing a combustor that can create a fuel-rich condition in its upstream area and a fuel-lean condition in its downstream area by adjusting the air distribution in the combustor as shown in Figure 16(b). We plan to suppress NOx generation as much as possible and combine this ammonia-firing combustor with an ultra-high-performance denitration facility toward the actual-plant validation, and we are proceeding with the development to conduct the validation in 2025.



(a) Principle of fuel NOx production control (b) Concept of combustor configuration

Figure 16 Overview of gas turbine combustor for ammonia

7. Conclusion

This report introduced carbon neutrality initiatives for the thermal power generation industry, centering on the Takasago Hydrogen Park. The Takasago Hydrogen Park, which will be located adjacent to T-Point 2, is currently under construction, including the installation of a hydrogen storage facility. To begin with, we will install an alkaline electrolytic hydrogen production unit manufactured by Hydrogen-Pro in the Takasago Hydrogen Park and aim to start operation in 2023 as an integrated validation facility of hydrogen production and power generation.

At the same time, we are developing several hydrogen production technologies. We plan to install a validation facility of the technology that has reached the validation phase at the Takasago Hydrogen Park and to conduct validation operations there. Among them, this report also introduced the turquoise hydrogen production technology and AEM water electrolysis technology.

Using the energy transition technologies described in this report, we aim to achieve our MISSION's declaration "MISSION NET ZERO" for 2040 and contribute to the realization of a carbon-neutral society.

“Hydrogen is Not the Future, This is Real. ”