Periodic Table of the Elements

Atomic number — Element symbol — Element name — Atomic weight (key: 1 H Hydrogen 1.008)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.81	6 C Carbon 12.01	7 N Nitrogen 14.01	8 O Oxygen 16.00	9 F Fluorine 19.00	10 Ne Neon 20.18
11 Na Sodium 22.99	12 Mg Magnesium 24.31											13 Al Aluminum 26.98	14 Si Silicon 28.09	15 P Phosphorus 30.97	16 S Sulfur 32.07	17 Cl Chlorine 35.45	18 Ar Argon 39.95
19 K Potassium 39.10	20 Ca Calcium 40.08	21 Sc Scandium 44.96	22 Ti Titanium 47.87	23 V Vanadium 50.94	24 Cr Chromium 52.00	25 Mn Manganese 54.94	26 Fe Iron 55.85	27 Co Cobalt 58.93	28 Ni Nickel 58.69	29 Cu Copper 63.55	30 Zn Zinc 65.38	31 Ga Gallium 69.72	32 Ge Germanium 72.63	33 As Arsenic 74.92	34 Se Selenium 78.97	35 Br Bromine 79.90	36 Kr Krypton 83.80
37 Rb Rubidium 85.47	38 Sr Strontium 87.62	39 Y Yttrium 88.91	40 Zr Zirconium 91.22	41 Nb Niobium 92.91	42 Mo Molybdenum 95.95	43 Tc Technetium (99)	44 Ru Ruthenium 101.1	45 Rh Rhodium 102.9	46 Pd Palladium 106.4	47 Ag Silver 107.9	48 Cd Cadmium 112.4	49 In Indium 114.8	50 Sn Tin 118.7	51 Sb Antimony 121.8	52 Te Tellurium 127.6	53 I Iodine 126.9	54 Xe Xenon 131.3
55 Cs Cesium 132.9	56 Ba Barium 137.3	57-71 Lanthanoid	72 Hf Hafnium 178.5	73 Ta Tantalum 180.9	74 W Tungsten 183.8	75 Re Rhenium 186.2	76 Os Osmium 190.2	77 Ir Iridium 192.2	78 Pt Platinum 195.1	79 Au Gold 197.0	80 Hg Mercury 200.6	81 Tl Thallium 204.4	82 Pb Lead 207.2	83 Bi Bismuth 209.0	84 Po Polonium (210)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89-103 Actinoid	104 Rf Rutherfordium (267)	105 Db Dubnium (268)	106 Sg Seaborgium (271)	107 Bh Bohrium (272)	108 Hs Hassium (277)	109 Mt Meitnerium (276)	110 Ds Darmstadtium (281)	111 Rg Roentgenium (280)	112 Cn Copernicium (285)	113 Nh Nihonium (278)	114 Fl Flerovium (289)	115 Mc Moscovium (289)	116 Lv Livermorium (293)	117 Ts Tennessine (293)	118 Og Oganesson (294)

57 La Lanthanum 138.9	58 Ce Cerium 140.1	59 Pr Praseodymium 140.9	60 Nd Neodymium 144.2	61 Pm Promethium (145)	62 Sm Samarium 150.4	63 Eu Europium 152.0	64 Gd Gadolinium 157.3	65 Tb Terbium 158.9	66 Dy Dysprosium 162.5	67 Ho Holmium 164.9	68 Er Erbium 167.3	69 Tm Thulium 168.9	70 Yb Ytterbium 173.0	71 Lu Lutetium 175.0
89 Ac Actinium (227)	90 Th Thorium 232.0	91 Pa Protactinium 231.0	92 U Uranium 238.0	93 Np Neptunium (237)	94 Pu Plutonium (239)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (252)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

Source：“SCIENCE & TECHNOLOGY WEEK ”（MEXT） https://www.mext.go.jp/stw/series.html

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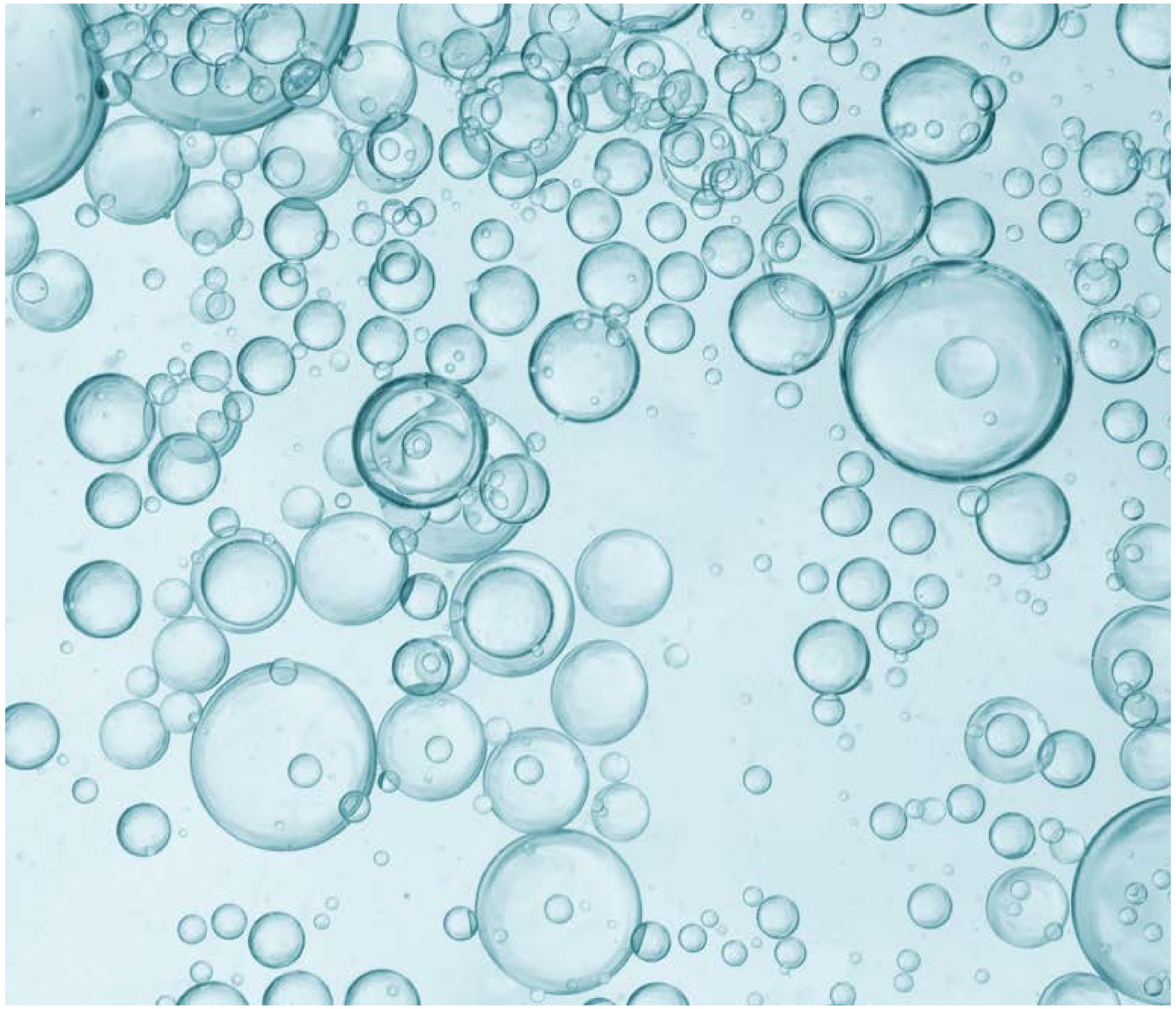
MITSUBISHI POWER

HYDROGEN POWER GENERATION HANDBOOK

(Fourth Edition)

Towards the realization of integrated hydrogen technologies from production to power generation



Mitsubishi Power is a power solutions brand
of Mitsubishi Heavy Industries.

MOVE THE WORLD FORW>RD MITSUBISHI HEAVY INDUSTRIES GROUP

INTRODUCTION

Hydrogen—atomic number 1.
It's the first element we learn about as students.
It forms water, which is essential for life on Earth, the planet of water.
It is abundant throughout the universe.
It is light, diffuses rapidly, and burns.

"Burning" forms the foundation of civilization, because it is a source of energy.
Energy is essential to our daily lives, and meeting the world's increasing needs, while reducing CO_2 emissions, is a critical issue of our times.

We have arrived at a watershed in the history of energy with the diversification of energy sources such as renewables and the impact of their evolution on the best energy mix.

Hydrogen is a clean energy source that does not emit CO_2 upon combustion.
The accelerated introduction of IT, continued economic development in emerging nations, and a forecast for increased demand, plus reliable technology for control of the highly flammable element, make hydrogen power generation—clean and abundant—a viable alternative.

Competition among developers of the technology is taking place around the world, where engineers are solving a host of issues.

INDEX

Notes on the Publication of the Revised Edition (fourth edition) of the "Hydrogen Power Generation Handbook"

In this revision, we have updated the content regarding new trends related to hydrogen energy, our efforts, and the introduction of technical papers by engineers.
We have recently started verification and demonstration of one of hydrogen production technologies which are covered in this edition. We hope that this book will be useful to you.

Realizing a carbon-neutral society

Decarbonization with a power-generation technology that emits no CO_2.

The world faces a tipping point that could be called the "decarbonization revolution." Energy industries around the world have taken a major turn toward decarbonization, and the leaders of many countries have expressed their determination to achieve carbon neutrality.
At the same time, there is an urgent need for a stable supply of electricity to meet the increasing power demand due to population growth and economic development. Increasing supply of renewable energy such as wind and solar power also demand a stable power supply as they depend on natural conditions for their output.

Under such circumstances, the Mitsubishi Heavy Industries, Ltd. (MHI) Group announced the 2040 Carbon Neutrality Declaration "MISSION NET ZERO" in October 2021. Achieving a carbon-neutral society is a global issue, and we at Mitsubishi Power, as a leader with a proven track record in the decarbonization field, believe it is our responsibility to lead climate change measures. We will contribute to the realization of a carbon-neutral society by cooperating with partners around the world through products, technologies, and services that can promote CO_2 reduction. For some time, Mitsubishi Power, in collaboration with MHI Group companies have plotted a path toward solutions called "Energy Transition" that will balance the expansion of renewable energy with economic efficiency and stable supply, and have also established the direction of technological development needed to achieve this goal. Mitsubishi Power has been developing and cultivating highly efficient power generation and environmental technologies over the years and is working on the use of fuels that do not emit CO_2, such as hydrogen and ammonia, with the aim of reducing CO_2 emissions of and decarbonizing thermal power generation.

The hydrogen power generation technology introduced in this handbook changes the fuel for gas turbine combined cycle (GTCC), which currently has the lowest CO_2 emissions among fossil fuel-based thermal power generation, from natural gas to hydrogen, which does not emit CO_2 when burned. It is a technology that will greatly contribute to decarbonization on a global scale. Mitsubishi Power's hydrogen power generation technology makes it possible to reduce installation costs by maximizing the use of existing equipment and converting it to hydrogen power generation.

Hydrogen power will play an important role in decarbonizing thermal power generation, which account for the majority of global electricity supply at present. Furthermore, as reducing the cost of hydrogen is an issue, Mitsubishi Power aims to develop hydrogen production and power generation technology to help create a virtuous cycle of hydrogen value chain development and cost reduction, thereby contributing to the realization of a hydrogen society.

MHI Group has a track record of producing and supplying various hydrogen-related products including rocket engines that use hydrogen as a liquid fuel and hydrogen production facilities. In the half century between 1970 and the present, we have abundant accomplishments in the use of by-product gas that contains hydrogen for power generation purposes. In addition to supplying equipment, MHI Group is also involved in the entire fuel value chain, from the production, transportation, storage, and utilization of CO_2-free hydrogen and ammonia. With our proven technological capabilities and our promotion of decarbonized energy, we will continue to contribute to the protection of the global environment and move the world closer to a carbon-neutral society.

The world's fastest aircraft, the X-15, which flew at Mach 6.7, flew on ammonia!

Ammonia combustion, which is anticipated to be useful in carbon-free initiatives, is actually an old technology. The North American X-15, an experimental high-altitude hypersonic aircraft equipped with an ammonia engine, began flight in 1961 and in 1967, set the world speed record of Mach 6.7. This record remains unbroken in manned winged aircraft even today. Ammonia is fuel for the dreams of mankind.

Why are liquid oxygen and liquid hydrogen used as rocket fuel?

It can be said that the greater the speed a combusted gas is ejected from a rocket engine, the greater the propulsive force and the better the engine. Furthermore, the lighter the gas used in combustion, the easier it accelerates, which leads to higher ejection speed.
In other words, the combustion gas, mainly H_2O, generated by burning oxygen and hydrogen is a lighter substance than the combustion gas of other fuels.

Accelerating the shift to decarbonization. Driving the potential of hydrogen power generation.

The world is now aligned to become a Hydrogen Society

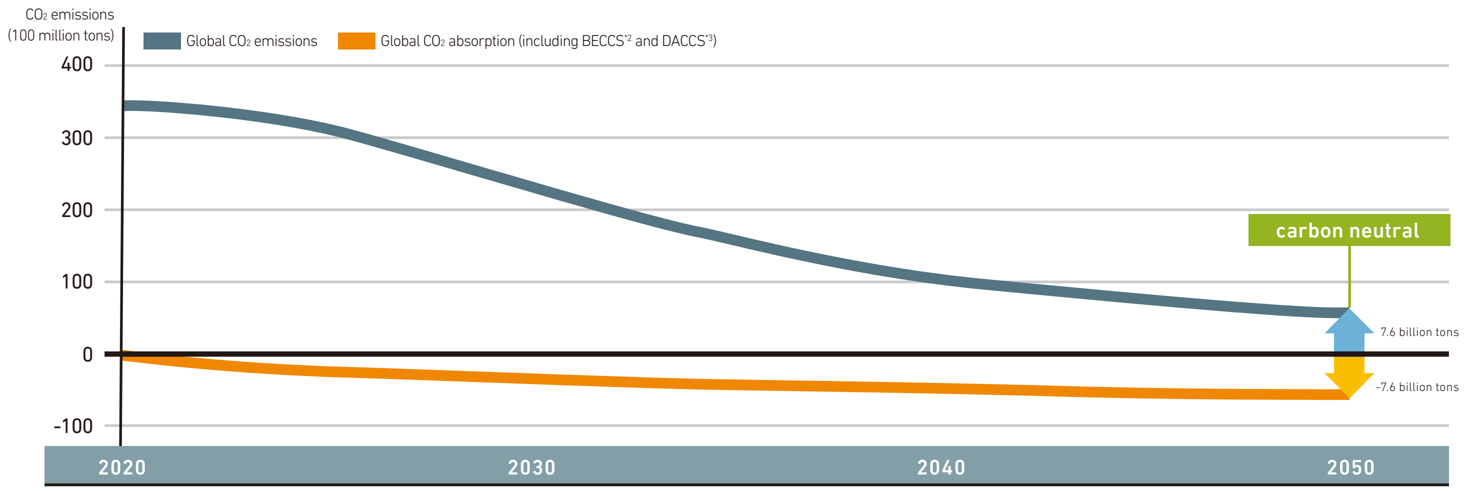
In 2019, the EU announced their action plan to achieve the carbon-neutral target by 2050. In October 2020, former Prime Minister Suga declared that by 2050, Japan aims to become a decarbonized nation with zero greenhouse gas emissions. A month earlier, President Xi Jinping of China announced that they aim to go carbon-neutral by 2060. And in January 2021, the U.S. president, Joe Biden signed an executive order to rejoin the Paris Agreement. The world is now picking up the pace to achieving carbon-neutrality with increasing usage of hydrogen to produce CO_2-free energy.

Looking at current hydrogen policy trends in various countries, the United States' aims include reducing the production cost of clean hydrogen to less than $1/kg within 10 years and shifting the current 10 million tons/year of gray hydrogen to 10 million tons/year of clean hydrogen by 2030. Meanwhile, the EU aims to introduce at least 6GW of renewable water electrolysis equipment by 2024, and at least 40GW of renewable energy water electrolysis equipment by 2040. Furthermore, Singapore aims to be able to meet up to 50% of its domestic electricity demand through hydrogen power generation by 2050 and is moving forward with the introduction of low-carbon hydrogen and infrastructure development. In the Middle East, the UAE aims to strengthen its ability to supply clean and sustainable energy, investing 150 billion to 200 billion dirhams (approximately $40 billion to $54.5 billion) by 2030 to triple its renewable energy capacity. It also aims to raise the share of clean energy in the total energy mix to 30% by 2031.

Accelerating the global energy transition

Three factors can be cited to accelerate the energy transition. Firstly, an energy crisis occurred due to Ukraine being invaded, and the energy transition efforts, which were expected to slow down as a result, began accelerating particularly in Europe. Unlike fuels that rely on imports, renewable energy is an independent power source for each region, so there is a growing momentum for its active development. Secondly, in August 2022, the IRA (Inflation Reduction Act) was enacted in the United States, guaranteeing many incentives for more than 10 years, and various projects became active. Thirdly, energy transition movement has also gained momentum in the Asia-Pacific region. Interest in our decarbonization technology is increasing in countries such as Singapore, which is promoting a decarbonization strategy, and Australia, which is aiming to become a clean energy exporter.

Forecast based on major reports*1



*1: Summary based on major reports (McKinsey 1.5°C scenario, IEA Net Zero by 2050, IEA SDS, IPCC, etc.)
*2: Abbreviation for Bio Energy with Carbon Capture and Storage, CO_2 capture and storage from biomass-derived exhaust gas.
*3: Abbreviation for Direct Air Carbon Capture and Storage, capture and storage of CO_2 from the atmosphere

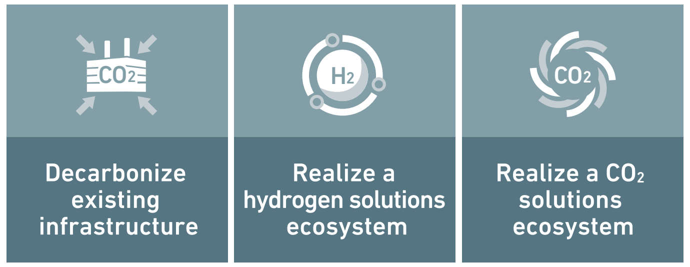
MHI Group's "MISSION NET ZERO"

"MISSION NET ZERO" is the MHI Group's 2040 carbon neutral declaration. Our first goal is to reduce our group's CO_2 emissions by 50% by 2030 (compared to 2014) and achieve net zero by 2040. The second goal is to achieve net zero CO_2 emissions from the entire value chain by 2040. As an intermediate goal, we aim to reduce CO_2 emissions by 50% (compared to 2019) by 2030 (taking into account the reduction in CO_2 emissions of our customers through the use of our products and the reduction contribution made by CCUS*). By introducing innovative technology and providing solutions that are both economical and reliable, we reduce transition costs and contribute to the realization of a sustainable society.

* Carbon dioxide Capture, Utilization and Storage

Energy Transition and the Solutions

The MHI Group is committed to promoting the energy transition to realize a carbon-neutral society. We will provide solutions based on the three pillars of "Decarbonize existing infrastructure," "Realize a hydrogen solutions ecosystem," and "Realize a CO_2 solutions ecosystem." We are already participating in large-frame projects around the world and supporting their success.



Mitsubishi Power's Hydrogen Project

Working toward conversion to the hydrogen-fired M701F gas turbine

Mitsubishi Power is participating in a decarbonization business plan for the largest industrial cluster in the country (Humber Cluster), which is in progress in the delta area of the Humber River Basin on the east coast of the United Kingdom. Twelve companies and institutions in the global decarbonization industry including Equinor ASA, a major energy company based in Norway, have joined forces to form the "Zero Carbon Humber Partnership (ZCH)". By utilizing hydrogen produced from natural gas and making full use of CO_2 capture technology and removal technologies, the industrial cluster aims to achieve virtually zero CO_2 emissions by 2040.

As such, Mitsubishi Power will undertake technical studies and a feasibility study (FS) to convert fuel from a natural gas to a hydrogen for its three M701F gas turbines operating at a natural gas-fired 1,200MW class GTCC power plant in Saltend Chemicals Park, an industrial cluster in the northern part. Using this project participation as an impetus for MHI Group's strategic business, Energy Transition, we will stimulate demand for the utilization of hydrogen by thermal power generation companies. In addition, we will contribute to the realization of a decarbonized society by being involved in the construction of an international hydrogen value chain for hydrogen supply, transportation, and storage while working closely with these technologies and partners.

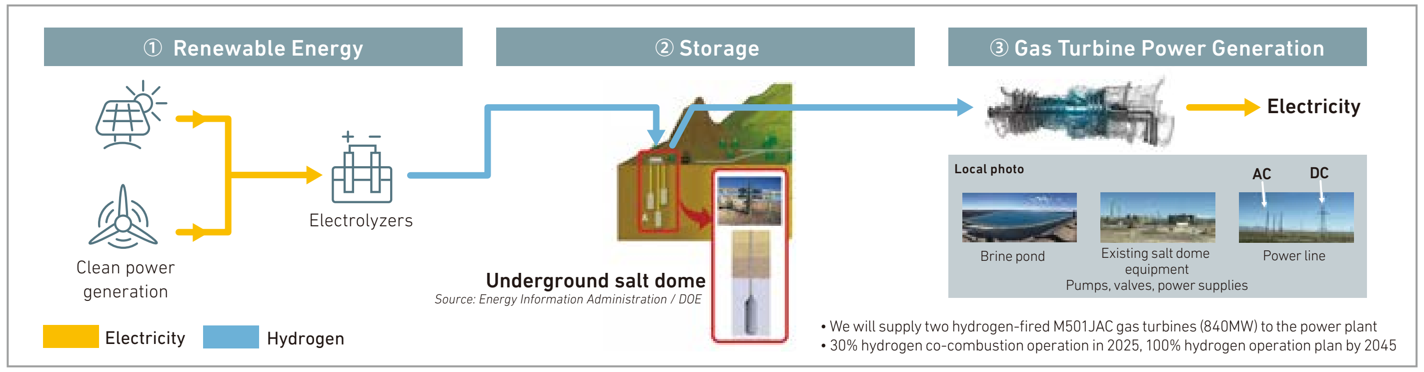
Zero Carbon Humber Partnership:ZCH
Source: https://www.zerocarbonhumber.co.uk/

Saltend GTCC Power Plant

Storing green hydrogen in salt domes

Mitsubishi Power Americas, Inc., an MHI group company, is promoting the Advanced Clean Energy Storage Hub (ACES Delta Hub), a joint project with Chevron U.S.A. Inc.'s New Energies Company (formerly Magnum Development) in Utah, U.S.A. The green hydrogen produced by electrolyzing water using wind and solar power will be stored in two massive underground salt domes, each with a storage capacity of over 5,500 tons of hydrogen. The idea is to supply this hydrogen to power plants and other facilities. The amount of power to be generated is approximately 150GWh each. In June 2022, the world's largest green hydrogen hub entered the execution phase with a loan guarantee from the U.S. Department of Energy.

Mitsubishi Power has cutting-edge hydrogen combustion technologies, and its hydrogen gas turbine requires minimum modification to the existing infrastructures at the power plants. In 2018, Mitsubishi Power had already achieved 30% hydrogen co-firing and aims to make this 100% hydrogen by 2025. Large-frame hydrogen generation is a crucial piece in creating a truly sustainable society across the globe. Cost is a challenge today, however as technology evolves, we will continue to reduce the cost of green hydrogen. Mitsubishi Power is fully committed to playing a significant leadership role in addressing this global obligation and deliver technological advancements to attain a carbon-free hydrogen society.

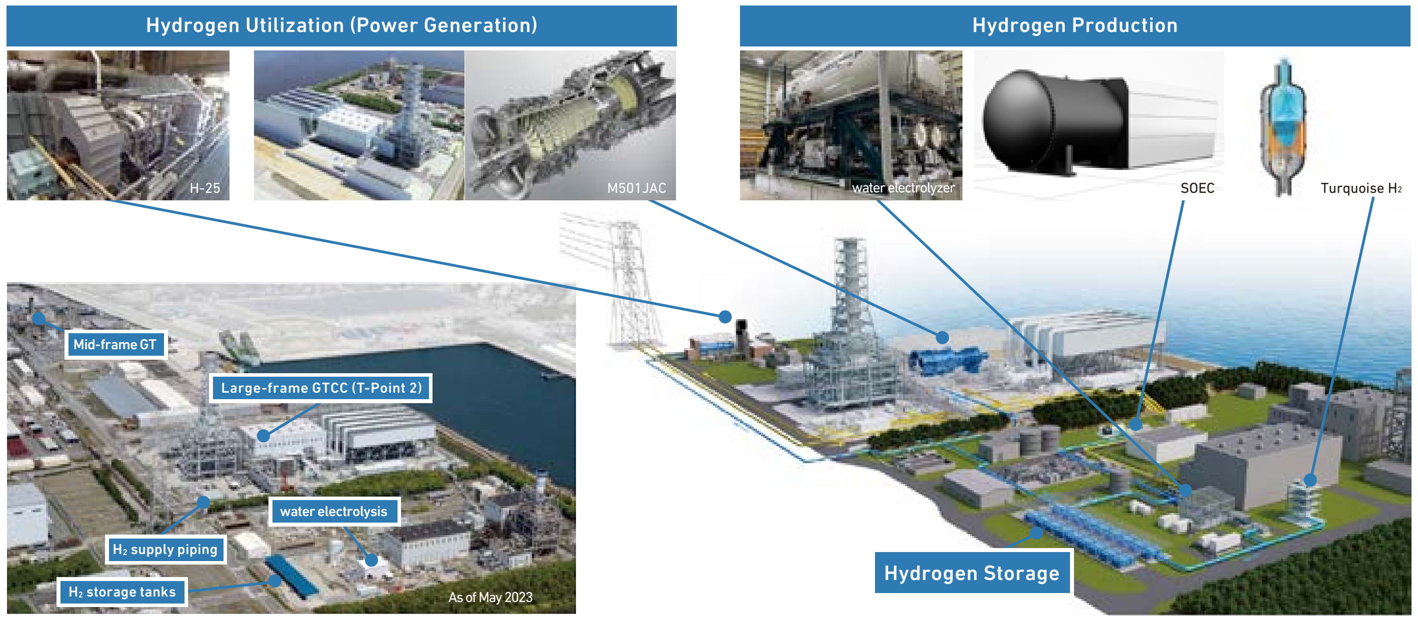


Mitsubishi Power's decarbonization technology development bases and initiatives

Takasago Hydrogen Park, the World's First Integrated Validation Facility for Technologies from Hydrogen Production to Power Generation, Enters Full-Scale Operation
-- Electrolysis Hydrogen Production Begins --

Mitsubisi Power has started full-scale operation of the Takasago Hydrogen Park (Takasago City, Hyogo Prefecture), which is the first facility in the world to be able to validate technologies from hydrogen production to power generation, in an integrated way, with the aim of early commercialization of hydrogen gas turbines. The main focus is to improve product reliability through technological validation and to contribute to the social implementation of hydrogen power generation and manufacturing technologies. In addition to hydrogen production using water electrolysis equipment, we will sequentially expand the introduction of next-generation hydrogen production technologies and demonstrate hydrogen co-firing and hydrogen firing (100% hydrogen) using actual gas turbines. The park is divided into three areas: hydrogen production, storage, and utilization. In the "Hydrogen Production" area, we have installed and begun operating an alkaline water electrolyzer manufactured by Norway's HydrogenPro AS, which has one of the world's largest hydrogen production capacities of 1,100Nm³/h. The hydrogen produced at the facility is stored in hydrogen storage tanks with a total capacity of 39,000Nm³ installed in the "Hydrogen Storage" area. In addition, actual verification of hydrogen combustion will be conducted using a large JAC type gas turbine (450MW class) at the demonstration facility combined cycle power plant and a small to medium-sized H-25 gas turbine (40MW class) installed to drive a compressor at the combustion test facility, both of which are located in the "Hydrogen Utilization" area. For hydrogen production, we are developing our own technologies such as SOEC (Solid Oxide Electrolysis Cell), AEM (Anion Exchange Membrane) water electrolysis, and turquoise hydrogen, which generates hydrogen without CO_2 emission by pyrolysis of methane into hydrogen and solid carbon. Regarding hydrogen production technology, elemental technologies will be developed at the Nagasaki Carbon Neutral Park and then verified and demonstrated under actual operating conditions. Takasago Hydrogen Park will become an important base for creating a hydrogen ecosystem by building a value chain of production, storage, and utilization.

HYDROGEN PARK TAKASAGO



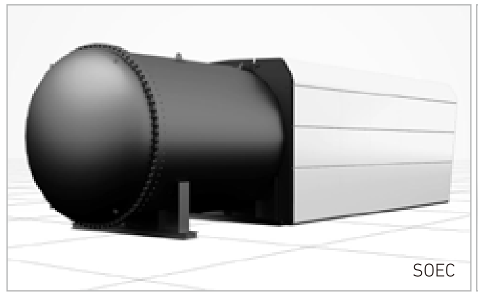
"Nagasaki Carbon Neutral Park" begins operation
Promoting technology development related to energy decarbonization
We have established and begun operating the Nagasaki Carbon Neutral Park in Nagasaki City as a central base for technology development related to energy decarbonization. The design, manufacturing, and development departments work together to put product technology into practical use. In particular, the Nagasaki District Research & Innovation Center, is a research facility that is a symbol of our base, and conducts research and development including the elemental technologies related to hydrogen production, biomass synthetic fuel production, ammonia combustion, and CO_2 capture.

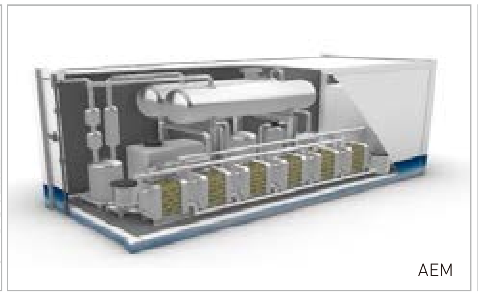
Furthermore, we will conduct research and accelerate development toward productization and commercialization by utilizing the design and manufacturing functions of various thermal energy equipment cultivated at the Nagasaki Shipyard & Machinery Works, where the Nagasaki Plant handles design and manufacturing, and the Koyagi Plant conducts manufacturing. Following these steps, after developing key technologies at the Nagasaki Carbon Neutral Park, we will conduct hydrogen production demonstration operations and power generation demonstrations in conjunction with hydrogen gas turbines at the hydrogen production and power generation demonstration facility, Takasago Hydrogen Park.

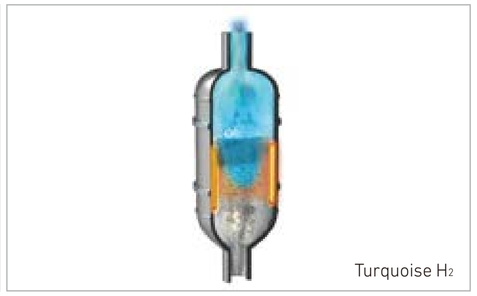
CARBON NEUTRAL PARK NAGASAKI

Introduction to hydrogen production technology development
We are developing next-generation hydrogen production technologies such as SOEC, AEM, and turquoise hydrogen.

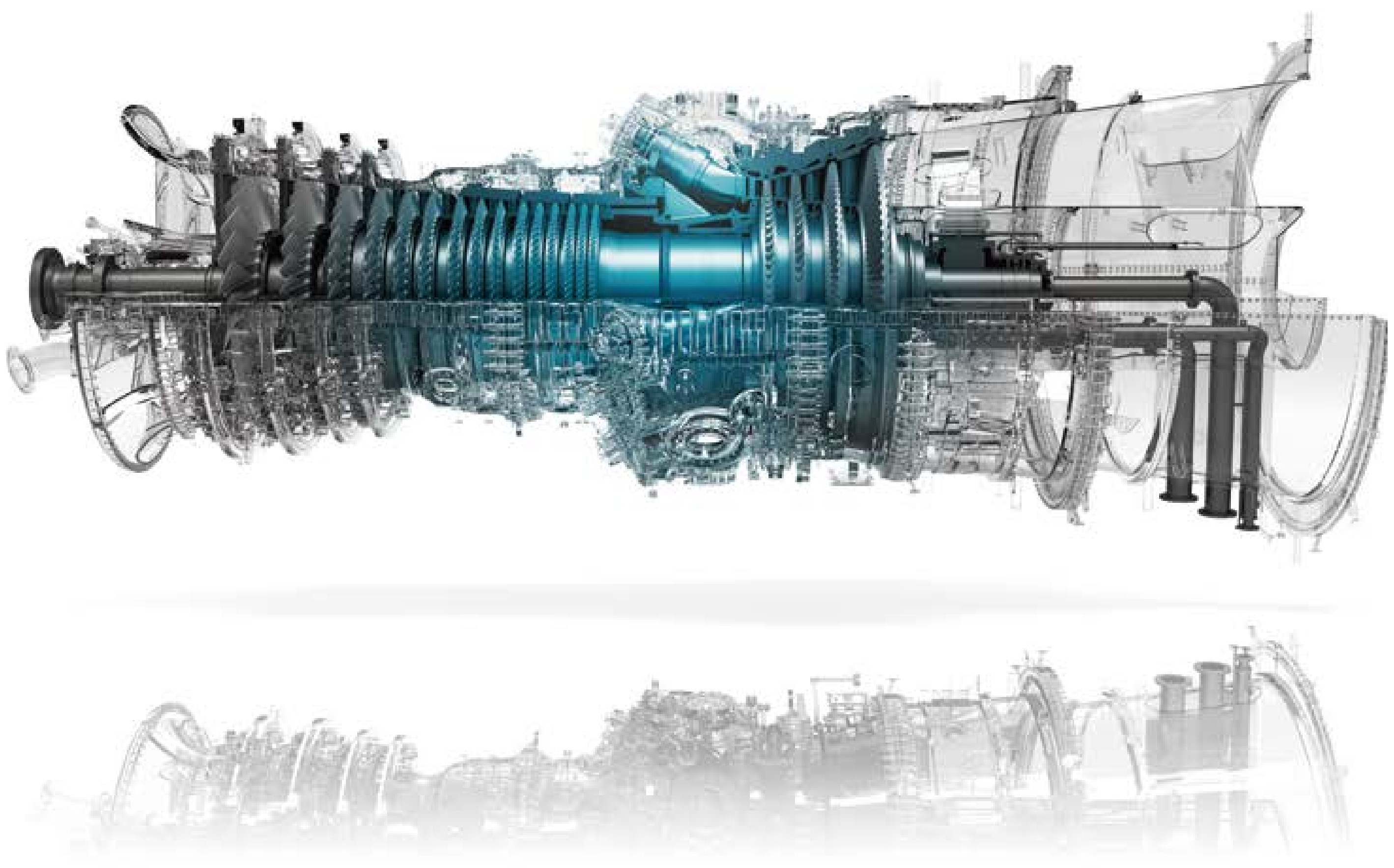
SOEC is an application of the developed SOFC technology, which enables high-efficiency and large-capacity hydrogen production. We aim to realize a large-scale SOEC plant by combining this technology with technologies dealing with high-temperature, high-pressure steam and gas in steam power generation. AEM is a hydrogen production technology using electrolysis technology using a solid polymer electrolyte membrane, and its high current density operation allows electrolyzers to be made smaller and lower in cost. Turquoise hydrogen is technology that uses pyrolysis of methane to yield hydrogen and solid carbon, making it possible to efficiently produce hydrogen. Decarbonization can be achieved by adding turquoise hydrogen production equipment to natural gas-fired thermal power generation equipment and replacing the gas turbine combustors for hydrogen.


SOEC


AEM


Turquoise H_2

Moving toward commencing demonstration of the hydrogen gas turbine 30% co-firing technology



Expectations for hydrogen energy and technologies

Coping with the conflict between robust energy demand and global decarbonization

"Energy is the cornerstone of industry," said Satoshi Tanimura—Chief Engineer, GTCC Business Division, Energy Systems, Mitsubishi Heavy Industries, Ltd.—a leader in the development of hydrogen-fueled gas turbines that feature CO_2-free combustion technology. "If demand exists, supply will be provided by electric power companies, and power-generating facilities are necessary to provide this supply. At the same time, there is increasing public scrutiny toward power-generation that produces CO_2 emissions. They want electricity, but they don't want the attendant CO_2 emission. It's the mission of engineers to pursue thermal power generation that emits zero CO_2."

Electricity is the main source of primary energy conversion in Japan, accounting for approximately 48% of the total. The proportion of electricity supplied by fuel is LNG at 34.4%, oil at 7.4%, coal at 31.0%, and thermal power generation accounts for 72.8%. (As of 2021).
Source: https://www.enecho.meti.go.jp/about/whitepaper/2023/pdf/2_1.pdf

As energy choices steadily increase, thermal power still remains a key energy source. "With regard to thermal power using fossil fuels, efforts have continuously been made toward reducing emissions by enhancing efficiency through technological innovation," said Tanimura. "CO_2 emissions per unit with GTCC plants, which combine gas and steam turbines, are less than half of those generated by coal-fired thermal power. But it doesn't change the fact that CO_2 is still emitted in the generation of gas-fired thermal power; we cannot close our eyes to this fact. As an engineer, I'm particularly sensitive to global issues and expectations toward resolving them. And we must develop technology to cope with the conflicting issues of strong demands for energy and for CO_2 reduction."

A clear roadmap to the achievement of a hydrogen society

Satoshi Tanimura's focus is on thermal power generation that does not emit CO_2. "Our area of involvement is the development of hydrogen gas turbines," he said.

Japan's Basic Hydrogen Strategy includes the target of commercialization of hydrogen power generation by 2030.
However, is it possible to commercialize hydrogen power generation in about seven years? Even if technology is successfully developed, how many power plant operators can afford to renew their facilities? Also, how will we secure large quantities of hydrogen to serve as fuel?

"Even if hydrogen power-generating facilities are installed at power plants already scheduled for renewal, it's not realistic to expect substantial power generation volume to be secured in only seven years," said Tanimura. "That's where Mitsubishi Power comes in—we conceived a hydrogen power generation system that utilizes existing gas turbine facilities."

Tanimura and his colleagues at MHI have developed a gas turbine combustor that can steadily use a 30% hydrogen mix with LNG, which is the fuel for gas-fired power plants. It burns hydrogen while allowing suppression of NOx emissions to the level of gas-fired thermal power. The technology is compatible with an output equivalent to 840MW, and it offers a reduction of about 12% in CO_2 emissions compared with GTCC.

As this technology enables the use of existing facilities, large-frame modification of power generation facilities becomes unnecessary. This makes it possible to lower costs and other hurdles, promoting a smooth transition to a hydrogen society.

But can hydrogen be infused into the fuel mix of existing facilities so easily? Aspects such as fusion, combustion, and the quality and behavior of hydrogen must be different from those of LNG. What is this hydrogen-mixed combustion technology developed by Mitsubishi Power? Where was the technological breakthrough? And what is the next move? We will now introduce the many challenges that Tanimura had to overcome.

Commercialization of 30% hydrogen co-firing opens pivotal door to a hydrogen-powered society

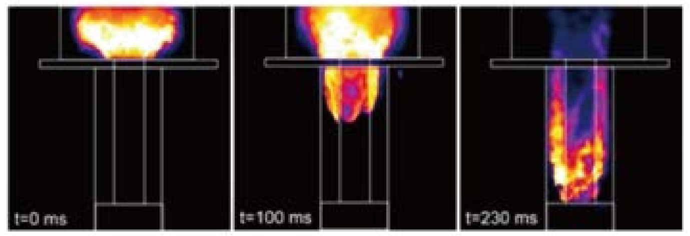
Easy-to-burn hydrogen and the struggle for safety

Hydrogen—atomic number 1—is the first element students learn about, and the lightest of all elements. Hydrogen is clean—when it burns, it produces only water. Conversely, it is a substance that is difficult to handle. It burns violently, so the idea of hydrogen is often accompanied by the fear of explosions. It is highly combustible, only needs energy equivalent to static electricity to ignite, and has a broad combustion range. These are difficulties that come with such a combustible element. Thus there are many challenges that engineers must overcome in order to realize a 30% hydrogen co-firing.

"We had already confirmed through in-house combustion tests at Mitsubishi Power that 20% hydrogen co-firing could be handled with existing gas turbines. June 2022, the validation test at the McDonough-Atkinson power plant, a large-frame plant in the United States, had been undertaken together with Georgia Power and the Electric Power Research Institute (EPRI). The success of the demonstration cemented our ability to achieve 20% hydrogen co-firing. At the same time, gas turbine designers gained considerable confidence in the prospect of 30% hydrogen co-firing, which had been a big challenge up until then. In the future, we need to further improve our understanding of combustion characteristics and further control the mixing with air and its behavior at that time." Even with excellent materials, it cannot be called technology unless it is controllable, durable, and capable of producing high-quality results on a continuous basis. Engineers are the ones who solve these problems.

Obstacles standing in the way of a 30% hydrogen co-firing are flashback, combustion pressure fluctuation, and NOx.

The unique characteristics of hydrogen and the mixing of hydrogen with air are the cause of flashbacks. Flashback is a phenomenon where the flames inside the combustor travel up the incoming fuel and leave the chamber. As hydrogen burns rapidly, flashback commonly occurs.



Source: University of Michigan at the 2014 University Turbine Systems Research Workshop

Burning of fuel anywhere but inside the combustor absolutely must be avoided. If flashback cannot be prevented, a hydrogen gas turbine cannot be successfully developed. Mitsubishi Power has completed the development of a 30% hydrogen co-firing combustion test, and is also having success with 50% hydrogen co-firing combustion.

Innovative technology to control combustion pressure fluctuation that can destroy a combustor

Combustion oscillation presents yet another obstacle. Temperatures inside the combustor reach 1,650°C, and it is known that imposing an extremely high thermal load on the combustor cylinder results in the generation of a very loud noise due to the cylinder's specified eigenvalue. This is the phenomenon known as combustion pressure fluctuation.

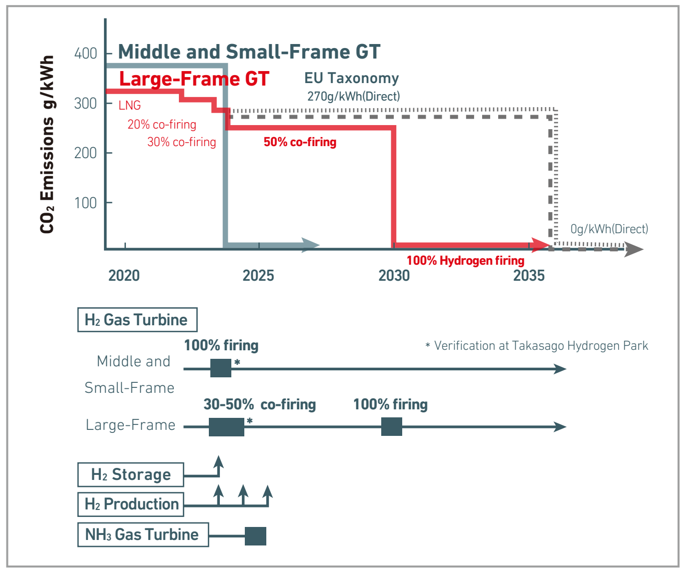
Put the oscillation from the loud sound together with the oscillation of the flames from combustion and they amplify, producing immense power. Also, given the particularly short interval when combusting hydrogen, the flame and the oscillation are more likely to match, increasing the likelihood of combustion pressure fluctuation.

So how loud is the sound?

"It's actually beyond loud. And once oscillation occurs, it will destroy the combustor in an instant," said Tanimura. "In order to avoid this, not only do we adjust the location and method of fuel burning, we continue to incorporate a number of innovations such as a sound absorption device."

While suppressing these phenomena and satisfying the necessary conditions, Tanimura and his team must also extend the service life of the facility by enhancing maintenance capabilities and the performance of the facility overall. Moreover, they must constantly search for the best materials, the optimum form, and the ideal combination—from the optimization of the shape and material of the fuel delivery nozzle and the combustor shape and material to the quality of the thermal insulation ceramic coating and adjustment of particle size. The repetition of this trial-and-error process brings them ever closer to the development of a CO_2-free power generation system and ultimately to the realization of a carbon-free society.

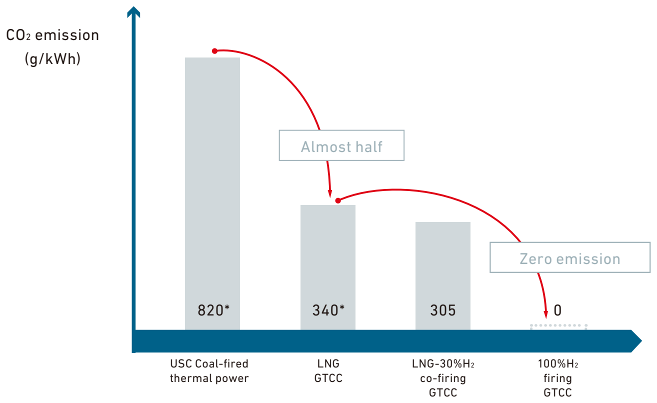
EU CO_2 Emission Regulations and H_2/NH_3 Gas Turbine Development Schedule



100% hydrogen power generation — achieving a complete hydrogen-fired gas turbine

The dream of a CO_2-free society—100% hydrogen thermal power generation
The values below are emissions per unit indicating CO_2 emission volume when generating 1kWh of electricity.

Standard coal-fired power generation: 863g-CO_2 /kWh
Ultra-supercritical (USC) coal-fired power generation: 820g-CO_2 /kWh
GTCC power generation: 340g-CO_2 /kWh
Hydrogen 30% mixed-combustion gas turbine: 305g-CO_2 /kWh



*Source: METI Web Site
(https://warp.da.ndl.go.jp/info:ndljp/pid/11402477/www.meti.go.jp/committee/kenkyukai/energy_environment/jisedai_karyoku/pdf/001_01_00.pdf)

Development Status of Hydrogen Combustion Technology
As Mitsubishi Power has successfully achieved mixed-combustion power generation at 30% hydrogen, Satoshi Tanimura's next objective is CO_2-free power generation, or 100% hydrogen power generation technology. However, with a high concentration of hydrogen, the risk of flashback rises, as does the concentration of NOx. A combustor for hydrogen-fired power generation demands technology that enables efficient mixing of hydrogen and air, and stable combustion.

"There are important conditions concerning the mixing of hydrogen and air as well," said Tanimura. "It is difficult to mix hydrogen and air in a large space, and using a rotational current and mixing them well requires a rather large space. This is what pushes the risk of flashback upward. In order to mix hydrogen and air in a short period of time, it has to be done in as confined a space as possible. The problem is that in this case the fuel nozzle jets and flame are in closer proximity, making flashback increasingly likely. We thought about how to deal with this, and it occurred to us that we needed to disperse the flame and reduce the fuel spray particle size. The key technology to this method is the fuel delivery nozzle. We upgraded the design, which normally features eight nozzles, and created the distributed lean burning, or multi-cluster combustor, which incorporates many nozzles. We reduced the size of the nozzle opening and injected air, and then sprayed hydrogen and mixed them. As this method does not employ a rotational current, mixing is possible on a smaller scale, and low-NOx combustion can be accomplished."

Hydrogen is an excellent fuel, but difficult to handle. Changing thinking in mixing methods by upgrading the nozzle, that's the kind of challenge engineers are wrestling with in the battlefield of development.

Creating a hydrogen fuel supply chain as a bridge to the future

A gas turbine alone is not enough to achieve 100% hydrogen-fired combustion technology: Stable sources of hydrogen must be secured; a supply source and way to transport the hydrogen to a pipe-less Japan must be considered; technology to extract hydrogen from the source material, and technology to collect and retain the CO_2 emitted during the process must be developed. Such hydrogen infrastructure must mature along with the development of hydrogen combustion technology.

"Simply increasing gas turbine efficiency does not necessarily lead to enhanced efficiency overall," said Tanimura, when taking a comprehensive perspective of the practical use of hydrogen. "In Japan, we simply assume we'll have hydrogen transported from abroad and use it in fuel-cell vehicles and industry. Meanwhile, there is a blueprint overseas from the hydrogen supply phase through to use, including the CCS scheme for processing CO_2 emitted during manufacturing. In Europe, with the advantage of their existing natural gas pipeline being well-developed, they are proceeding with hydrogen use while taking a holistic view through to supply, considering it part of the overall infrastructure," he said.

As engineers developing gas turbines, Tanimura and his colleagues have a clear understanding of the need for a comprehensive hydrogen usage plan. "In Japan, as we don't have a developed pipeline, naturally the transport of hydrogen constitutes a major issue," Tanimura said. "As of now, there are schemes for extracting hydrogen from renewable energy, petroleum, and natural gas. If renewable energy, regarded as unstable, is converted into hydrogen, the storage and transport of energy becomes possible, which is a huge benefit. Today, liquid hydrogen, methyl cyclohexane (MCH), and ammonia (NH_3) are regarded as the most promising hydrogen transport vehicles, and if demand increases further, we should see economies of scale emerge in transport as well. We have also begun the development of a 40,000kW class gas turbine system that uses 100% ammonia directly as fuel, and are currently conducting verification aiming for actual operation and commercialization from 2025 onwards." said Tanimura.

Gas turbine engineers factor in everything from production to costs. "We need a vision for hydrogen use, encompassing everything from creation of infrastructure to the various methods of use," Tanimura said. "For instance, a fuel mix of 20% hydrogen can be used without any technological improvements, and if we use a gas turbine with an output capacity of 500MW, and a turbine efficiency rating of 60%, it requires 1.4 tons of hydrogen per hour. This equals the volume of hydrogen used by around 100,000 to 130,000 fuel-cell vehicles. If we are going to proceed in earnest with hydrogen use, it's imperative that we quickly move to upgrade the hydrogen infrastructure, through measures such as proactively increasing the number of turbines using hydrogen. This is another reason hydrogen gas turbines will drive the forthcoming hydrogen society," he said.

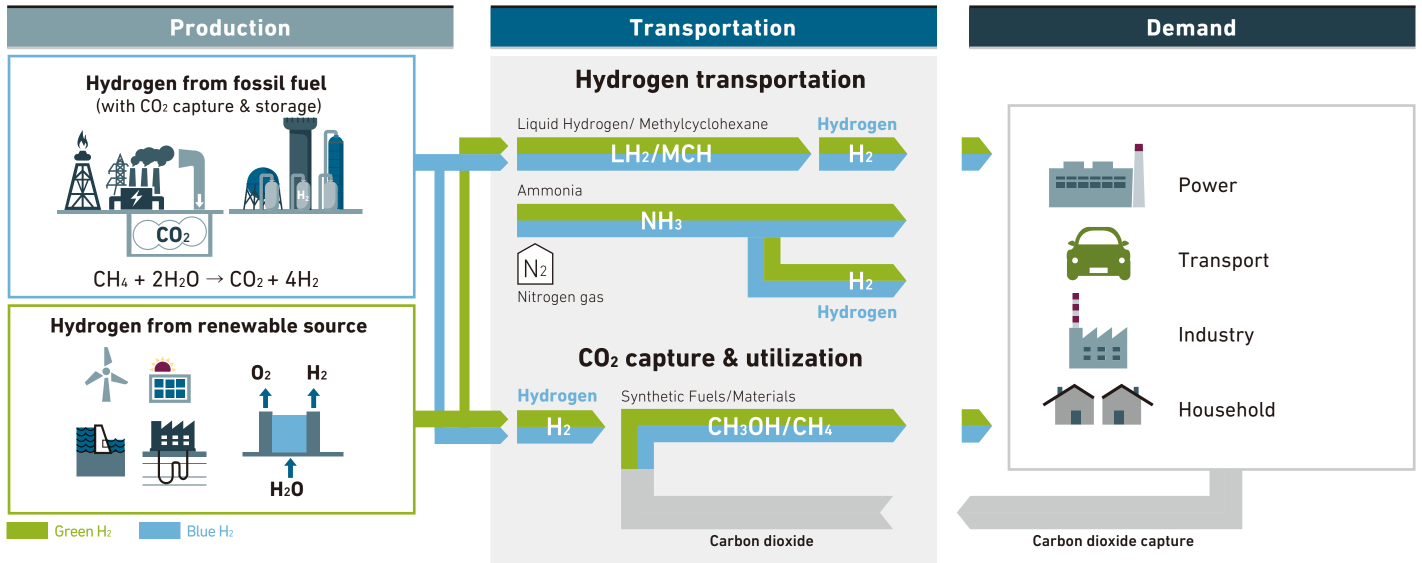
Human beings discovered fire and began using it purposefully about 500,000 years ago. And now with CO_2-free combustion in hand, we can set our sights on the energy that will support a carbon-neutral society.

Tanimura and his colleagues remain dedicated to achieving 100% hydrogen combustion technology by 2025.

Hydrogen Gas Turbine Combustor Development Status

	Combustion method	Low NOx technology	Performance	Hydrogen Content	Development/operation status
Type 1	Diffusion Combustion	N_2 Dilution Water/Steam Addition	Combustion Temperature 1200℃ - 1400℃ Class	100%	Development completed
Type 2	Premixed Combustion	Dry Low NOx	Combustion Temperature 1650℃ Class	30%	Development completed
				50%	Successful combustion test in 2022
Type 3	Multi-Cluster	Dry Low NOx	Combustion Temperature 1650℃ Class	100%	Development scheduled to be completed after 2025

Overview of Global Hydrogen Supply Chain



Satoshi Tanimura

Chief Engineer, GTCC Business Division,
Energy Systems,
Mitsubishi Heavy Industries, Ltd.

An expert with a focus in gas turbine combustor development, from basic design to combustion adjustment. Tanimura joined Mitsubishi Heavy Industries in 1986 and was assigned to the Gas Turbine Engineering Department, where he pursued the development of large-frame gas turbine combustors and also served as an engineer. He worked on the development of a 1300°C-class gas turbine combustor, and spearheaded efforts to develop low-NOx technology for the 1500°C-, 1600°C-, and 1650°C-class models.

TECHNICAL REVIEW

Mitsubishi Power is developing high efficiency power generation technologies. This includes the field of gas turbine power generation technologies where Mitsubishi Power has made possible hydrogen co-firing and is in the process of taking the technology to it's next phase. Additionally, the needs of the electricity market are diversifying, and we are proceeding with the development of technologies that will contribute to the energy transition. From here on, we will introduce large hydrogen gas turbines that are expected to play a large role in decarbonizing existing infrastructure, ammonia-fired gas turbines that can directly combust ammonia as fuel, hydrogen production technology, and their development and demonstration equipment through Mitsubishi Heavy Industries Technical Review.

- **Operation Status of 1650°C Class M501JAC Gas Turbine at T-point 2 Power Plant Demonstration Facility**
  Verification test results and operation status of the 1650°C class M501JAC gas turbine, which uses an enhanced air-cooled combustor system, ultra-thick film TBC, and high-pressure ratio compressor as core technologies.
- **Hydrogen/Ammonia-fired Gas Turbine Initiatives for Carbon Neutrality**
  The development status and future demonstration schedule of hydrogen and ammonia-fired gas turbine combustors and combustion technology, which continues to work towards achieving carbon neutrality as early as possible.
- **"Hydrogen Park Takasago" and "Carbon Neutral Park Nagasaki" Initiative to Create Decarbonized World**
  The development status of hydrogen-fired gas turbines at Takasago Hydrogen Park, which began partial operation in 2023, and decarbonization technology initiatives including hydrogen production underway at Nagasaki Carbon Neutral Park.

Source: Mitsubishi Heavy Industries Technical Review
Authors and affiliation names shown here are true and accurate at the time of writing

Mitsubishi Heavy Industries Technical Review Vol. 58 No. 3 (September 2021)

Operation Status of 1650°C Class M501JAC Gas Turbine at T-point 2 Power Plant Demonstration Facility

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Renewable energy has become more widespread in recent years. At the same time, the importance of gas turbine combined cycle (GTCC) power generation has also been on the rise because of the power supply instability of renewable energy. For higher GTCC efficiency, a higher temperature of the gas turbine is important. Mitsubishi Power, Ltd. (Mitsubishi Power) developed the high-efficiency M501J gas turbine, which attained the world's first turbine inlet temperature of 1600°C, utilizing the development results from the "1700°C class Ultrahigh-Temperature Gas Turbine Component Technology Development" national project in which it has participated since 2004. We have since steadily accumulated operating results. At T-point 2 in January 2020, we started test operation of the next-generation 1650°C class JAC series gas turbine, which is based on the proven J series and uses an enhanced air-cooled system for cooling the combustor, a thicker TBC (thermal barrier coating) and a compressor with a high pressure ratio as its core technologies, all of which have been validated as individual elements at the T-point demonstration facility. The final confirmation of the integrity of equipment reliability, performance, etc., was completed and commercial operation started in July 2020. This report presents the verification results of the test operation and the operation status thereafter.

1. Introduction

Since it has recently become very important to reduce CO2 emissions, power supply by renewable energy sources such as wind power generation and solar photovoltaic power generation has been planned and carried out. However, such renewable energy sources are unstable and natural fluctuations are unavoidable and present concerns such as sudden frequency and load fluctuations in the power system. Against this background, GTCC power generation, which is more efficient and more operable than conventional thermal power generation, is becoming more important in terms of global environmental conservation and a stable energy supply. For higher GTCC efficiency, a higher temperature of the gas turbine plays an important role. We developed the M701D, a 1150°C class large-capacity gas turbine, in the 1980s. This was followed by the M501F, which had a turbine inlet temperature of 1350°C and the M501G, which employed a steam-cooled combustor and had a turbine inlet temperature of 1500°C (**Figure 1**). Through these developments, we have verified the high plant thermal efficiency and reliability, as well as low emissions. From 2004, we participated in the "1700°C class Ultrahigh-Temperature Gas Turbine Component Technology Development" national project to conduct research and development of the latest technology necessary for higher temperature and efficiency and utilized the results of these efforts to develop the M501J, which attained the world's first turbine inlet temperature of 1600°C. Verification operation of the M501J GTCC started in 2011 at the gas turbine combined cycle power plant demonstration facility (T-point) located in Mitsubishi Power Takasago Works and operating results have been steadily accumulated.

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The J series gas turbine adopts a steam-cooled system for cooling the combustor, but if an air-cooled system can be used while maintaining the high turbine inlet temperature, further improvement in the efficiency and operability of GTCC is expected. Therefore, we worked on the development of next-generation GTCC that realizes air cooling of high-temperature gas turbines and devised the enhanced air-cooled system that is one of its core technologies. In the spring of 2015, we completed the validation test of the entire system at T-point and since then the system has been in operation for more than 10,000 hours. This core technology is applied to the next-generation high-efficiency JAC (J-Air-Cooled) series gas turbine, which has achieved a high turbine inlet temperature of 1650°C. We have been proceeding with the construction of the second gas turbine combined cycle power plant demonstration facility (hereinafter referred to as T-point 2) located in Mitsubishi Power Takasago Works for long-term actual-equipment validation of the JAC series gas turbine. T-point 2, which is state-of-the-art GTCC equipment with an output of 566 MW that combines the 1650°C next-generation JAC high-efficiency gas turbine and the newly-developed high-efficiency steam turbine, has been in test operation since January 2020 and achieved a combined rated output of 566 MW on April 2. We then carried out various tests and adjustments necessary to operate T-point 2 as a power plant, completed all the functional confirmations and started commercial operation on July 1. Due to the adoption of the JAC series gas turbine, the power generation efficiency of the GTCC reached 64%. During test operation, in order to verify the underlying technology, we carried out thousands of temporary large-scale measurements in addition to those provided by regular measurement instruments and monitored and evaluated them online. This report presents the development concept of the state-of-the-art high-efficiency JAC series gas turbine, the verification results obtained at the T-point 2 demonstration facility and the operation status including commercial operation for about one year thereafter.

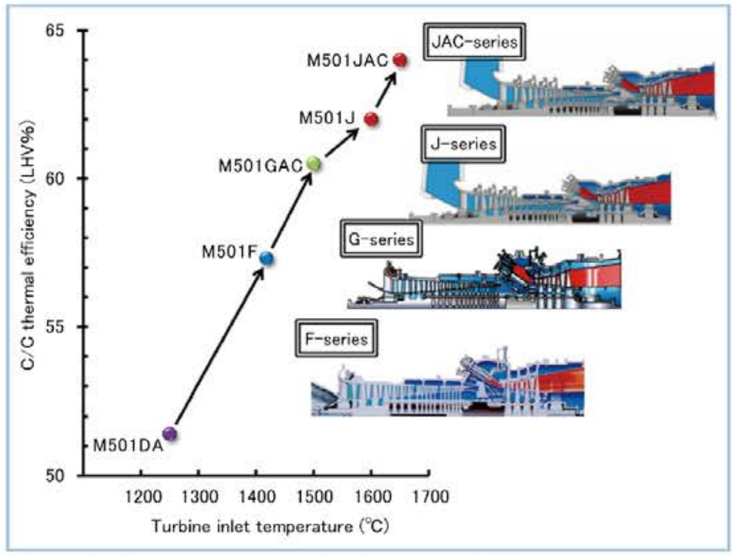

Figure 1 Developmental trend of large gas turbine models

2. Development concept of 1650°C class M501JAC gas turbine

We proceeded with the development of the next-generation 1650°C class JAC series gas turbine in order to further improve the efficiency and operability by applying to the proven M501J gas turbine the following validated component technologies: (1) an enhanced air-cooled system for cooling the combustor, (2) a thicker TBC and (3) a compressor with a high pressure ratio.

The basic concept of this gas turbine is as follows (**Figure 2** and **Figure 3**). Validation of these individual component technologies was completed at the T-point demonstration facility and they were then applied to the 1650°C class JAC series gas turbine (**Table 1**).

(1) Adopting an enhanced air-cooled system to improve operability and increase the turbine inlet temperature in comparison to that of the J series.

(2) Adopting a thicker TBC developed based on the technology resulting from the national project to achieve both high performance and reliability despite the increased turbine inlet temperature.

(3) Adopting a compressor with a high pressure ratio design equivalent to the M501H (validated from 1999 to 2000, hereinafter referred to as the H series) to suppress the increase in the exhaust gas temperature at the gas turbine outlet.

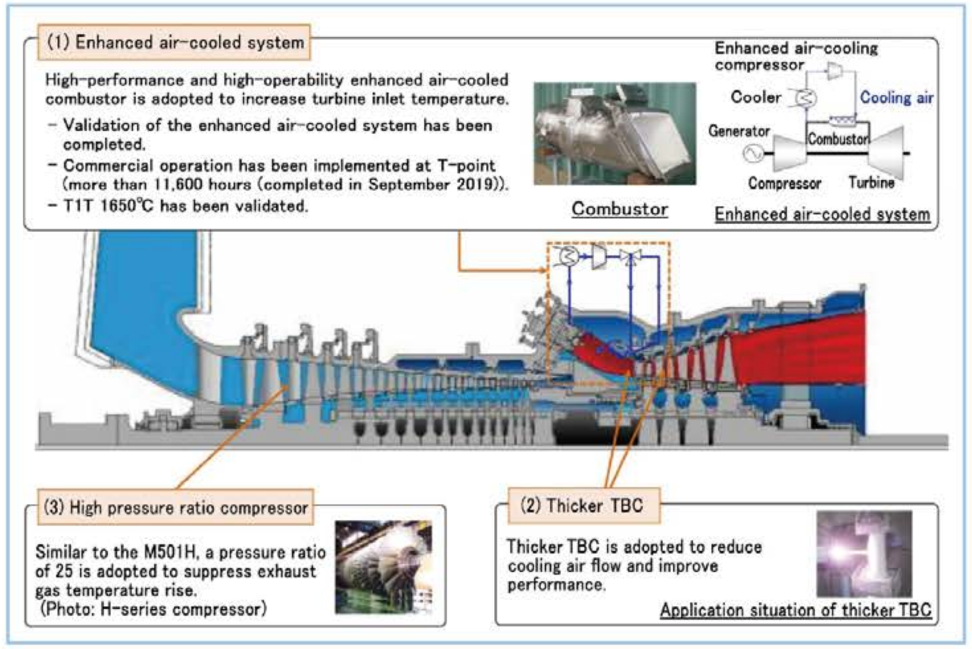

Figure 2 Development concept of 1650°C class JAC gas turbine

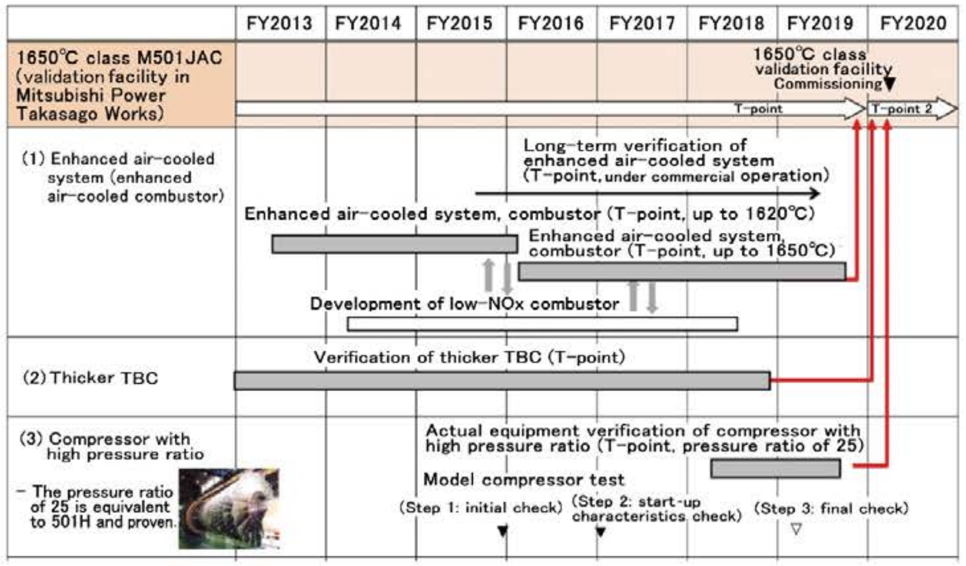

Figure 3 Application flow of component technology to 1650°C class JAC gas turbine

Table 1 Comparison of gas turbine performance (ISO, standard conditions)

	M501J	M501JAC
Frequency (Hz)	60	60
Pressure ratio (-)	23	25
Gas turbine output (MW)	330	435
Gas turbine efficiency (%-LHV)	42	44
Combined cycle output (MW)	484	630
Combined cycle efficiency (%-LHV)	62	>64

3. Verification results and operation status of the 1650°C class M501JAC gas turbine at T-point 2

T-point 2 is a state-of-the-art GTCC facility with an output of 566 MW that combines a 1650°C next-generation high-efficiency JAC series gas turbine and a newly-developed high-efficiency steam turbine. The M501JAC gas turbine was shipped and installed in the spring of 2019 and test operation at T-point 2 commenced in January 2020. In this test operation, first the gas turbine alone was operated and reached its rated load after 10 starts from the first ignition. After steam ventilation, the operability confirmation test was carried out by Combined Cycle (CC) operation and commercial operation began on July 1 (**Figure 4** and **Figure 5**). In test operation, we constantly monitored the start-up acceleration, no-load rated speed and state quantity during partial-load and rated-load operation of the gas turbine in order to make a final confirmation of the reliability, actual performance, exhaust gas emissions, etc., of the equipment. Next, functional tests and special tests required for actual commercial plants were completed.

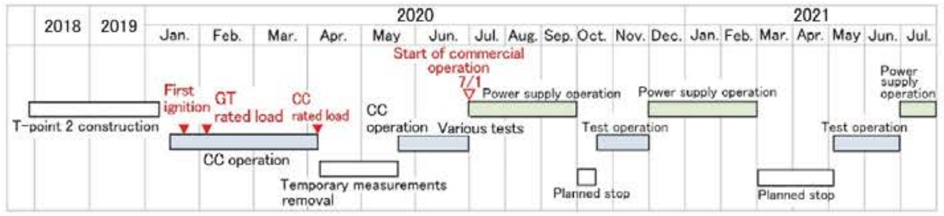

Figure 4 Test operation schedule at T-point 2

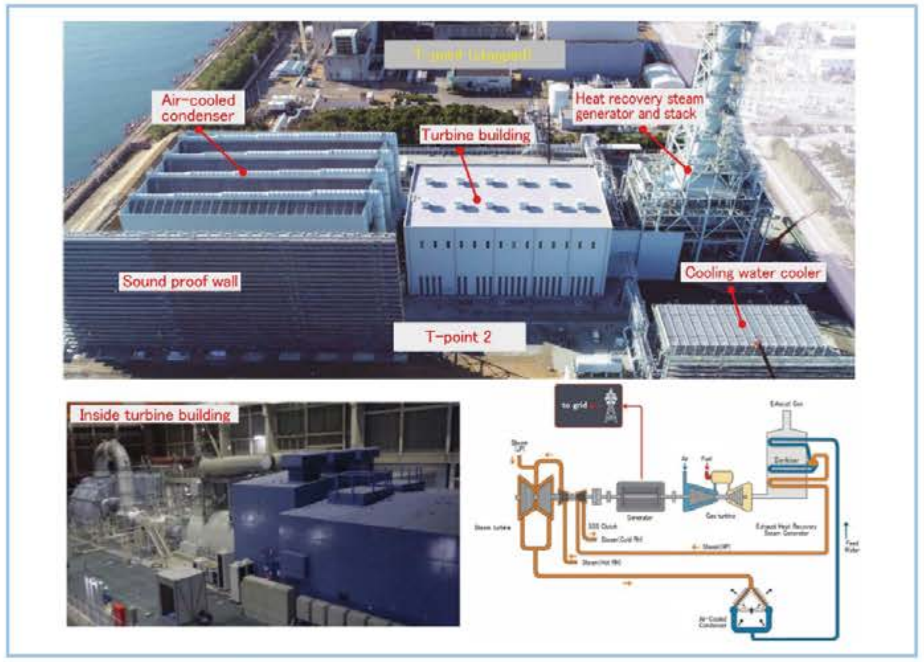

Figure 5 Overview of T-point 2 combined cycle plan

During test operation, more than 2,800 temporary large-scale measurements were conducted to evaluate the integrity in order to verify the technologies that are the basis of the JAC series gas turbine. For the rotating parts, roughly 100 large-scale telemetric measurements were carried out to confirm the metal temperature and vibration stress integrity of the compressor rotors and turbine blades. This chapter presents the final confirmation results of the integrity of each component (**Figure 6**), as well as the status following the commercial operation verification test run over approximately one year after the final integrity confirmation observed in the inspection during a planned stop in March 2021.

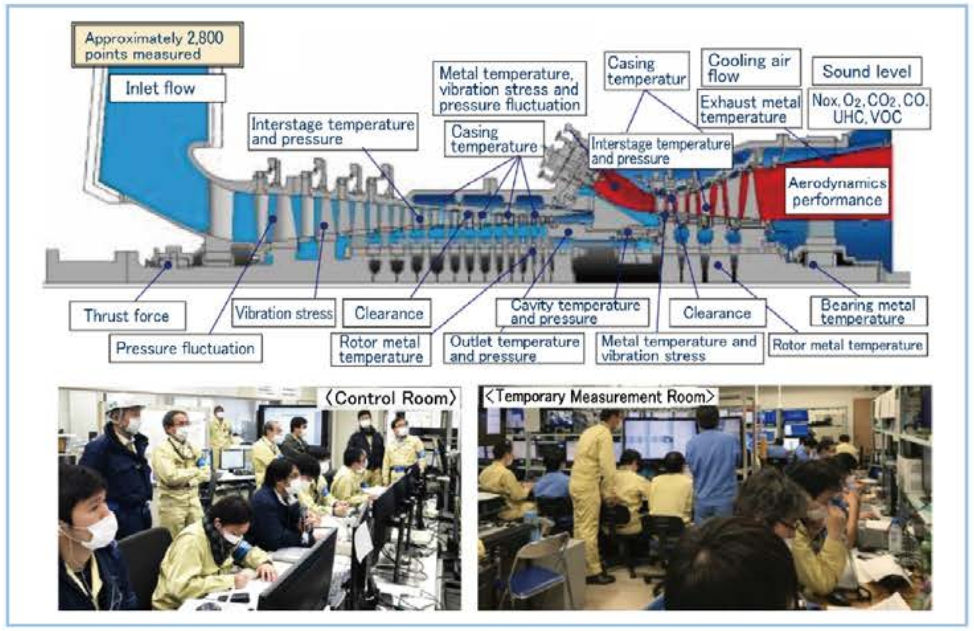

Figure 6 Implementation status of test operation and temporary measurements

3.1 Enhanced air-cooled combustor and enhanced air-cooled system

The enhanced air-cooled system had already been validated at the T-point demonstration facility, including its ability to follow transient changes. In addition, the metal temperature of the enhanced air-cooled combustor was measured in this test operation and its cooling performance in the actual equipment was ultimately validated. As a result, it was confirmed that the combustion casing metal temperature distribution was lower than the design allowance value, so there were no problems in terms of cooling performance (**Figure 7**). It was also confirmed that there were no particular problems with the combustion vibration characteristics and exhaust gas emissions and stable operation was possible under partial-load to rated-load conditions.

The JAC series gas turbine uses a system that enables clearance control during under-load operation based on the enhanced air-cooled system. This system uses two cooling air supply methods: one causes cooling air to bypass the turbine blade ring and introduces it directly into the combustor and the other causes cooling air to pass through the turbine blade ring in advance to supply it to maximize the performance by reducing the turbine clearance during load operation. These two systems can be switched by the switching valve (three-way valve) even during load operation. The former can handle operation with large load fluctuations by opening the clearance (Flexible Mode). On the other hand, the latter can close the clearance during load-hold operation and maximize the performance of steady operation (Performance Mode). **Figure 8** shows the behavior of the clearance when the three-way valve is switched during load operation. It was ultimately confirmed that this system can improve operability more than before while maximizing performance.

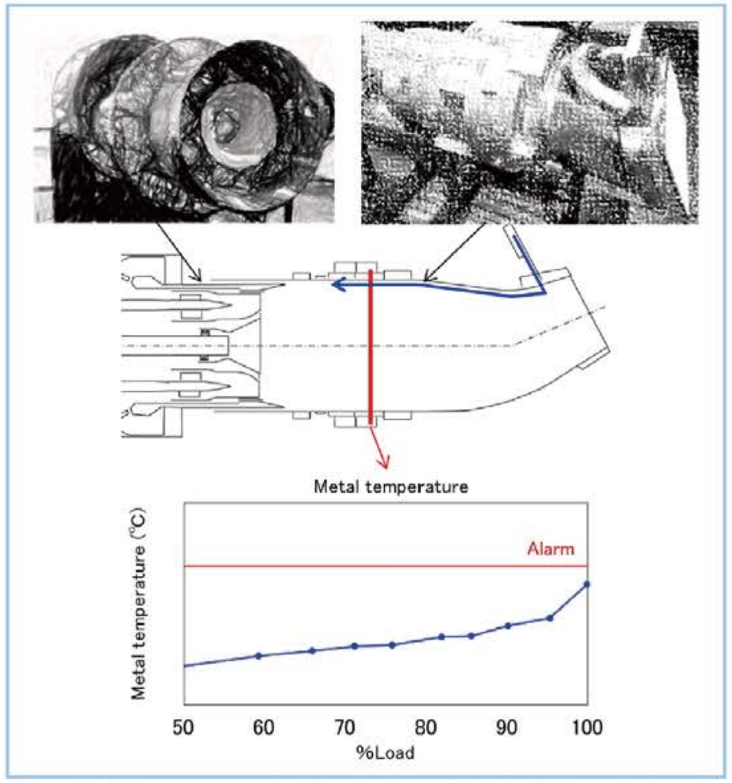

Figure 7 Measurement results of enhanced air-cooled combustor metal temperature

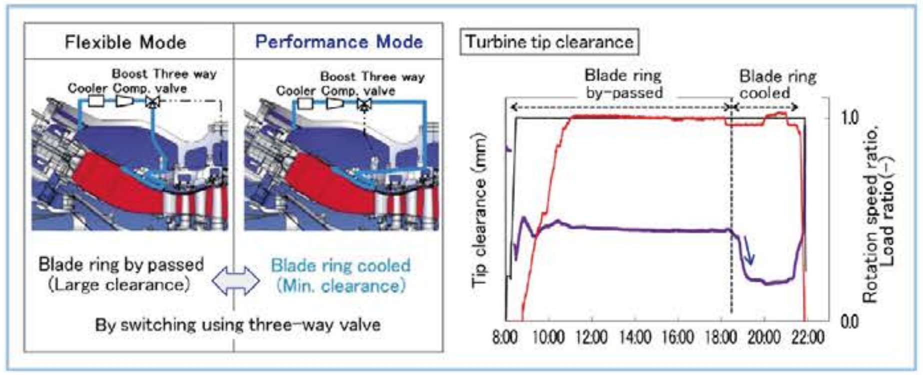

Figure 8 Turbine clearance control using enhanced air-cooled system

3.2 Turbine blade metal temperature

The turbine inlet temperature of the 1650°C class JAC series gas turbine can become 50°C higher than that of the J series and adopts a thicker TBC to achieve both high performance and reliability. As mentioned above, the integrity of the thicker TBC has been verified and confirmed at T-point over the long term. **Figure 9** shows the specially-measured metal temperature distribution of the JAC series turbine row 1 vane to which the TBC is applied in order to optimize the cooling design. It was confirmed that although the turbine row 1 vane was subjected to the strictest heat load and its cooling structure was complicated, there were no local high temperature parts, all parts were below the design allowance temperature and the integrity was maintained under the condition of an inlet gas temperature of 1650°C. The integrity was also confirmed in the inspection after operation.

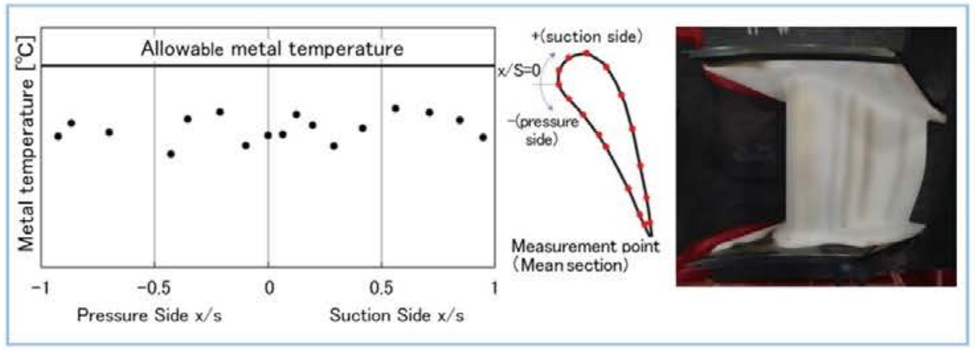

Figure 9 Metal temperature distribution measurement results of turbine row 1 vane and inspection results after operation

For the turbine row 1 blade, in addition to confirmation of the blade surface metal temperature and vibration stress using telemetric measurements, pyrometric measurement, which has been introduced at T-point, was carried out. The pyrometer was inserted into the gas path from the standby position through the insertion hole provided in the combustor casing and the turbine row 1 vane to confirm the integrity of the blade surface temperature distribution around the leading edge of the blade surface, which was subjected to a particularly high heat load. The integrity was also confirmed in the inspection after operation (**Figure 10**).

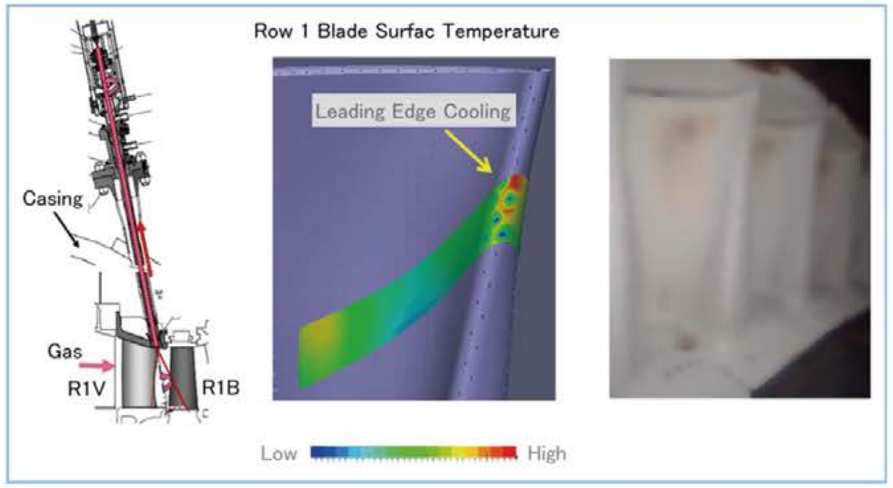

Figure 10 Surface temperature distribution measurement results of turbine row 1 blade and inspection results after operation

3.3 High pressure ratio compressor

The compressor of the 1650°C class JAC series gas turbine has a pressure ratio that was increased from 23 to 25. However, since a high pressure ratio compressor has a design in which the outlet flow path area is relatively narrow, there is a concern that the flow rate will decrease and the rotating stall will relatively deteriorate during startup with a low pressure ratio. As mentioned above, an H series compressor with a similar pressure ratio of 25 was validated, as was a compressor with a pressure rate of 25 based on the J series in May 2018 at T-point. Detailed temporary measurements were also carried out for the JAC series and it was ultimately confirmed that the starting characteristics, blade vibration stress and aerodynamic performance were favorable (**Figure 11**).

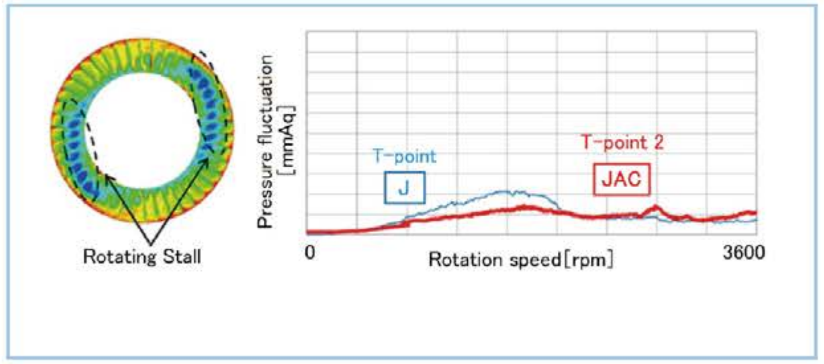

Figure 11 Verification results of JAC gas turbine high pressure ratio compressor

3.4 Status of gas turbine after one year of operation

Commercial operation commenced on July 1, following the test operation that started in January 2020. It has been confirmed that the components are sound after about one year of power supply operation and verification test operation, as a result of inspection of various parts including the compressor, combustor, turbine and inlet/exhaust systems and thus there is no problem in terms of the long-term reliability (**Figure 12**). After the completion of the verification test operation in the spring of 2021, power supply operation will be continued again and operational hours and the number of starts will be further accumulated to continuously confirm the long-term reliability.

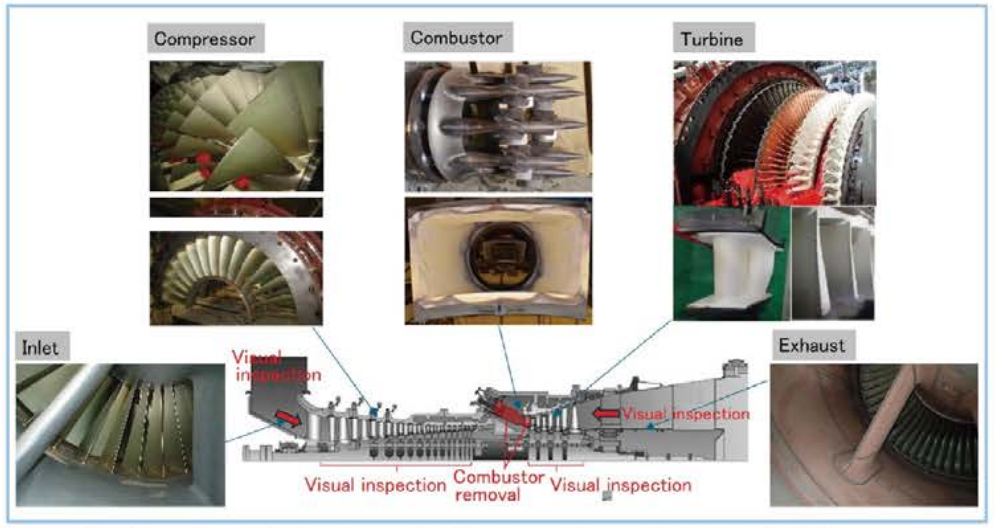

Figure 12 Overview of JAC series gas turbine inspection results in March 2021

3.5 Future development of JAC series gas turbine

As shown below, the construction and operation of customers' commercial plants using JAC series gas turbines that have been verified at our power plant demonstration facility T-point 2 and confirmed to offer long-term reliability as described above have commenced, striving steadily for realizing a more stable global energy supply. 60 Hz M501JAC gas turbines have been shipped to commercial plants in North America and other countries one after another since September 2020 and the local installation work is being carried out (**Figure 13**). The first of the eight 50 Hz M701JAC gas turbines for Thailand started operation on March 31, 2021, as scheduled despite the COVID-19 disaster. The construction work of the remaining units is progressing toward the start of operation of all turbines in 2024 (**Figure 14**).

Figure 13　Shipping of commercial 60 Hz M501JAC gas turbine

Figure 14　Operation start of commercial 50 Hz M701JAC gas turbine

4. Conclusion

For higher GTCC efficiency, a higher temperature of the gas turbine plays an important role. Mitsubishi Power has participated in the "1700°C class Ultrahigh-Temperature Gas Turbine Component Technology Development" national project since 2004. We utilized the results of these efforts to develop the high-efficiency M501J gas turbine, which attained the world's first turbine inlet temperature of 1600°C and we have since steadily accumulated operating results. In order to further improve the efficiency and operability of GTCC, we developed the next-generation 1650°C class JAC series gas turbine, which is based on the proven J series and uses an enhanced air-cooled system for cooling the combustor, a thicker TBC and a compressor with a high pressure ratio as its core technologies and completed the validation of the individual elements at the T-point demonstration facility.

We had been proceeding with construction of the second gas turbine combined cycle power plant demonstration facility (T-point 2) at our Takasago Works for long-term verification of the JAC series gas turbine. We started its test operation in January 2020, carried out as many as about 2,800 temporary large-scale measurements and made final confirmation of the integrity of the JAC series components, such as the reliability and performance during 1650°C operation. At T-point 2, the combined rated output reached 566 MW on April 2 and all the functional confirmations as a power generation facility were completed. Commercial operation commenced on July 1. Since then, both operational hours and number of starts continue to be accumulated in the operation according to the supply and demand requirements. It has been confirmed that the components after about one year of operation are sound and that they offer long-term high reliability.

Verified M501JAC gas turbines have been shipped to commercial power plants in North America, etc., one after another and the 50 Hz M701JAC gas turbine also started operation in Thailand in March 2021 as scheduled despite the COVID-19 disaster. Hydrogen co-firing is planned for a future GTCC power generation project in Utah in the United States. By incorporating our proprietary combustor technology, we aim to start the operation of the JAC series gas turbine with a hydrogen co-firing rate of 30% and to realize 100% hydrogen-fired operation in the future.

The long-term verification operation at T-point 2 is carried out from our RMC (remote monitoring center). We aim to improve the reliability of not only major equipment such as gas turbines, but also the entire plant including auxiliary equipment, validate various applications

included in the "TOMONI" digital solution, such as shortening the startup time and automatically optimizing operating parameters and realize autonomous operation in the future.

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Hydrogen/Ammonia-fired Gas Turbine Initiatives for Carbon Neutrality

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Toward the goal of achieving carbon neutrality by 2050, Mitsubishi Heavy Industries, Ltd. (MHI) is expanding its line-up of carbon-free power generation systems. With regard to gas turbines using hydrogen, the development of a gas turbine combustor that can operate on a blend of 30 vol% hydrogen and natural gas has been completed. Combustion tests have been conducted on a combustor with hydrogen dry single-firing and the development is in progress toward practical application. Furthermore, for gas turbines using ammonia, the combustion system is currently in development to enable 100% ammonia to be fired in small-to-middle gas turbines. These power generation systems will be verified one by one through actual-unit demonstration testing by 2025 with the aim of realizing their early commercialization.

1. Introduction

Achieving net-zero emissions of carbon dioxide (CO_2) around 2050 is becoming the world's common goal. Countries do not remain in the stage of setting ambitious targets. They have now entered the stage of executing action plans to fulfil their targets. In Japan, the energy sector is attributable to more than 80% of the greenhouse gas emissions. While electricity is mainly converted from primary energy, the Sixth Strategic Energy Plan has set the energy sector to work toward the goal of hydrogen and ammonia serving as a power source accounting for 1% of the electricity generated in 2030[(1)].

MHI has declared "MISSION NET ZERO" and is promoting thereunder decarbonization from the perspectives of both energy transition and the smartification of social infrastructure to achieve carbon neutrality. As shown in **Figure 1**, decarbonization through energy transition focuses on "reducing," "capturing" and "eliminating" CO_2 emissions from thermal power plants. Specifically, it includes (1) CO_2 reduction by replacing the coal-fired systems with the low-carbon and high-efficiency gas-fired systems (GTCC : Gas Turbine Combined Cycles) and promoting the application of hydrogen co-firing in gas turbines and ammonia or biomass co-firing in coal-fired systems, (2) promotion of utilizing Carbon dioxide Capture, Utilization and Storage (CCUS) by optimizing the entire power plant that is equipped with GTCC and CO_2 capture equipment, and (3) promotion of adapting gas turbines to use new fuels with a view to hydrogen (H_2) or ammonia (NH_3) single-firing, neither of which emits CO_2. The development under the sponsorship of New Energy and Industrial Technology Development Organization (NEDO) is moving forward regarding the hydrogen co-fired combustor for large gas turbines in which 30 vol% hydrogen is blended with natural gas, and the combustor with hydrogen dry single-firing. The development of a GTCC system using ammonia has also started. As shown in **Table 1**, the line-up of carbon-free gas turbine systems is expanding. MHI aims to achieve decarbonization through energy transition with these power generation systems by 2030.

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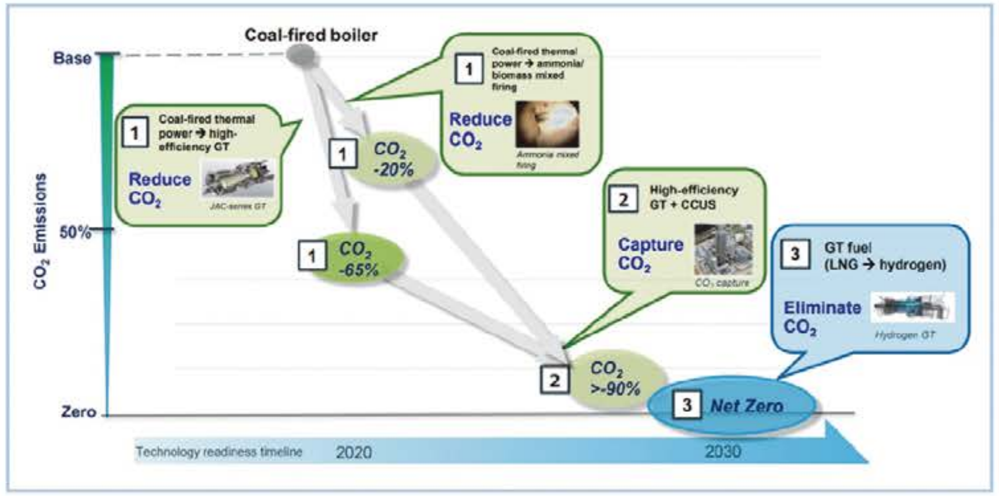


Figure 1 MHI's Initiatives for decarbonization of thermal power generation infrastructure

Table 1 MHI product line-up of carbon-free gas turbine systems

Equipment		Summary	Availability
Hydrogen gas turbine	30% co-firing	A blend of 30 vol% hydrogen and natural gas is fed into a natural gas-fired, low-NOx combustor. Applicable without any changes in existing gas turbines or with minimum retrofitting.	Development completed in 2018
	Single-firing	A multi-cluster combustor for hydrogen single-firing is in development.	Development to be completed in: 2025 for large frame GT 2023 for small frame GT
Ammonia cracking GTCC		Waste heat from a gas turbine is used to decompose ammonia into H_2 and N_2. The former is then used as a fuel for the gas turbine. It is possible to co-fire natural gas and the product gases from ammonia decomposition (H_2 and N_2), or fire only these product gases. Suitable for the application to large units with high-temperature waste heat.	In development
Ammonia direct-fired GTCC		The system remains simple, because no cracking equipment is needed. Ammonia combustion involves generating NOx in large quantities, requiring a dedicated combustor to be developed. NOx removal equipment for exhaust gas is also essential.	Development to be completed in 2024 before aiming for verification

Hydrogen is considered the most effective carbon-free fuel in replacing or supplementing fossil fuels. This is because hydrogen has a high potential for converting existing fossil fuel equipment and systems into carbon-free alternatives while keeping them operating. In the value chain including hydrogen production, transportation, storage and utilization, large-capacity and high-efficiency hydrogen-fired gas turbines give the following advantages for those who aspire to achieve carbon neutrality: (1) low-carbonization or decarbonization of existing gas turbine facilities is possible with minimum retrofitting and the lowest investment costs, (2) hydrogen is expected to become cheaper as a result of growing hydrogen demand on a large scale, because a single power generation facility with a large hydrogen-fired gas turbine (hydrogen single-firing) at an output of 500 MW class requires hydrogen equivalent to 2 million fuel cell vehicles, (3) not only liquid hydrogen but also various types of hydrogen carriers such as methylcyclohexane and ammonia can be handled, and (4) the high start-up and load-changing (ramp rate) capabilities of gas turbines, which can follow sudden variable renewable energy output (influenced by weather and seasons), can flexibly balance the gap between the electricity demand and the supply capacity of renewable energy.

However, there are some difficulties with hydrogen, namely, mass transportation and storage. Japan largely depends on imported energy. If a hydrogen society is to be realized in Japan, the use of ammonia is considered to be another effective means. Among the carriers for hydrogen transportation and storage, ammonia has a higher volumetric hydrogen density than liquid hydrogen or methylcyclohexane, therefore enabling efficient hydrogen transportation and storage. Ammonia is also advantageous in terms of handling, as the existing transportation/storage infrastructure can be used for it. Furthermore, it is possible to directly burn ammonia as a carbon-free fuel. If GTCCs are able to be introduced ammonia at an early stage, it will become a promising carbon-free fuel of the future.

Focusing on hydrogen or ammonia-fired gas turbines among MHI's projects for carbon neutrality, this report presents the development status of the main items (i.e., gas turbine combustors and combustion technologies) and the schedule for their validation.

2. Development status of hydrogen or ammonia-fired gas turbines

2.1 Challenges of combustion hydrogen and ammonia

The conversion of a gas turbine from natural gas firing to hydrogen/ammonia firing becomes possible by adding a new combustor and fuel supply system, and is therefore characterized by the minimum retrofitting as the main body can continue to be in use. Therefore, the development of gas turbine combustor and combustion technology is the key to success in developing a hydrogen or ammonia-fired gas turbine.

Figure 2 shows the combustion types and features of MHI gas turbine combustors. In diffusion combustion, fuel and combustion air are injected separately into the combustor. Compared with the premixed type, there are more localized rises in the flame temperature within the combustor, and nitrogen oxides (NOx) emissions are increased. It is therefore necessary to take measures by injecting steam/water and reduce NOx emissions. On the other hand, the stable combustion range is relatively wide, and the tolerance for fuel property fluctuations is large.

In premixed combustion, fuel and air are mixed in advance before being fed into the combustor. Compared with the diffusion type, the pre-mixed system can reduce local rises of flame temperature in the combustor. NOx reduction measures such as steam/water injection are therefore unnecessary, and there is no decline in the cycle efficiency. Because of its capability of simultaneously achieving low NOx and CO_2 reduction (high efficiency), the premixed type is used as the base for the development of hydrogen/ammonia-fired combustor. However, the stable combustion range is narrow, there are risks of combustion instability and flashback, and unburned fuel tends to be discharged.

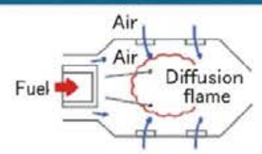
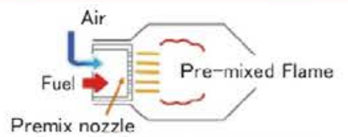
Type	Diffusion combustion	Premixed combustion
Configuration		
Combustion Characteristics	· Fuel and Air are injected individually. · High gas temperature (High NOx) · Stable flame	· Fuel and Air are mixed before combustion. · Low gas temperature (Low NOx) · Unstable flame (Risks of combustion instability and flash back)
Specification	· Wide allowable range of fuel · Simple fuel supply system · Low efficiency due to steam and N2 injection	· Establishing both low NOx abd high efficiency · Complicated fuel supply system
Combustor	Diffusion combustor 	Multi-nozzle combustor  Multi-cluster combustor 

Figure 2 Diffusion and premixed combustion systems

Figure 3 compares natural gas which contains methane (CH_4) as the main component and is the most common fuel used in gas turbines, hydrogen and ammonia in terms of their lower heating values and burning velocity. Hydrogen has a higher lower-heating value and a higher burning velocity than methane; hydrogen burns about seven times quicker. When natural gas and hydrogen are co-fired in a premixed combustor or 100% hydrogen single-fired, the flame position moves further upstream than when only natural gas is fired. This results in the high flame temperature combustion occurring before fuel is sufficiently mixed with air, which leads to an increase in NOx production. There is also an increased risk of flashback by which the flame traveling upstream of the combustor burns out the areas along the route. Therefore, the combustor of hydrogen-fired gas turbine needs to be improved to achieve low NOx emissions and stable combustion, particularly focusing on preventing flashback.

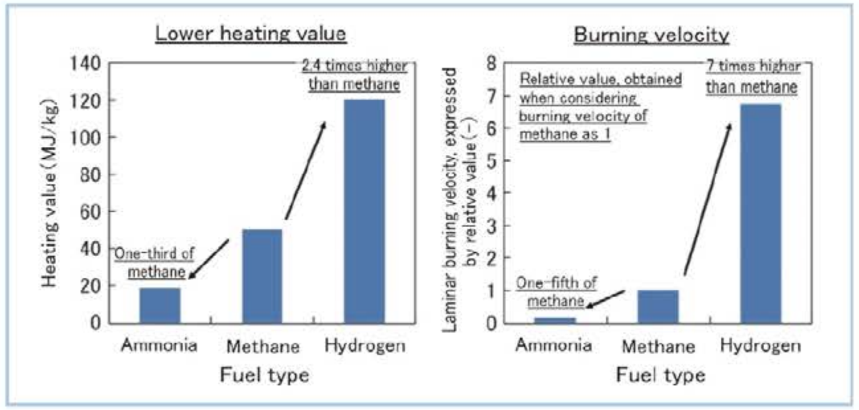


Figure 3 Comparison of methane, hydrogen and ammonia in terms of lower heating values and burning velocity

On the other hand, ammonia has a lower heating value that is about one-third lower than methane, and the burning velocity is lower nearly one-fifth. As the combustion tends to be unstable, the challenge lies in keeping the flame stable. As shown in **Table 2**, fuel NOx is produced in large quantities in the process of combustion, because ammonia contains nitrogen (N). The produced amount is larger by an order of magnitude than that of thermal NOx produced by the combustion of natural gas. As the mechanism of fuel NOx generation is different, an unconventional approach is needed to reduce such NOx.

Hydrogen and ammonia have thus dissimilar characteristics. The following sections describe the status in the development of MHI gas turbine combustors and combustion technologies, with which hydrogen or ammonia can be handled.

Table 2 NOx generation mechanisms

Fuel	NOx generation mechanism	Amount of NOx generated (with no measures taken)
Conventional fuel (e.g., LNG)	Nitrogen oxides are formed, as a result of nitrogen in the air being oxidized in the high-temperature combustion field (thermal NOx) N_2 (air) + O_2 → NOx *NOx is generated by the thermal decomposition of N_2	On a scale of several hundred ppm
Ammonia (NH_3)	Nitrogen oxides are formed, as a result of oxidation of the fuel (fuel NOx) NH_3 (fuel) + O_2 → N_2 + H_2O + NOx *NOx is generated by the chemical reaction of fuel	On a scale of several thousand ppm

2.2 Development of hydrogen-fired combustors

(1) Dry Low NOx (DLN) multi-nozzle combustor for hydrogen co-firing

A new hydrogen co-fired combustor was developed based on the conventional DLN multi-nozzle combustor design, with the aim of preventing the risk of flashback from increasing due to hydrogen co-firing. **Figure 4** gives an outline. This premixed multi-nozzle combustor has eight premixed fuel nozzles and one pilot flame fuel nozzle in the center to stabilize combustion. Each nozzle is equipped with a swirler. The air passing through the swirler is mixed more uniformly with the fuel injected through the nozzle. There is a low flow velocity zone, which is located in the center of the swirling flow (hereafter referred to as the vortex core). It is believed that flashback occurs when the flame travels upstream through this vortex core. In the new combustor, therefore, air is injected from the tip of the nozzle to increase the flow velocity in the vortex core, thereby compensating for the low flow velocity therein to prevent flashback.

A single unit of this combustor was used to conduct a combustion test under the operating conditions (i.e., pressure and temperature) equivalent to a large gas turbine with the turbine inlet temperature of the 1,600°C class (hereafter referred to as the actual-pressure test) (Figure 4, left below). No flashback occurred at the rated load, while the hydrogen co-firing ratio with natural gas was increased up to 30 vol%. The combustion was stable without a marked rise in combustion instability. NOx emissions were below the permissible level. These results support the feasibility of operation in actual units.

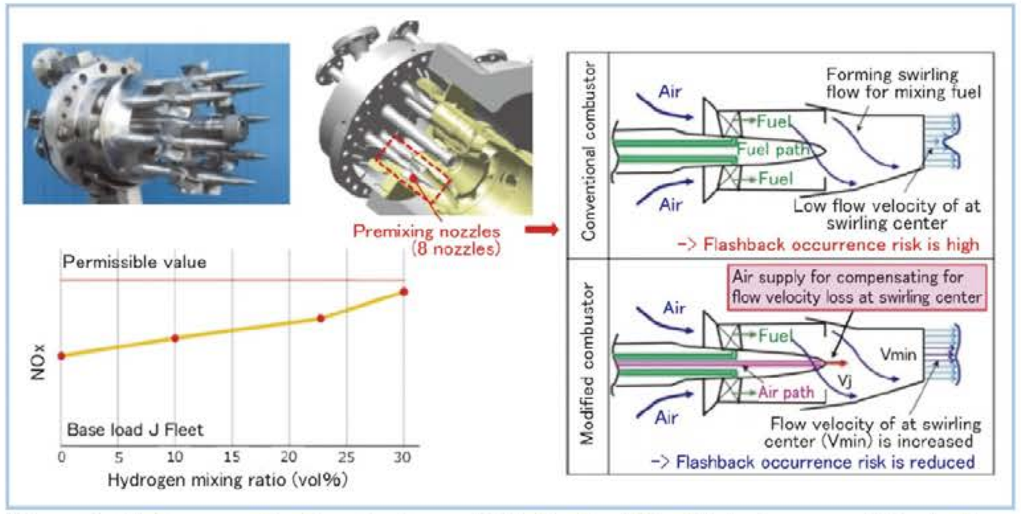


Figure 4 Hydrogen co-fired combustor and NOx levels at 30 vol% hydrogen co-firing testing

Moreover, as a measure to achieve a higher co-firing ratio of hydrogen, the pilot flame fuel nozzle in the center of the combustor employs diffusion combustion, which does not entail the risk of flashback, as shown in **Figure 5**. Our plan is to further improve this design for enabling hydrogen single-firing. It is possible to increase the average hydrogen co-firing ratio for the entire combustor up to 50 vol% by feeding the fuel blended with 30 vol% hydrogen through the eight premixed nozzles. Although NOx production may increase in the diffusion combustion zone, it can be prevented by injecting water therein. The actual-pressure test has demonstrated the operability of this combustor with NOx emissions below the permissible level and the stable operation without flashback or marked rise in combustion instability. The continuous improvement for a higher hydrogen co-firing ratio is still necessary. The development is in progress toward the validation with an actual unit.

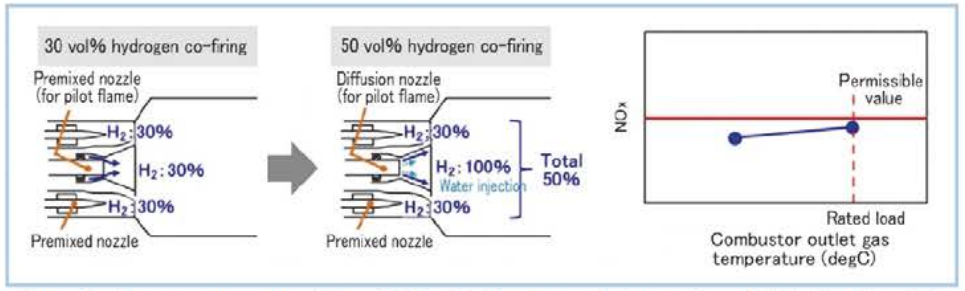


Figure 5 Improvement to achieve higher hydrogen co-firing ratio and NOx levels at 50 vol% hydrogen co-firing

(2) Multi-cluster combustor for hydrogen single-firing

As the hydrogen concentration becomes higher, the risk of flashback gets higher. The resistance to flashback is considered higher, if the mixing distance can be shortened by mixing air and hydrogen at a higher flow velocity on a smaller scale, rather than the multi-nozzle system described in the earlier section in which air and hydrogen are mixed together using a swirling flow at a relatively low velocity in a large space. **Figure 6** shows a multi-cluster combustor for hydrogen single-firing, which is currently in development. There are many holes (premixing tubes) in the combustor, in which air and fuel are rapidly mixed. Formation of many dispersed flames can also reduce NOx production.

In order to verify the combustion concept mentioned above and the combustibility, a combustion test was conducted under the pressure conditions equivalent to the actual unit using an elemental burner, which is a part taken from the multi-cluster nozzle. **Figure 7** shows the combustion test equipment and the images of the flame during combustion. Hydrogen burns with a flame with almost no emission of visible light; luminescence particular to hydrogen occurs in the ultraviolet range. The ultraviolet imaging shows the uniform formation of stable

flames a little away from the outlets of single premixing tubes in the burner. The test has confirmed the occurrence of no flashback and stable combustion under the designed test conditions.

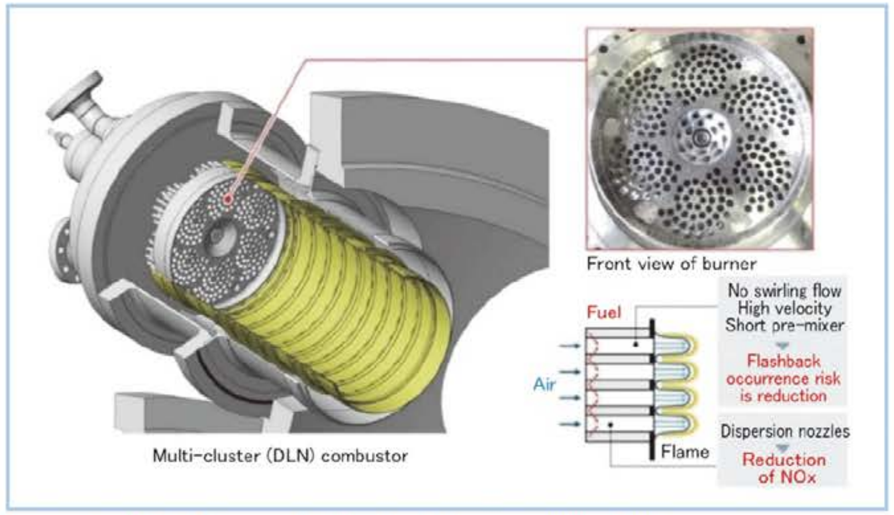


Figure 6 Multi-cluster combustor for hydrogen single-firing

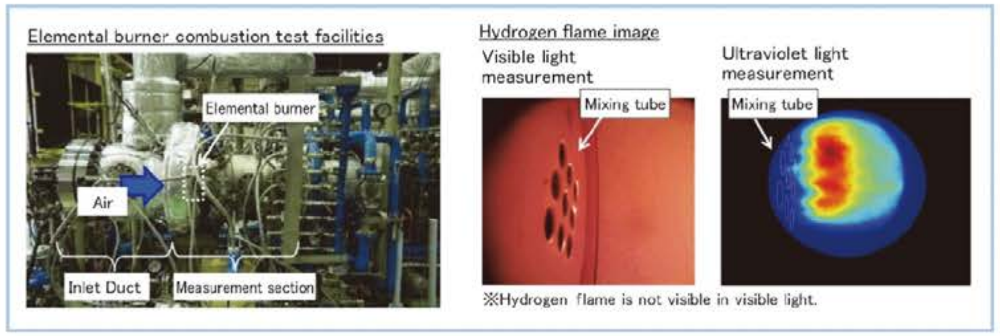


Figure 7 Elemental burner combustion test facility with a multi-cluster burner and hydrogen flames image

Furthermore, for small-to-middle class H-25 gas turbines, a full-scale actual-pressure test was conducted using a multi-cluster combustor for hydrogen single-firing, which is currently in development. In this test, the load was increased under the simulated operating conditions (i.e., temperature and flow rate) of an actual unit in which hydrogen is single fired. Without any flashback or sudden rise in combustion instability, the combustion temperature reached the level equivalent to the rated load of the actual unit. **Figure 8** shows the NOx measurements with increasing load. While attempting to further reduce NOx, the development will continue toward the validation with an actual unit.

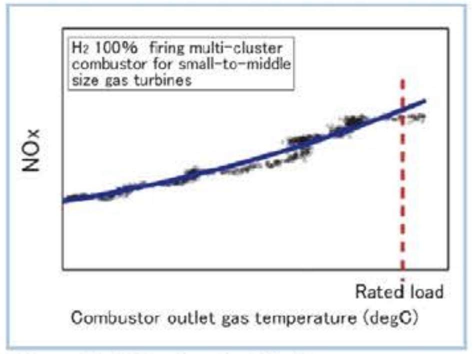


Figure 8 NOx levels at hydrogen single-firing

These findings are also used as the basis for the design of multi-cluster combustors for large gas turbines. An actual-pressure combustion test with one full-scale combustor is underway with a view to the validation for an actual unit in the future. The validation test will be conducted using the actual-pressure combustion test facility at MHI's Takasago Machinery Works, as in the case of the hydrogen co-firing test as shown in **Figure 9**. Hydrogen fuel, which is required in large quantities for the hydrogen single-firing test, will be supplied from the hydrogen storage facility newly installed at the Hydrogen Park Takasago (described later) on the premises of Takasago Machinery Works. In the actual-pressure combustion test, the small-to-middle class H-25 gas turbine drives the air compressor, which supplies air for combustion. This gas turbine will be used as the test unit, when hydrogen single-firing in a small-to-middle gas turbine is verified.

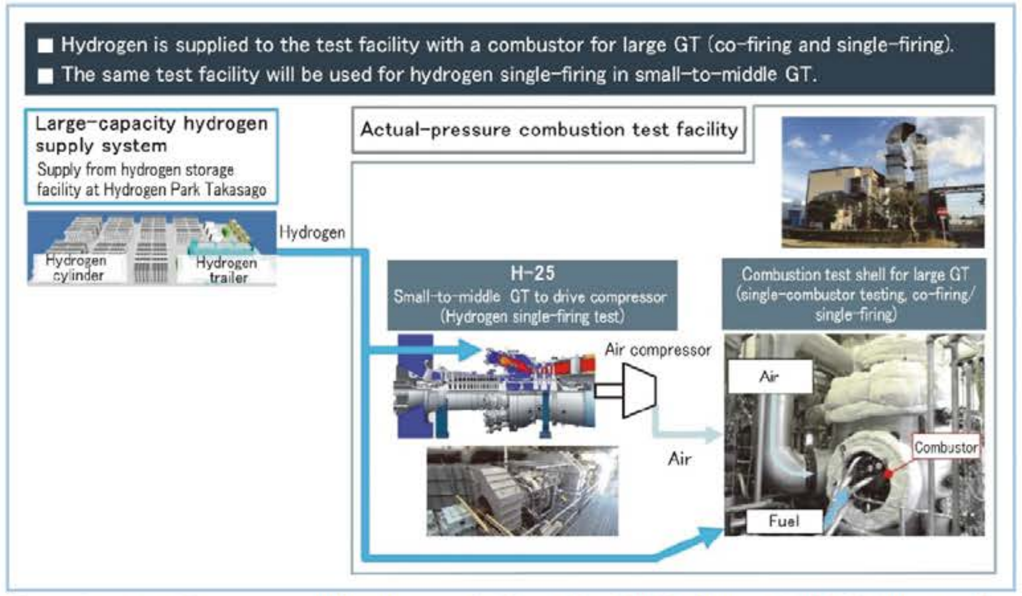


Figure 9 Actual-pressure combustion test facility with which hydrogen single-firing test will be conducted

2.3 Development status of ammonia-fired combustion systems

The technical challenges for burning ammonia as a fuel in gas turbines lie in keeping the flame stable in the combustor and controlling emissions of fuel NOx (i.e., NOx generated as a result of oxidation of nitrogen in ammonia fuel), as described in Section 2.1. MHI is looking into two types of GTCC systems using ammonia, as shown in **Figure 10**.

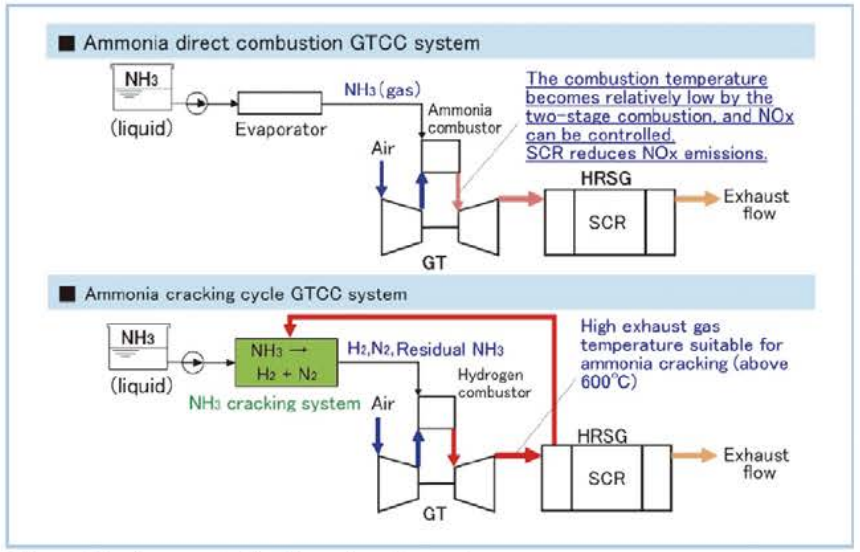


Figure 10 Ammonia-fired combustion systems

(1) Ammonia direct combustion GTCC system

In this gas turbine system, an ammonia combustor with less NOx emissions is combined with high-efficiency NOx removal equipment. For the combustor, a rich-lean two-stage combustion scheme based on the diffusion combustor is under consideration as shown in **Figure 11**. **Figure 12** shows a schematic representation of fuel NOx emission characteristics during ammonia combustion. There is a peak of fuel NOx generation in the neighborhood of a stoichiometric equivalence ratio of $\varphi = 1$ (at which stoichiometric complete combustion occurs between ammonia and air without excess or lack of either). In our rich-lean two-stage combustion scheme, however, ammonia fuel and air (primary combustion air) are burnt in the upstream side of the combustor in a fuel-rich state ($\varphi \geq 1$ in the Rich Zone), before it is shifted to a lean combustion state (in the Lean Zone) by rapidly mixing with secondary combustion air. In this way, NOx generation is prevented.

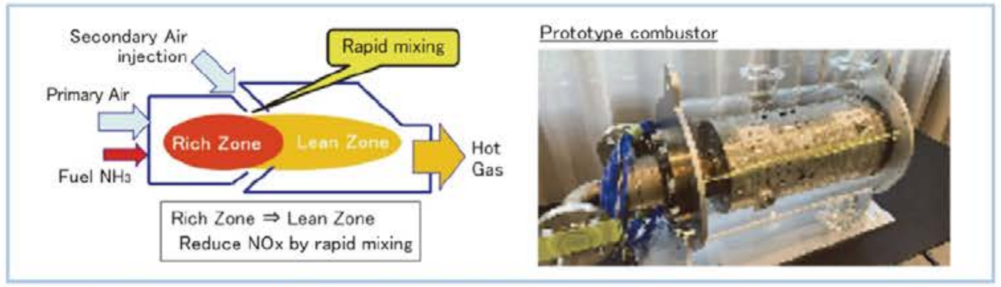


Figure 11 Ammonia combustor with a two-stage combustion scheme

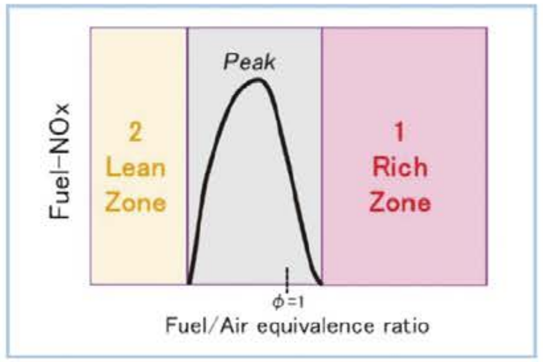


Figure 12 Fuel NOx emission characteristics during ammonia combustion

The development of this system will proceed first with targeting small-to-middle class H-25 gas turbine series. The ammonia combustion test facility at the Nagasaki District of MHI Research and Innovation Center is used to conduct an atmospheric pressure combustion test using a full-scale test combustor (one unit) for evaluation of the items such as flame stability, NOx emissions and changes in the properties when fuel is switched from hydrocarbons to ammonia. **Figure 13** shows the visualized images in the combustor, when the fuel (hydrocarbons or ammonia) is combusted. Hydrocarbons burn with a blue flame, while ammonia produces a distinctive orange flame. The actual-pressure combustion test facility with a high-pressure ammonia supply system at the Hitachi Works (Katsuta) will be used to conduct a combustion test under the pressure conditions equivalent to the actual unit. The development will be continued with the view to enabling operation in an actual unit and commercialization in or after 2025.

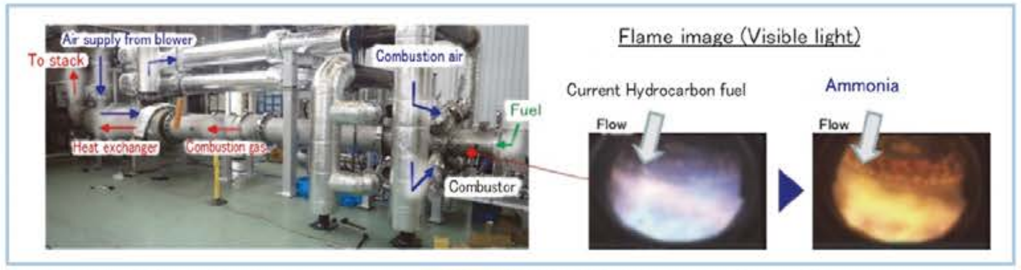


Figure 13 Atmospheric-pressure combustion test facility for ammonia and flame images in combustor

(2) Ammonia cracking GTCC system

In the ammonia cracking GTCC system, high-temperature waste heat from the gas turbine is used to decompose ammonia into hydrogen and nitrogen. The hydrogen is then burnt in the hydrogen co-fired combustor (Section 2.2 (1)) or the combustor for hydrogen single-firing under development (Section 2.2 (2)). The main component of the system is the ammonia cracking equipment. It is also considered usable as a system by which hydrogen is released from ammonia transported as a hydrogen carrier, to supply to other facilities/equipment using hydrogen. For the practical application, research will be continued considering the transfer of heat with a power generation system and the operability of the entire system as well.

3. Verification schedule

Actual gas turbines will be used for verification to enable early commercialization of hydrogen or ammonia-fired gas turbines. For the enhanced reliability of MHI products through verification using in-house facilities, the "Hydrogen Park Takasago" has been constructed on the premises of Takasago Machinery Works, to make it possible to perform the world's first integrated technological validation from hydrogen production to power generation (**Figure 14**). The facility has been in operation since 2023.

Figure 14 Hydrogen Park Takasago

Figure 15 shows the schedule for actual-unit verification, together with the reduction timetable for CO_2 emissions from gas turbines. The single-combustor test has confirmed that the multi-nozzle combustor for large gas turbines with hydrogen co-firing can operate with blends of hydrogen fuel (up to 50 vol%). This satisfies the European CO_2 emission standards (the criteria by the EU taxonomy, which prescribe that gas thermal power plants with construction approval by the end of 2030 must not emit more CO_2 than 270 g/kWh[2]). From 2023, the validation of hydrogen co-firing in the actual unit is underway using the hydrogen supply system at the Hydrogen Park Takasago, with the aim of confirming the reliability for commercialization. Furthermore, hydrogen single-firing in an actual small-to-middle gas turbine will be validated using a multi-cluster combustor. Specifically, the H-25 gas turbine of the actual-pressure test facility (Figure 9) will be used as the test unit for validation. The commercial operation of hydrogen co-firing (30 vol%) including the U.S. project described later will be started in 2025. For large gas turbines, hydrogen single-firing is aimed to be verified by demonstration in 2030. Regarding ammonia firing, a demonstration will also be conducted on the small-to-middle class H-25 gas turbine to realize practical application.

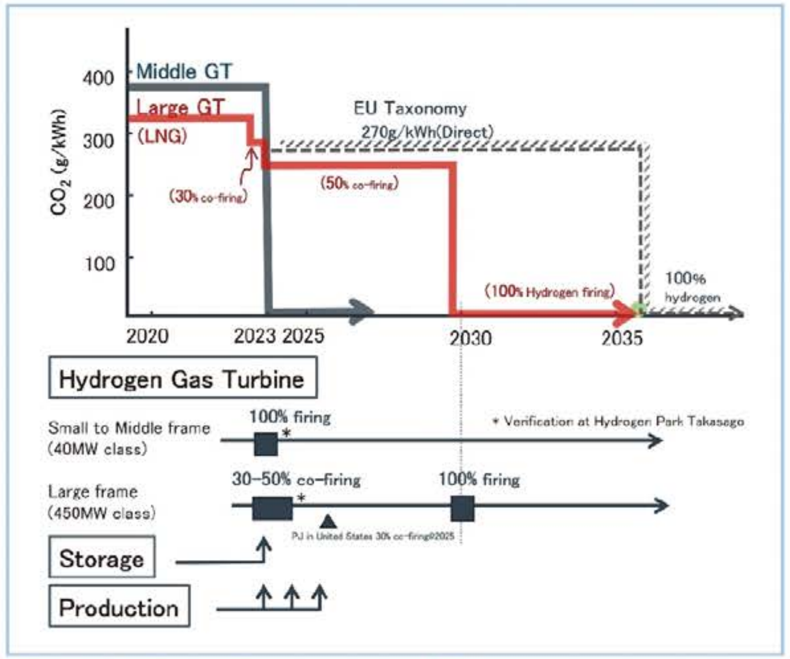


Figure 15 Schedule for actual-unit validation

4. Overseas projects for hydrogen or ammonia-fired gas turbines

In parallel with the scheduled demonstrations with an actual unit mentioned above, MHI takes part in business development in the leading regions for the utilization of hydrogen and ammonia in Japan as well as overseas, thereby working toward enabling the products to be practically applied while promoting collaboration with external parties. Some examples are given below.

4.1 Advanced Clean Energy Storage project in Utah, USA

Green hydrogen is produced using electricity from renewable energy sources found in abundance in the U.S. West Coast, before being stored in an underground rock salt cavern. When electricity is needed, the stored green hydrogen is taken out to feed the gas turbine for power generation. The generated electricity is then supplied widely in the states of California and Utah, aiming to stabilize the regional electricity supply and demand over a medium and long-term period. MHI received an order for a GTCC power generation facility consisting of two 840 MW class M501 JAC-type gas turbines as the core component, whose power generation plans involve 30 vol% hydrogen co-firing by 2025 and hydrogen single-firing by 2045. It is expected that power generation with 30 vol% hydrogen co-firing contributes to a reduction of up to 4.6 million tons of CO_2 emissions per year.

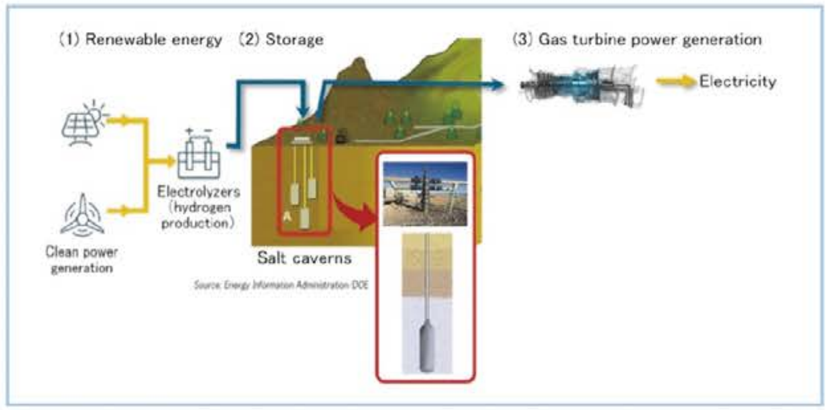


Figure 16 Advanced Clean Energy Storage project in Utah, USA

4.2 Hydrogen co-firing demonstration project at McDonough Atkinson Power Plant, USA

In 2022, as a hydrogen co-firing demonstration project at an existing gas turbine power plant, MHI Group together with Georgia Power, a U.S. electric utility, and the Electric Power Research Institute (EPRI) conducted a combustion verification test in which an MHI M501G-type natural gas-fired gas turbine (with a DLN multi-nozzle combustor) successfully operated on a blend of hydrogen and natural gas at the McDonough Atkinson Power Plant in Georgia, shown in **Figure 17**[3]. This project was the world's first demonstration of 20 vol% hydrogen co-firing in a large, high-efficiency GTCC power generation facility, and was the largest test of its kind in history. CO_2 emissions are reduced by about 7% from the level of natural gas firing, without affecting the turbine inlet temperature, emissions and maintenance intervals. This verification test has also demonstrated the following: the operation at a hydrogen blend ratio of 20 vol% throughout the full-load range of gas turbines while maintaining the same NOx level as natural gas-fired operation, and the improved combustion efficiency as a result of the decreased carbon monoxide (CO) emissions at partial load by co-firing hydrogen, thereby resulting in a 10% reduction (absolute value) in the minimum load at which the gas turbine can operate in compliance with the emission regulations.

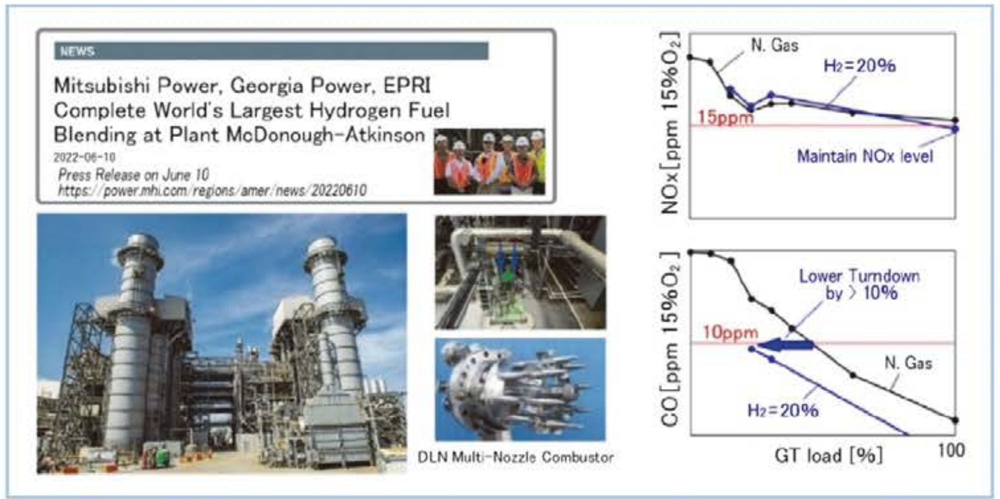


Figure 17 U.S. McDonough Atkinson Power Plant and the verification test results of combustion with a hydrogen blended fuel

4.3 Implementation plan of ammonia-fired gas turbines

Many countries are planning to introduce ammonia to existing thermal power plants. Although the application of ammonia co-firing in coal-fired boilers is ahead of the curve, there is also a growing worldwide demand for ammonia-fired gas turbines, as indicated by the implementation of the feasibility study (FS) for GTCC. MHI is also taking part.

5. Conclusion

Focusing on hydrogen or ammonia-fired gas turbines among MHI's projects for achievement of carbon neutrality, this report presents the development status of the main item (i.e., gas turbine combustors) and the schedule for validation.

Regarding the co-firing system of hydrogen and natural gas, the single-combustor test has demonstrated operability under the conditions in which 30 to 50 vol% hydrogen is co-fired. The development will be advanced to the next stage of actual-unit validation for commercialization. For the hydrogen single-firing system, actual-unit validation will be started with small-to-middle gas turbines. The development of gas turbine systems using ammonia will also be continued for commercialization. Expanding its product line-up of carbon-free power generation systems, MHI aims for decarbonization through energy transition by 2030.

Through cooperation with its partners across the world for the development and commercialization of hydrogen/ammonia-fired GTCCs that can contribute to CO_2 reduction, MHI continues to make efforts to achieve carbon neutrality as soon as possible.

Acknowledgements:

The description of the combustors for hydrogen co-firing and hydrogen single-firing in Section 2.2 of Chapter 2 in this paper is part of the results of a NEDO-funded project (Development of Technologies for Realizing a Hydrogen Society: JPNP14026). The ammonia cracking GTCC system described in Section 2.3 of Chapter 2 has been developed with support from NEDO as part of a project (Development of Technologies for Realizing a Hydrogen Society: JPNP14026).

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https://power.mhi.com/regions/amer/news/20220610

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"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.

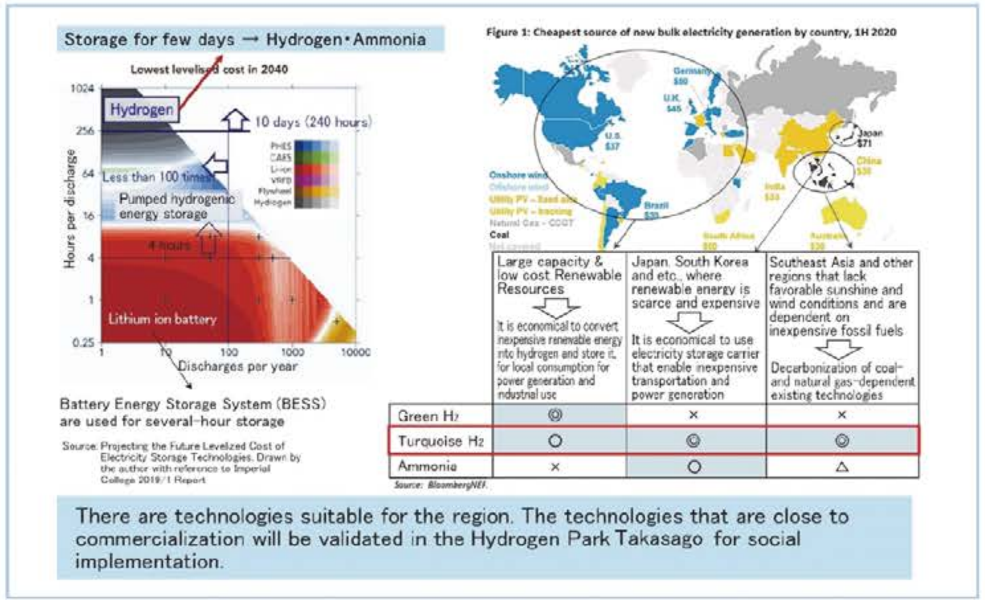


Figure 1 Background for hydrogen and ammonia utilization

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.

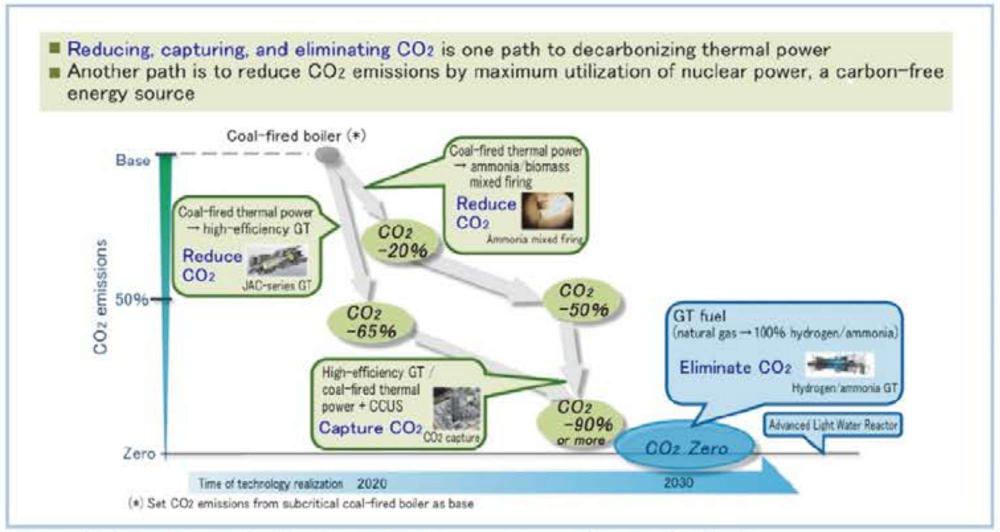


Figure 2 Road map for development of power generation technologies

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.

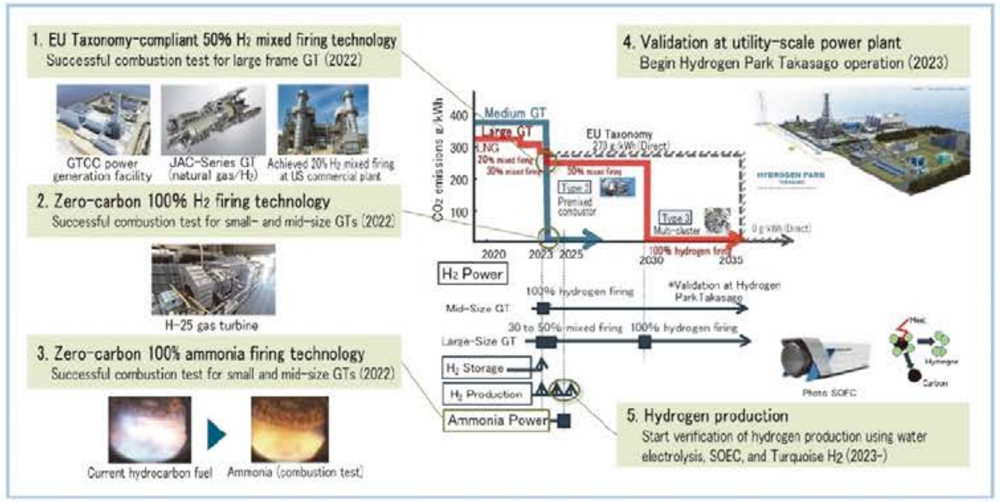


Figure 3 European CO_2 emission standards and schedule for gas turbine development

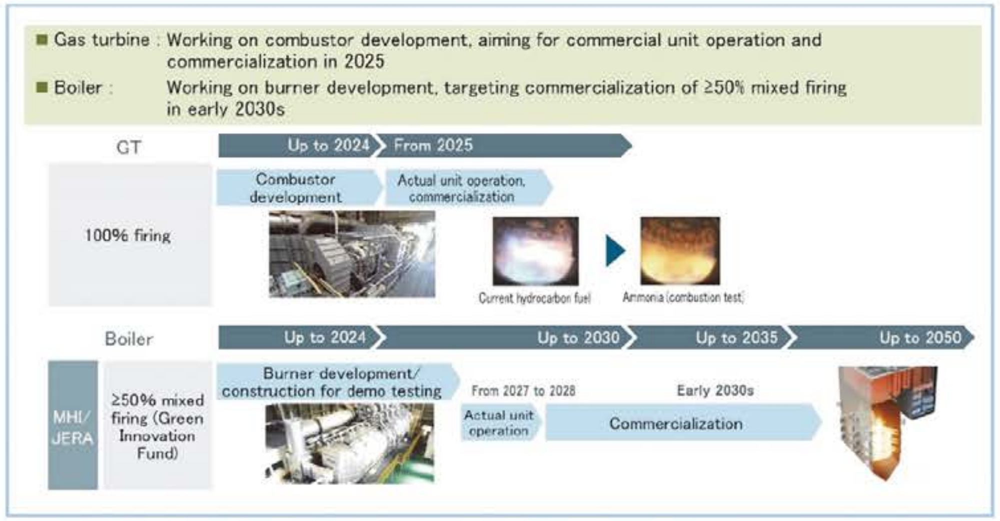


Figure 4 Road map for ammonia power generation technology

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.

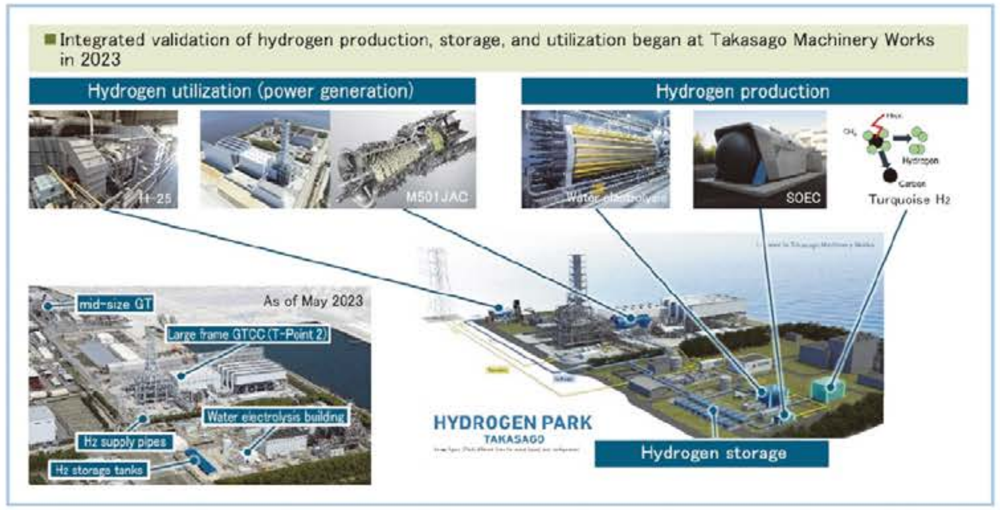


Figure 5　Overall concept of Hydrogen Park Takasago

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.

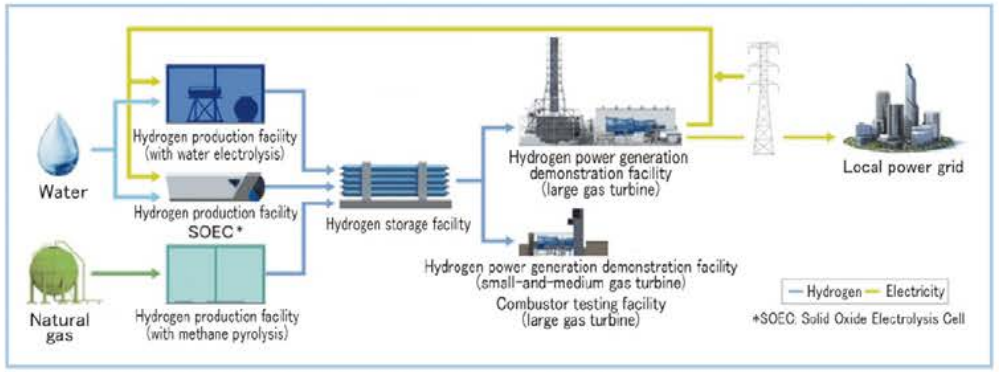


Figure 6　Configuration diagram of Hydrogen Park Takasago

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)

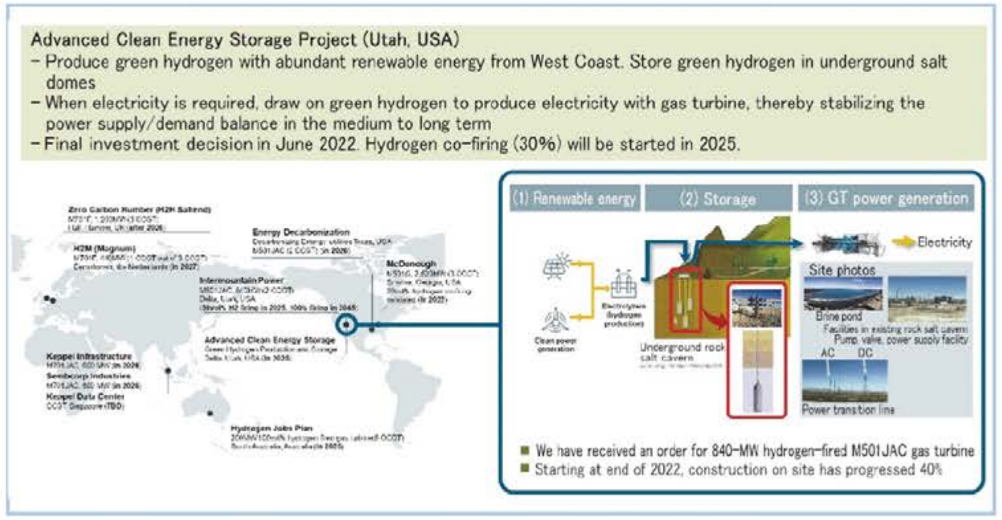


Figure 8　Example of hydrogen storage and gas turbine project in US

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.

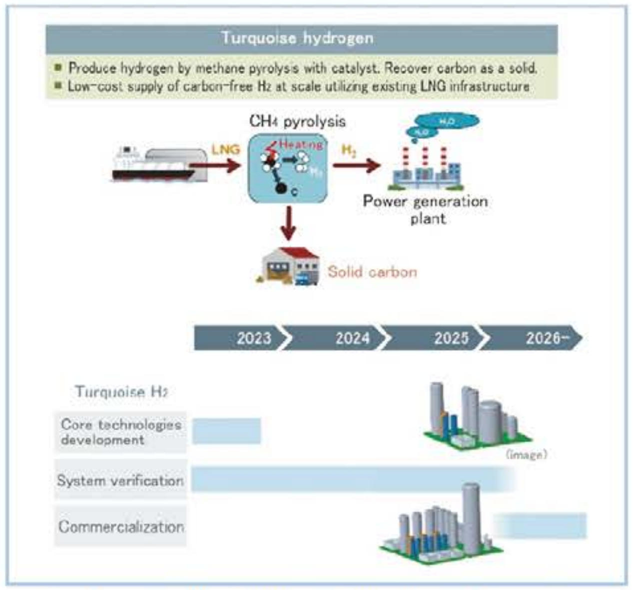


Figure 12　Turquoise hydrogen development status

(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.

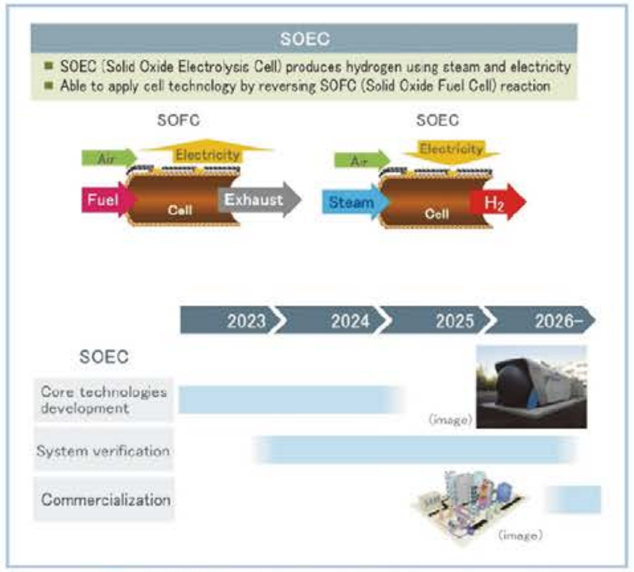


Figure 13 SOEC development status

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.

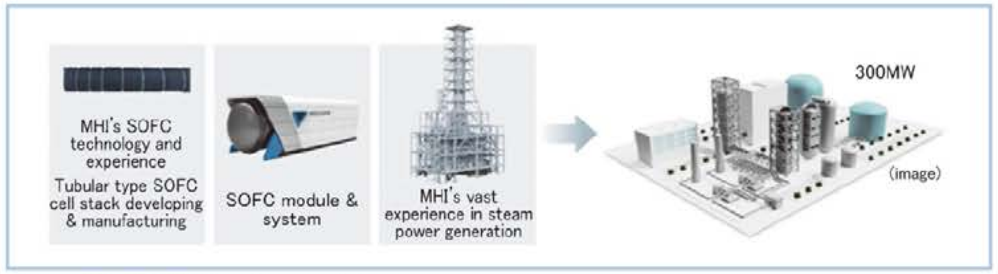


Figure 14 SOEC development plan

(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.

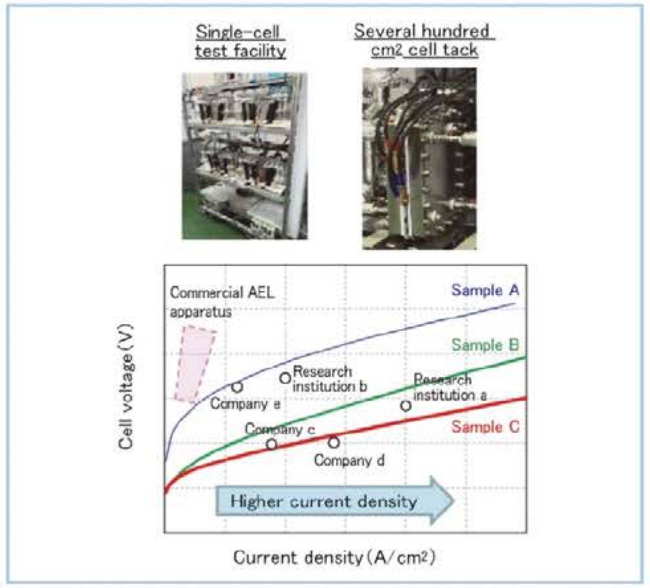


Figure 15 Development status of AEM water electrolysis

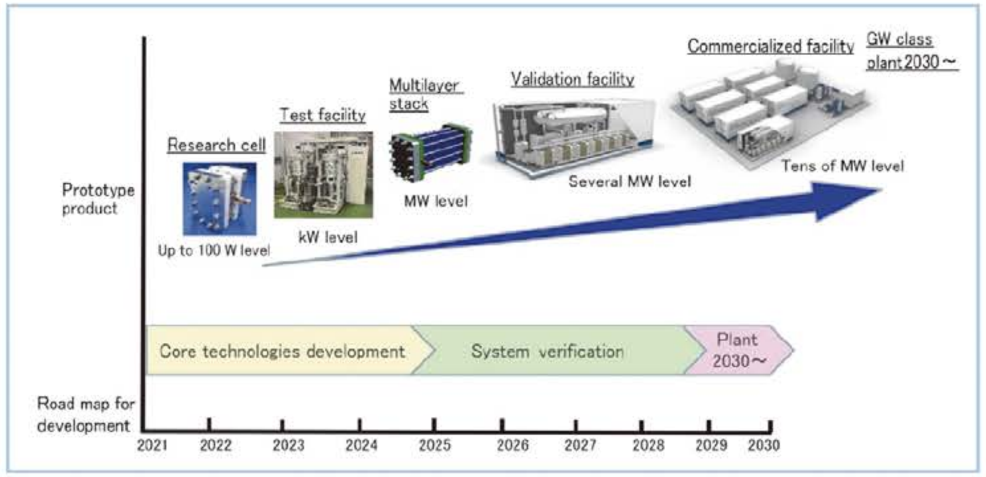


Figure 16 Road map for AEM water electrolysis

(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.

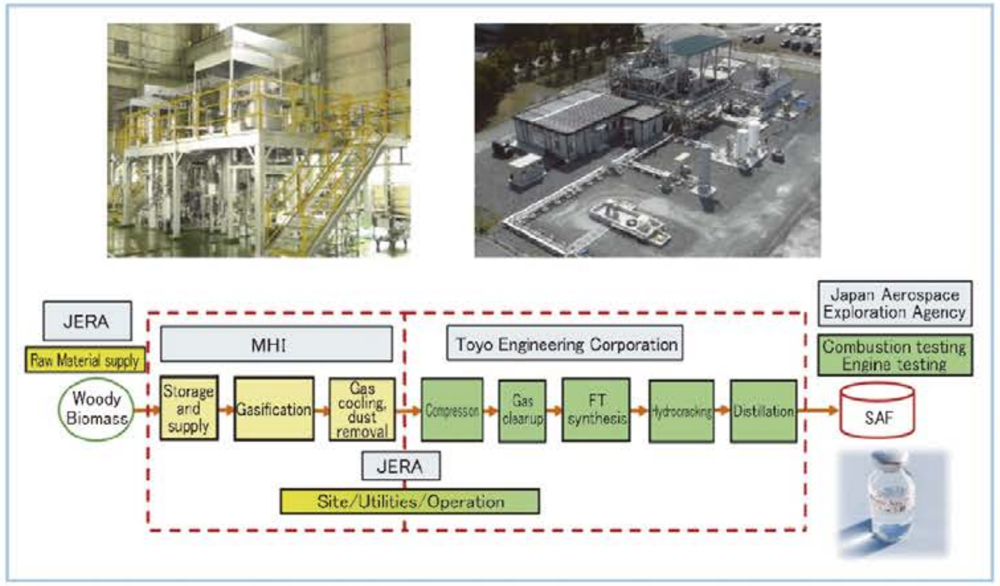


Figure 17 Technology of SAF production by biomass gasification

(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".

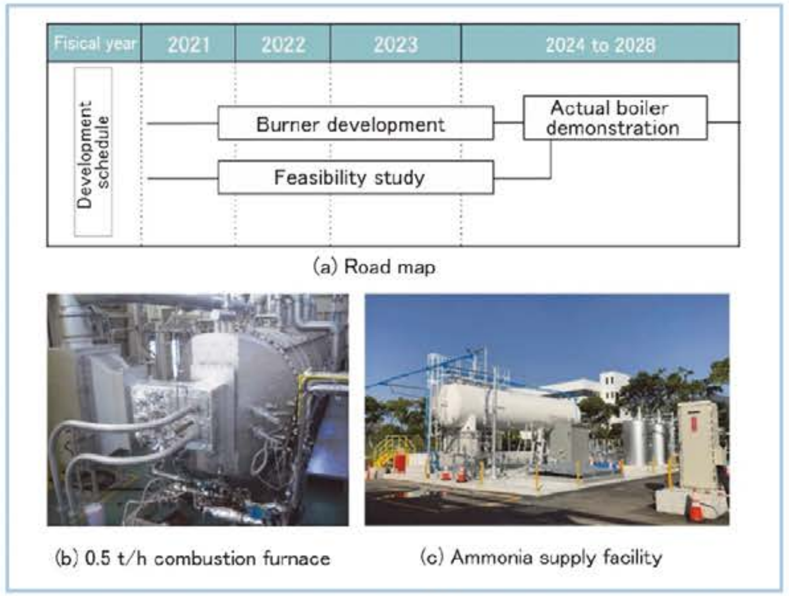


Figure 18 Overview of development of high-ratio ammonia co-firing technology funded by Green Innovation Fund

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."

COMPENDIUM

In this section, we list the characteristics of hydrogen and information pertaining to engineering for your use.
We also provide information about ammonia, which is seen as a potential hydrogen energy carrier from the *Mitsubishi Heavy Industries Technical Review*.

Contents

1. Basic Data

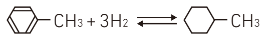
	Hydrogen H_2	Methane CH_4	Ammonia NH_3	Air	Nitrogen N_2	Carbon Dioxide CO_2
Molecular Weight*1	2.016	16.04	17.03	28.97	28.02	44.01
Density (gas)*2 kg/Nm³	0.08987	0.717	0.771	1.2932	1.2506	1.977
Density (liquid)*3 kg/L	0.071 (-252.9℃, 0.1MPa)	0.427 (-165.0℃, 0.1MPa)	0.682 (-33.7℃, 0.1MPa)	0.898 (N_2:O_2=0.79:0.21) (-200.0℃, 0.1MPa)	0.807 (-196.0℃, 0.1MPa)	1.032 (-20.1℃, 2MPa)
Specific Heat*4 **Cp kJ/(kg·K) [25℃,1atm]**	14.306	2.2317	2.1645	1.0063	1.0413	0.85085
Heat Capacity Ratio*4 **K (-) [25℃,1atm]**	1.4054	1.3062	1.316	1.4018	1.4013	1.2941
Gas Constant R J/(kg·K)	4124.3	518.4	488.2	287.0	296.7	188.9
Freezing Point*5 **℃ [1atm]**	-259.14	-182.76	-77.7	-	-209.86	-56.6
Boiling Point*5 **℃ [1atm]**	-252.87	-161.49	-33.4	-	-195.8	-78.5 (rise)

Source *1: 14102 chemical products (The Chemical Daily), p.1, p265, p275, p277, p288 (excluding Air) *2: Revised 4th edition Chemistry Handbook Basics (Maruzen) I-28, II-3, Gas Density and Specific Gravity (Heishin Mono Pump) *3: NIST Chemistry WebBook, SRD 69 (https://webbook.nist.gov/chemistry/fluid/), Refprop_ver9.0 (NIST Reference Fluid Thermodynamic and Transport Properties Database) *4: Calculated with Refprop_ver9.0 *5: Revised 4th Edition Chemistry Handbook Basics (Maruzen) I-28, I-409, I-176, I-131 (excluding Air)

2. Transport Property

	Liquid Hydrogen H_2	Compressed Hydrogen H_2 (350 atm)	Compressed Hydrogen H_2 (700 atm)	Methane CH_4 (liquid)	Ammonia NH_3 (liquid)	Natural Gas (LNG 13A)	Propane C_3H_8 (liquid)	Methylcyclohexane C_7H_{14} (MCH*)
Molecular Weight	2.016	2.016	2.016	16.04	17.03	18.36	44.1	98.18
Hydrogen Content (weight %)	100	100	100	25.13	17.76	23.77	18.29	6.16
Hydrogen Density (kg-H_2/m³)	70.8	23	39	108.1	120.0	103.0	107.0	47
Boiling Point (℃)	-252.87	-	-	-161.49	-33.4	-161.49 (Methane) Varies by composition	-42.07	101.05
Other properties	High hydrogen density No recycling required High purity	High inflammable Highly combustible Explosive		-	High hydrogen density No recycling required Can be used directly	Composition (%) Methane CH_4: 89.60 Ethane C_2H_6: 5.62 Propane C_3H_8: 3.43 Butane C_4H_{10}: 1.35	-	Normal temperature and pressure Petroleum infrastructure Available for use

* Carrying hydrogen using the difference of hydrogen between MCH toluene (C_7H_8) (molecular weight 92) and MCH (C_7H_{14}) (molecular weight 98)



3. Combustion Property

Fuel Name		Hydrogen H_2	Methane CH_4	Ammonia NH_3	Propane C_3H_8
Density [kg/Nm³]*1		0.08987	0.717	0.771	2.02
Boiling Point (@hPa) [℃]*2		-252.87	-161.49	-33.4	-42.1
Lower-heating Value	**[MJ/kg]***2	120.4	50.2	18.6	46.6
	[MJ/Nm³]	10.82	35.99	14.34	93.67
	[MJ/mol]	0.243	0.805	0.317	2.055
Higher-heating value	**[MJ/kg]**	141.77	55.5	22.5*3	50.32
	[MJ/Nm³]	12.75	39.72	17.1	99
	[MJ/mol]	0.286*4	0.89*4	0.383	2.219*4
Flammability Equivalence Ratio [-]*2		0.10~7.17	0.50~1.69	0.63~1.40	0.51~2.51
Maximum Burning Velocity [m/s]*2		2.91	0.37	0.07	0.43
Minimum Self-ignition Temperature [℃]*2		500	537	651	432
Generated CO_2 [g/MJ]		0	54.8	0	64.4
Generated H_2O [g/MJ]		74.8	44.8	85.4	35.1

Source *1: Chronicle of Scientific Tables 2021, 31 (397) *2: Journal of the Combustion Society of Japan Vol.58, No.183, (2016), 41-48 *3: https://www.jstage.jst.go.jp/article/jsssj/36/11/36_583/_pdf, https://www.jccme.or.jp/11/pdf/2021-06/josei01.pdf *4: Calculated from figures published on page 285 of Combustion Engineering Handbook, edited by the Japan Society of Mechanical Engineers, 1995

The secret of the hydrogen visualization burner

At MHI's Research & Development Center (Takasago), demonstrations of hydrogen combustion are being conducted for visitors. In fact, the burner used there is one of many prototypes that were produced to confirm the manufacturing limits of metal 3D printers when developing a 100% hydrogen firing multi-cluster combustor. It managed to avoid being scrapped and is living a second life.

What is the flame color of hydrogen (H_2), methane (CH_4) and ammonia (NH_3)?

Pale/Translucent (invisible), blue, and orange, respectively. In the process of burning a substance, intermediate products called radicals that cannot exist in normal conditions are formed. Radicals emit light of specific wavelengths when they are formed and dissolved, but the type and ratio of radicals change depending on the combustible material and combustion method, resulting in flames of different colors.

4. Comparison of Heat Required to Produce 1mol of Hydrogen

	Method	Thermochemical Equation	Heat Required to Produce 1mol of Hydrogen
(1)	**Methane Pyrolysis**	CH_4 (g) + 74.4kJ = $2H_2$ (g) + C	37.2kJ/mol
(2)	**Methane Reforming**	① CH_4 (g) + H_2O (g) + 205.7kJ = CO (g) + $3H_2$ (g) ② CO (g) + H_2O (g) = H_2 (g) + CO_2 (g) + 41.2kJ ⇒ CH_4 (g) + $2H_2O$ (g) = CO_2 (g) + $4H_2$ (g) - 164.5kJ (=①+②)	41.1kJ/mol
(3)	**Ammonia Decomposition**	NH_3 (g) + 46.1kJ = $3/2H_2$ (g) + $1/2N_2$ (g)	30.7kJ/mol
(4)	**MCH Dehydrogenation**	$C_6H_{11}CH_3$ + 202.5kJ = $C_6H_5CH_3$ + $3H_2$ (g)	67.5kJ/mol
	(liquid) water electrolysis	H_2O (l) + 286kJ = H_2 (g) + $1/2O_2$ (g)	0.079* kWh/mol

* In water electrolysis, electrical energy is added to water to generate hydrogen. So, the energy required to generate 1 mol of hydrogen is expressed here as 0.079 kWh/mol in terms of kWh (1 kWh = 3600 kJ).

5. Conversion Tables

5-1. Unit Conversion Table

Energy

	Per Million British Thermal Units (MmBtu)	Per British Thermal Unit (Btu)	Kilowatt Hour (kWh)	Megajoule (MJ)	Kilocalorie (kcal)	Tonne of Oil Equivalent (toe)
Per Million British Thermal Units (MmBtu)	1	1.000×10^{6}	2.931×10^{2}	1.055×10^{3}	2.519×10^{5}	2.519×10^{-2}
Per British Thermal Unit(Btu)	1.000×10^{-6}	1	2.930×10^{-4}	1.055×10^{-3}	2.519×10^{-1}	2.519×10^{-8}
Kilowatt Hour (kWh)	3.412×10^{-3}	3.412×10^{3}	1	3.6	8.598×10^{2}	8.598×10^{-5}
Megajoule (MJ)	9.478×10^{-4}	9.478×10^{2}	2.777×10^{-1}	1	2.388×10^{2}	2.388×10^{-5}
Kilocalorie (kcal)	3.968×10^{-6}	3.968	1.163×10^{-3}	4.186×10^{-3}	1	1.000×10^{-7}
Tonne of Oil Equivalent (toe)	3.968×10^{1}	3.968×10^{7}	1.163×10^{4}	4.186×10^{4}	1.000×10^{7}	1

Volume

	Cubic Meter (m^3)	Cubic Feet (cf)	US Gallon (US gal)	US Barrel (bbl)	Liter (litre)
Cubic Meter (m^3)	1	3.531×10^{1}	2.641×10^{2}	6.29	1×10^{3}
Cubic Feet (cf)	2.831×10^{-2}	1	7.480	1.781×10^{-1}	2.831×10^{1}
US Gallon (US gal)	3.785×10^{-3}	1.336×10^{-1}	1	2.38×10^{-2}	3.785
US Barrel (bbl)	1.589×10^{-1}	5.614	42	1	1.589×10^{2}
Liter (litre)	1×10^{-3}	3.531×10^{-2}	2.641×10^{-1}	6.289×10^{-3}	1

Mass

	Kilogram (kg)	Ton (t)	UK Ton (UK ton)	US Ton (US ton)	Pound (lb)
Kilogram (kg)	1	1.000×10^{-3}	9.842×10^{-4}	1.102×10^{-3}	2.204
Ton (t)	1×10^{3}	1	9.842×10^{-1}	1.102	2.20462×10^{3}
UK Ton (UK ton)	1.016×10^{3}	1.016	1	1.120	2.240×10^{3}
US Ton (US ton)	9.071×10^{2}	9.071×10^{-1}	8.928×10^{-1}	1	2×10^{3}
Pound (lb)	4.535×10^{-1}	4.535×10^{-4}	4.464×10^{-4}	5×10^{-4}	1

5-2. Hydrogen Cost Simple Conversion Table

H_2 Cost		$/Nm³	€/Nm³	Yen/kg	$/kg	€/kg	Yen/MmBtu	$/MmBtu	€/MmBtu	Yen/MJ	$/MJ	€/MJ	Yen/kWh-th	$/kWh-th	€/kWh-th
30.00	Yen/Nm³	0.216	0.216	334	2.41	2.40	2480	17.9	17.8	2.35	0.0169	0.0169	8.46	0.0610	0.0608

- Based on the Japanese government's target of 30 yen/Nm³ by around 2030, the following assumptions have been applied to create the conversion table.
  Gas density: 0.08987 kg/Nm³ Higher heating value: 12.77 MJ /Nm³ – HHV Unit conversion: 1,055 MJ/MmBtu
  Exchange rate: 138.63 yen/US $, 139.03 yen/€ (TTM rate at the end of August 2022)

5-3. Ammonia Cost Simple Conversion Table

NH_3 Cost		Yen/ton	€/ton	Yen/MmBtu	$/MmBtu	€/MmBtu	Yen/MJ	$/MJ	€/MJ	Yen/kWh-th	$/kWh-th	€/kWh-th	Yen/Nm³H_2	$/Nm³$H_2$	€/Nm³H_2
350.00	**$/ton**	48500	351	2280	16.4	16.4	2.16	0.0156	0.0155	7.77	0.0561	0.0559	27.6	0.199	0.198

- Based on the $350/ton* that CFAA (Cree Fuel Ammonia Association) considers feasible by around 2030, the following assumptions have been applied to create the conversion table.
  Gas density: 0.771 kg/Nm³ Higher heating value: 22.47 MJ/kg – HHV Unit conversion: 1,055 MJ/MmBtu
  Exchange rate: 138.63 yen/US $, 139.03 yen/€ (TTM rate at the end of August 2022)
- The conversion between hydrogen and ammonia was performed using their respective higher heating values, and the mutual conversion loss, etc., were not taken into account.

* Source example of $350/ton: https://www.mlit.go.jp/kowan/content/001418024.pdf

6. Gas Turbines Lineup

Mitsubishi Power gas turbines made with cutting-edge technologies

Small and medium capacity gas turbines (41 MW to 116 MW)

- H-25-series (50Hz / 60Hz)
- H-100-series (50Hz / 60Hz)

Large capacity gas turbines (114 MW to 574 MW)

- J-series (50Hz / 60Hz)
- G-series (60Hz)
- F-series (50Hz)
- D-series (50Hz / 60Hz)

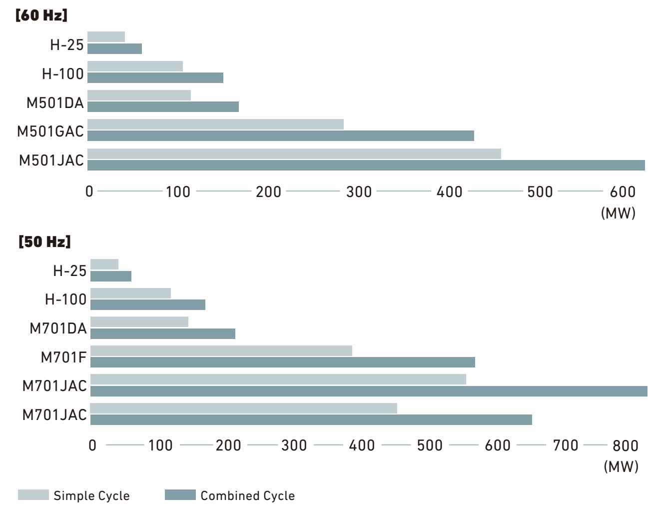
Aero-Derivative Gas Turbines (30 MW to 140 MW)

- FT8® MOBILEPAC®
- FT8® SWIFTPAC®
- FT4000® SWIFTPAC®

Powering the world with a full range of gas turbines

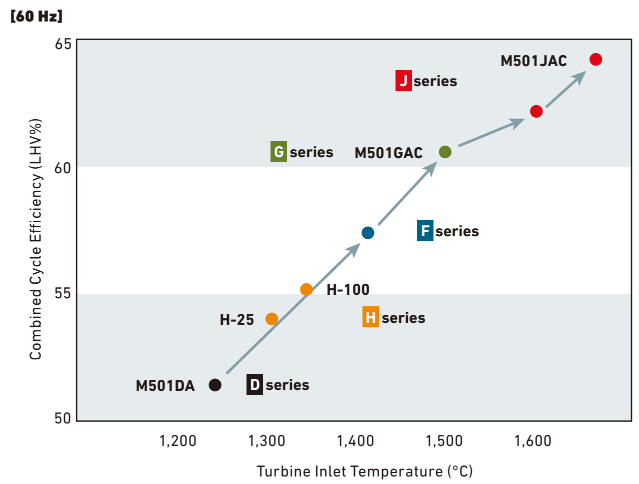
To meet the power demands of industries and societies around the world, Mitsubishi Power produces a wide range of gas turbines from the 30 MW to the 574 MW class for power generation and industrial use. These turbines drive the development and supply of highly-efficient, clean energy around the world. In fact, Mitsubishi Power has delivered more than 1,600 gas turbines to customers in more than 50 countries worldwide.

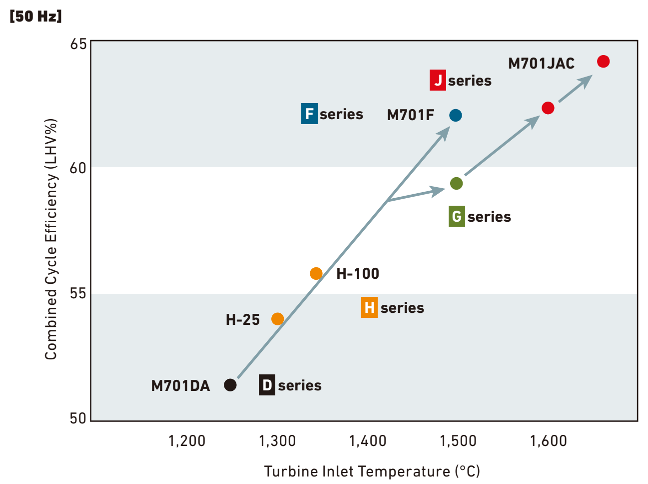
Gas Turbine and Combined Cycle Output



• (ISO, 1 GT + 1 ST, GAS FUEL)

Thermal Efficiency of Combined Cycle Systems





Performance

Simple Cycle Specs

	ISO Base Rating (kW)	LHV Heat Rate (kJ/kWh)	LHV Heat Rate (Btu/kWh)	Efficiency (%-LHV)	Pressure Ratio	Turbine Speed (rpm)	Exhaust Flow (kg/s)	Exhaust Temp (°C)
50Hz / 60Hz								
H-25*	41,030	9,949	9,432	36.2	17.9	7,280	114	569
50Hz								
H-100*	116,450	9,400	8,909	38.3	18	3,000	296	586
M701DA	144,090	10,350	9,810	34.8	14	3,000	453	542
M701F	385,000	8,592	8,144	41.9	21	3,000	748	630
M701JAC	448,000	8,182	7,755	44.0	25	3,000	765	663
M701JAC	574,000	8,295	7,862	43.4	25	3,000	1,024	646
60Hz								
H-100*	105,780	9,421	8,930	38.2	18.4	3,600	293	534
M501DA	113,950	10,320	9,780	34.9	14	3,600	354	543
M501GAC	283,000	9,000	8,531	40.0	20	3,600	618	617
M501JAC	453,000	8,182	7,755	44.0	25	3,600	815	649

Mechanical Drive Specs

	ISO Base Rating (hp)	ISO Base Rating (kW)	LHV Heat Rate (kJ/kWh)	LHV Heat Rate (Btu/hp-hr)	Efficiency (%-LHV)	Pressure Ratio	Turbine Speed (rpm)	Exhaust Flow (kg/s)	Exhaust Temp (°C)
H-100*	144,350	107,650	9,256	6,542	38.9	18.4	3,600	293	534
H-100*	160,780	119,900	9,266	6,549	38.9	20.1	3,000	315	552

Aero-Derivative Gas Turbine Specs

	ISO Base Rating (kW)	LHV Heat Rate (kJ/kWh)	LHV Heat Rate (Btu/kWh)	Efficiency (%-LHV)	Turbine Speed (rpm)	Exhaust Flow (kg/s)	Exhaust Temp (°C)
50Hz							
FT8®	28,528	10,376	9,834	34.7	3,000	92	496
FT4000®	70,154	8,908	8,443	40.4	3,000	183	431
FT4000®	140,500	8,896	8,431	40.5	3,000	367	431
60Hz							
FT8®	30,941	9,825	9,312	36.7	3,600	92	491
FT4000®	71,928	8,686	8,232	41.5	3,600	183	422
FT4000®	144,243	8,661	8,209	41.6	3,600	367	422

Notes: (1) All ratings are defined at ISO standard reference conditions: 101.3kPa, 15°C and 60% RH.
(2) All ratings are at generator terminals and are based on the use of natural gas fuel.
** without inlet and exhaust losses*

Combined Cycle Specs

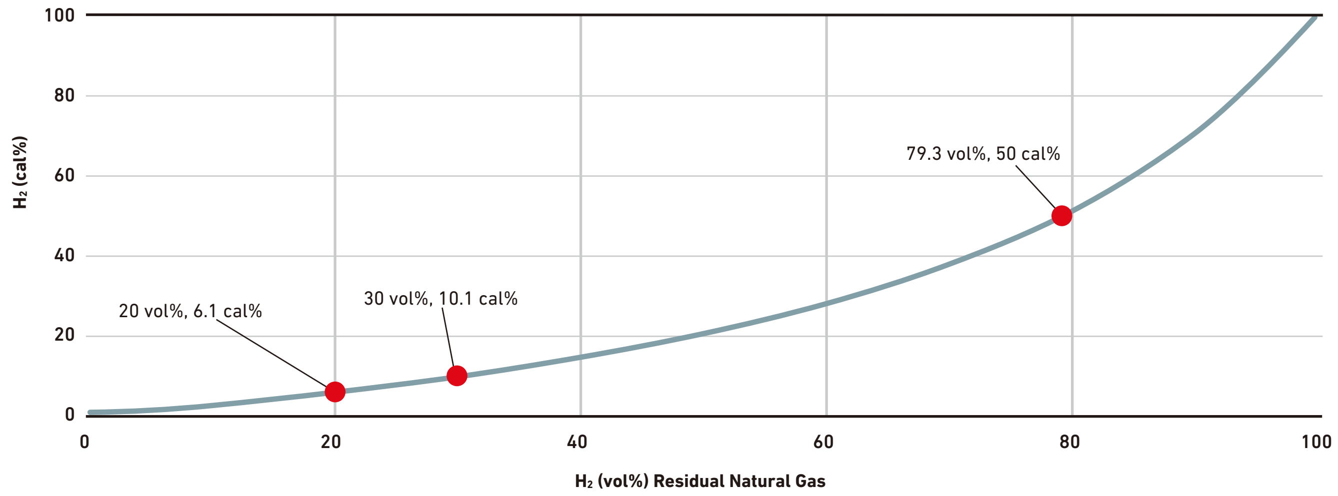
	Plant Output (kW)	LHV Heat Rate (kJ/kWh)	LHV Heat Rate (Btu/kWh)	Plant Efficiency (%)	Gas Turbine Power (kW)	Steam Turbine Power (kW)	Number & Type Gas Turbine
50Hz / 60Hz							
MPCP1(H-25)	60,100	6,667	6,319	54.0	39,600	20,500	1×H-25
MPCP2(H-25)	121,400	6,606	6,261	54.5	79,200	42,200	2×H-25
50Hz							
MPCP1(H-100)	171,000	6,272	5,945	57.4	112,700	58,300	1×H-100
MPCP2(H-100)	346,000	6,207	5,884	58.0	225,400	120,600	2×H-100
MPCP1(M701DA)	212,500	7,000	6,635	51.4	142,100	70,400	1×M701DA
MPCP2(M701DA)	426,600	6,974	6,610	51.6	284,200	142,400	2×M701DA
MPCP3(M701DA)	645,000	6,947	6,585	51.8	426,300	218,700	3×M701DA
MPCP1(M701F)	566,000	5,807	5,504	62.0	379,300	186,700	1×M701F
MPCP2(M701F)	1,135,000	5,788	5,486	62.2	758,600	376,400	2×M701F
MPCP1(M701JAC)	650,000	<5,625	<5,332	>64.0	441,700	208,300	1×M701JAC
MPCP1(M701JAC)	840,000	<5,625	<5,332	>64.0	570,900	269,100	1×M701JAC
60Hz							
MPCP1(H-100)	150,000	6,534	6,193	55.1	102,500	47,500	1×H-100
MPCP2(H-100)	305,700	6,418	6,083	56.1	205,000	100,700	2×H-100
MPCP1(M501DA)	167,400	7,000	6,635	51.4	112,100	55,300	1×M501DA
MPCP2(M501DA)	336,200	6,974	6,610	51.6	224,200	112,000	2×M501DA
MPCP3(M501DA)	506,200	6,947	6,585	51.8	336,300	169,900	3×M501DA
MPCP1(M501GAC)	427,000	5,951	5,640	60.5	280,800	146,200	1×M501GAC
MPCP2(M501GAC)	856,000	5,931	5,622	60.7	561,600	294,400	2×M501GAC
MPCP3(M501GAC)	1,285,000	5,931	5,622	60.7	842,400	442,600	3×M501GAC
MPCP1(M501JAC)	664,000	<5,625	<5,332	>64.0	450,300	213,700	1×M501JAC
MPCP2(M501JAC)	1,332,000	<5,608	<5,315	>64.2	900,600	431,400	2×M501JAC

7. Fuel Consumption by Gas Turbine Type

Gas Turbine Type	Catalog Performance		Hydrogen		Natural Gas		CO_2 Emissions
	ISO Base Rating (kW)	Efficiency (%-LHV)	(ton/hour)	(Nm^3/hour)	(ton/hour)	(Nm^3/hour)	(g/kWh)
50Hz / 60Hz							
H-25	41,030	36.2	4	45,000	9	12,000	550
50Hz							
H-100	116,450	38.3	10	112,000	24	30,000	520
M701F	385,000	41.9	28	312,000	72	90,000	470
M701JAC	448,000	44.0	31	345,000	79	99,000	460
M701JAC	574,000	43.4	40	445,000	103	128,000	450
60Hz							
H-100	105,780	38.2	9	101,000	22	28,000	520
M501GAC	283,000	40.0	22	245,000	55	69,000	500
M501JAC	453,000	44.0	31	345,000	80	100,000	450

• Atmospheric temperature 15°C base (ISO standard)
• Fuel consumption when 100% hydrogen-fired is estimated based on the performance of a natural gas-fired system.

8. Co-firing of Hydrogen and Natural Gas: The Relation between Volume Fraction and Calorie Fraction



9. Hydrogen Production Process

	Common name for hydrogen	Origin & Production Method	Related Products & Technologies in MHI Gr.
Carbon-free Hydrogen	Green	Renewable Electricity → Electrolysis $H_2O \rightarrow H_2 + ½O_2$	Wind Turbines Water Electrolysis Equipment (SOEC, AEM)*
	Pink	Nuclear Heat → Pyrolysis/Electrolysis $CH_4 \rightarrow 2H_2 + C$	High-temperature Gas-cooled Reactor
	Turquoise	Fossil Fuel → Pyrolysis $CH_4 \rightarrow 2H_2 + C$	Methane Pyrolysis Technology
	Blue	Fossil Fuel → Reforming & CO_2 Capture $CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$	Natural Gas Reforming Apparatus Coal Gasifier CO_2 Capture Technology
Conventional Hydrogen (with CO_2 emission)	Gray	Fossil Fuel → Reforming (CO_2 release into the atmosphere) $CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$	Natural Gas Reforming Apparatus Coal Gasifier

*SOEC = Solid Oxide Electrolysis Cell
AEM = Anion Exchange Membrane

Why is colorless and transparent hydrogen turquoise?

As shown in the table above, carbon-free hydrogen is color-coded according to its origin and production method. Although turquoise hydrogen is derived from fossil fuels thus making it blue, it does not generate CO_2, which causes global warming, during the manufacturing process thus also making it green. So, mixing two colors gives turquoise, today's hot trendy color!

What kind of hydrogen transport and storage methods are there?

The main methods are high pressure compression (most common), use of metal (high transport and storage efficiency), conversion to other substances (for lightweight and compact storage), use of pipelines (for stable mass transport). Nevertheless, each has its own challenges, so we are intensively researching toward the early realization of a hydrogen society.

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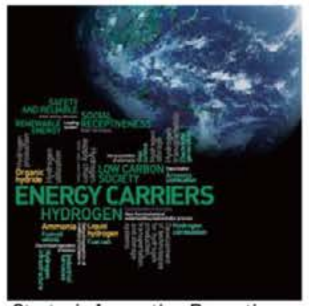
CO_2-Free Energy (Ammonia)



Strategic Innovation Promotion Program (SIP) Energy Carriers[(1)]

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In order to abide by the Paris Agreement, it is necessary for CO_2 emissions to be reduced to net zero in the second half of this century, and in other words, fuel that emits no CO_2 (CO_2-free fuel) is in demand. Among such fuel, ammonia is a portable fuel which is easy to carry, and it can be easily produced from natural gas. In addition, the capture and storage of CO_2 emitted in the production of ammonia prevent the emission of CO_2. The production of ammonia has a long history, and it is now distributed at relatively low prices throughout the world. The use of ammonia by direct combustion is also becoming feasible through research on Energy Carriers in the Strategic Innovation Promotion Program (SIP). We hope that a system for using CO_2-free fuel will be developed and such fuel will be used to prevent global warming.

1. Introduction

(1) Paris Agreement and zero CO_2 emissions target

In December 2015, the Paris Agreement was adopted. The general objective of the Paris Agreement is to cap the increase in the global average temperature at 2°C above pre-industrial levels. In addition, in consideration for countries especially vulnerable to climate change, it stipulates that efforts to limit the temperature increase to 1.5°C should be pursued.

To that end, the long-term goal that total global greenhouse gas emissions should be limited to the amount that the ecological system could absorb in the second half of this century was set. This goal is intended to reduce greenhouse gas emissions by human activities to substantially zero.

In order to abide by the Paris Agreement, CO_2 emissions reduction in every field, the reduction of CO_2 emissions to zero in the second half of this century and the introduction of methods for reducing CO_2 in the atmosphere known as negative emission technologies, are necessary.

(2) Need for CO_2-free fuel

In recent years, the introduction of renewable energy such as solar power and wind power has been promoted, and the ratio of renewable energy used in the electric power sector will further increase. In the future, the need for CO_2-free fuel will be diversified, for example, for use in time zones that cannot be covered by renewable energy, for the load adjusting function of electric power, for uses as heat sources of general industries where it is difficult to use renewable energy and for use in fields such as transportation where CO_2 capture and storage cannot be applied.

In Japan, the study of the use of hydrogen energy has been promoted since the WE-NET Project was carried out. Recently, the use of hydrogen has been studied for the purpose of preventing global warming rather than enhancing energy security.

For the transportation of hydrogen, the use of liquefied hydrogen, organic hydride and ammonia has been studied. If the production of hydrogen without the emission of CO_2 is made possible, the remaining challenge is how to transport and use hydrogen in economical ways.

In any case, the provision of inexpensive and CO_2-free fuel will be demanded in various fields in the future.

(3) SIP Energy Carriers

We have conducted research and development on liquefied hydrogen, organic hydride and ammonia as "Energy Carriers" in the Strategic Innovation Promotion Program (SIP). The research and development of the production of carriers (i.e., production from petroleum, natural gas and coal and production from renewable energy), transportation and utilization (i.e., use as hydrogen and direct use of ammonia) have been conducted in the 5-year plan since fiscal year 2014. In the production of CO_2-free fuel such as hydrogen and ammonia from fossil fuel such as petroleum, natural gas and coal, CO_2 capture and storage (CCS) is indispensable. We also conducted testing and research for the inexpensive production of hydrogen through the electrolysis of water using electric power and high-temperature heat produced from renewable energy. **Figure 1**[(1)] shows an overview of testing and research on energy carriers.

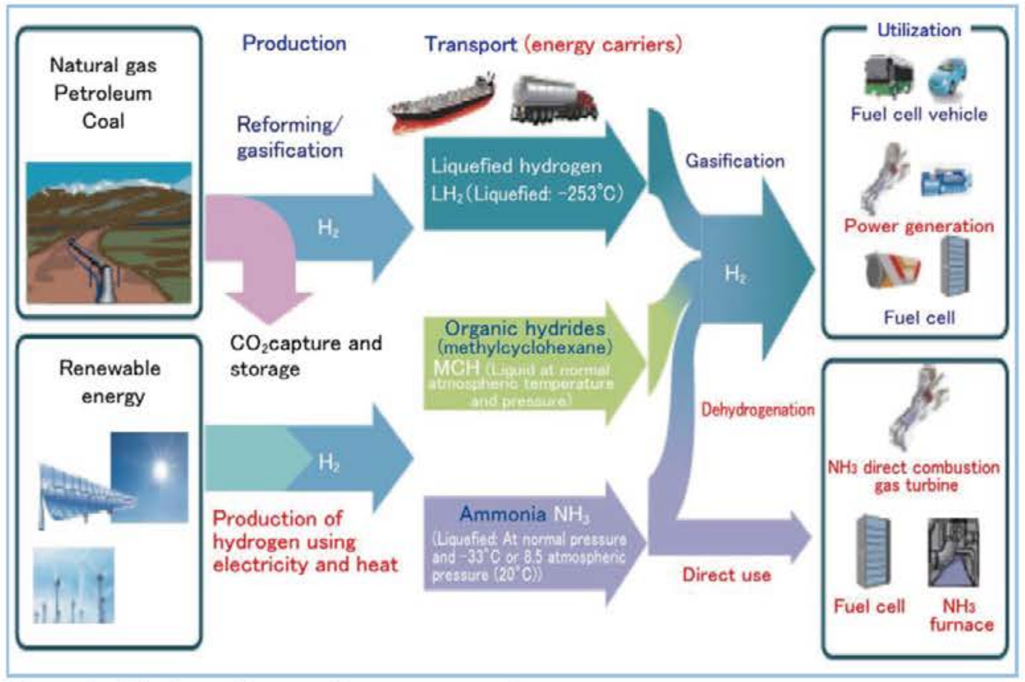

Figure 1 Testing and research on energy carriers

2. Efforts for SIP Energy Carriers

(1) Testing and research on energy carriers as fuel

Testing and research on Energy Carriers[(1)] have been conducted in the 5-year plan from FY2014 to FY2018 and three methods for carrying hydrogen have been evaluated.

a. High-temperature solar heat supply system
b. Hydrogen production using heat
c. Development of ammonia synthesis process using CO_2-free hydrogen
d. Basic technology for hydrogen station using ammonia
e. Ammonia fuel cell
f. Ammonia direct combustion
g. Development of hydrogen supply technology using organic hydride
h. Development of cargo loading/unloading system for liquid hydrogen and the relevant rules for operation
i. Development of hydrogen engine technology

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j. Safety assessment of energy carrier

This research on hydrogen production and the utilization of hydrogen/ammonia was conducted with the aim of evaluating which methods (including hydrogen transportation methods) are desirable, and to represent Japan's trailblazing development of hydrogen utilization technology ahead of other countries. In the latter half of the 5-year plan, research mainly focused on the direct use of ammonia, and testing and research on ammonia direct combustion in gas turbines, reciprocating engines, boilers and industrial furnaces and direct ammonia use in solid oxide fuel cells (SOFC) were conducted. In July 2017, ammonia mixed combustion testing was conducted at a coal-fired power plant of Chugoku Electric Power Co., Inc. Through this testing and research, the prospect of putting ammonia direct combustion into actual use was obtained, which was a significant outcome of testing and research on energy carriers.

(2) Evaluation of three methods

Japan has few petroleum, natural gas and coal resources, all of which have been conventionally used for fuel. Even if renewable energy is introduced to the fullest extent possible, it is said that it cannot cover all the energy required in Japan. Therefore, it is absolutely necessary to produce CO_2-free fuel from overseas energy sources or import it. In the case of the transport of materials such as fuel in large amounts, the most economical method for liquid or gaseous fuel is to use pipelines, but when transporting over long distances or across the ocean, it must be liquefied and transported by ship.

The liquefying temperature of hydrogen is very low at -253°C and the amount of power required for liquefying it is very large. Furthermore, it is not easy to maintain the temperature at -253°C.

Ammonia becomes a liquid at -33°C and under atmospheric pressure. On the other hand, when ammonia is pressurized, it becomes a liquid at 8.5 atm and at ambient temperature, providing the advantages of ease of handling and its usability as a direct fuel. Concerning organic hydride, methylcyclohexane produced by adding hydrogen to toluene can be transported at ambient temperature and under atmospheric pressure, but a large amount of energy is required for extracting hydrogen from methylcyclohexane.

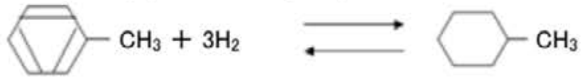
Based on the physical and chemical properties of ammonia and the fact that it is currently distributed throughout the world, the conclusion was reached on "Energy Carriers" in the SIP that ammonia can play an important role as a CO_2-free fuel.

Table 1[(2)] presents a comparison of the physical properties of compressed hydrogen, liquefied hydrogen, methylcyclohexane and ammonia.

Table 1 Physical properties of NH3 and major energy carriers

	Hydrogen content (weight %)	Hydrogen density ($kg \cdot H_2/m^3$)	Boiling point (°C)	Hydrogen release enthalpy change* ($kJ/molH_2$)	Other properties**
Ammonia	17.8	121	-33.4	30.6	Acutely toxic, corrosive
Methylcyclohexane (MCH)	6.16	47.3	101	67.5	Inflammable, irritant
Liquefied hydrogen	100	70.8	-253	0.899	
Compressed hydrogen (350 atm)	100	23.2	—	—	Highly inflammable, highly combustible, explosive
Compressed hydrogen (700 atm)	100	39.6	—	—	

* Carrying hydrogen using the difference of hydrogen between MCH toluene (C7H8) (molecular weight 92) and MCH (C7H14) (molecular weight 98)



* Hydrogen release enthalpy change: Energy required in extraction of hydrogen
** The descriptions in "Other properties" were excerpted from the summary of "Hazardous information" in the MSDS. For the exact properties of each material, see the MSDS for each material.

(3) Effectiveness of ammonia

The physical properties of ammonia are almost the same as those of LPG, and ammonia can be transported using LPG vessels. At present, the production of ammonia amounts to 180 million tons/year globally. About 80% of the production volume is used in fertilizer such as urea, and about 10%, which is 18 million tons/year, is internationally distributed.

At the present time (October 2018), the price of ammonia on an FOB basis in the Gulf of Mexico region in the U.S. is 250US$/T. This price is converted to 14.3US$ in terms of 1 million BTU (MMBTU), which is equal or slightly higher in terms of calorific value compared with the price of crude oil of 70US$/BBL (13.5 US$/MMBTU) (WTI price).

As with LPG, ammonia becomes a liquid when it is pressurized at ambient temperature and it is a portable fuel that is easy to handle in final use.

In particular, when it is used as a fuel for transportation, its ease of transportation at ambient temperature is a significant advantage. However, ammonia is toxic and emits an odor when it leaks, and if it is used near ordinary households, it may cause problems. Therefore, it is considered that ammonia will mainly be used in controlled areas such as in power plants, factories and cargo vessels.

3. Production method of CO_2-free ammonia

In 1913, Germans Haber and Bosch commercialized the process for synthesizing ammonia from hydrogen and nitrogen using an iron-based catalyst, and today the method is used in the production of ammonia. Mitsubishi Heavy Industries Engineering, Ltd. (MHIENG) has delivered many ammonia plants to various countries around the world since 1958. In current ammonia synthesis, natural gas is generally used as a feed stock.

By passing natural gas through a catalyst while heating it together with steam using a steam reformer, the natural gas is converted into hydrogen and CO. After that, air is injected, and the oxygen in the air is used for further combustion to convert the remaining methane into hydrogen and CO, and at the same time, nitrogen is supplied. Steam is added to the CO, which is converted into CO_2 and hydrogen using a catalyst. After that, the CO_2 is separated to produce hydrogen and nitrogen, and then ammonia is synthesized from the hydrogen and the nitrogen.

Figure 2 depicts the balance of CO_2 at a 2000 T/D-scale plant which is a standard ammonia plant. At the ammonia plant, about 2/3 of the CO_2 is separated from the process system, and about 1/3 of the CO_2 is discharged from the exhaust gas of the steam reformer and the auxiliary boiler. By capturing the CO_2 from this flue gases and storing it underground together with the CO_2 from the process system or using it for Enhanced Oil Recovery (EOR), this ammonia plant emits no CO_2. Thus. an ammonia fuel system that does not emit CO_2 can be established.

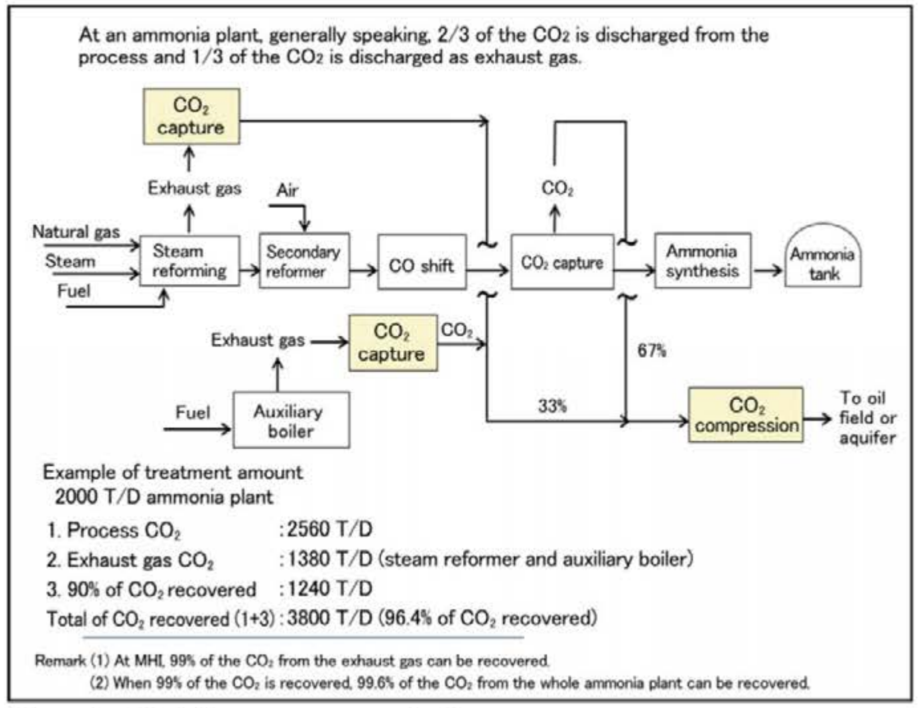
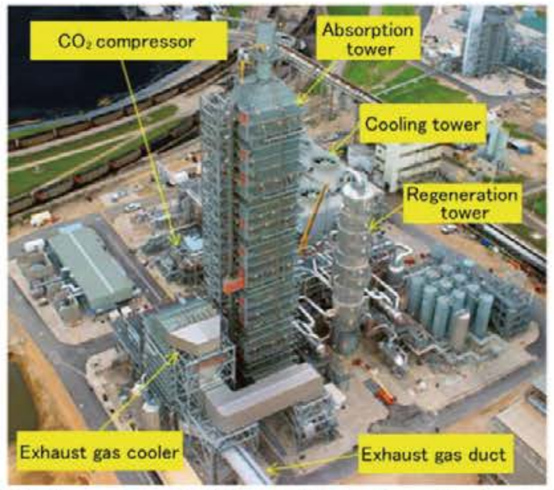


Figure 2 CO_2 balance at an ammonia plant

MHIENG delivered the world's largest CO_2 recovery system to a coal-fired power plant in Texas in the U.S. in January 2017, where the recovered CO_2 is used for EOR at the West Ranch oil field and crude oil is recovered, and CO_2 are stored in an oil reservoir. **Figure 3** gives an overview of the facility for recovering CO_2 from the coal-fired power plant.



NRG Energy, Inc. and JX Nippon Oil & Gas Exploration Corporation
Photo of Petra Nova project

Figure 3 Facility for recovering CO_2 from a coal-fired power plant

Since 2011, in Alabama in the U.S., MHIENG has conducted CO_2 capture from a coal-fired power plant and a demonstration test for storing the captured CO_2 in an aquifer (implemented by SECARB※1) jointly with Southern Company. **Figure 4** illustrates an overview of the CO_2 capture and storage project. As such, CO_2 capture and storage has been conducted on a commercial basis, and the technologies for CO_2 capture from exhaust gas at ammonia plants and the production of CO_2-free ammonia have already been established.

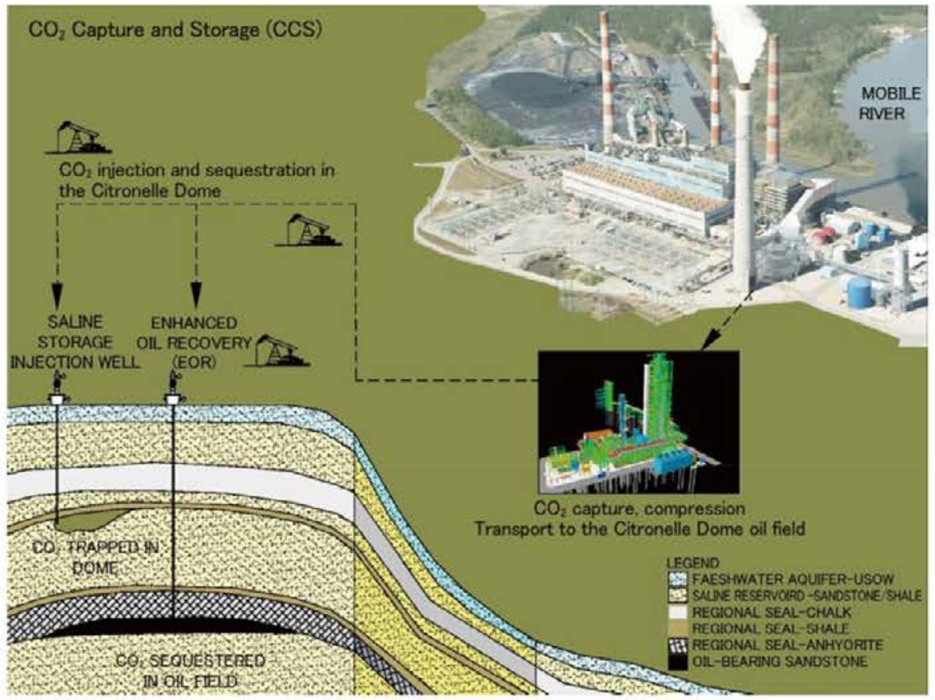


Figure 4 Overview of CO_2 capture and storage project

CO_2 from the process system can be stored as it is a total of 90% of the CO_2 from flue gas can be captured by the CO_2 recovery technology with which MHIENG has a significant amount of experience (KM CDR Process®※2 developed in cooperation with Kansai Electric Power Co., Inc.), and the captured CO_2 is stored together with CO_2 from the process. As a result, 96% of the CO_2 generated in the production of ammonia can be stored. If 99% is captured from exhaust gas, 99.6% of the CO_2 can be stored, allowing the production of ammonia with almost no CO_2 emissions into the atmosphere.

There is another CO_2-free ammonia synthesis method in which electricity produced from renewable energy is used to electrolyze water and separate nitrogen in the air for the synthesis of ammonia. At present, inexpensive natural gas is produced in massive amounts in various places around the world, and therefore ammonia can be produced at a much lower cost by synthesis from natural gas compared with the use of renewable energy.

※1 The Southeast Regional Carbon Sequestration Partnership

※2 KM CDR Process® is a registered trademark of Mitsubishi Heavy Industries Engineering, Ltd. in Japan, the U.S., European Union (EUTM), Norway, Australia and China.

4. History of use of ammonia as fuel

Some people may not be familiar with the use of ammonia as fuel, but looking back to the Second World War, 100 ammonia-powered buses were used in Belgium.

At that time, diesel fuel could not be procured, and out of necessity, ammonia was used as fuel.

In another example from 1959 to 1968, the X-15 manned jet fighter of the U.S. Air Force used ammonia as fuel, and it reached a record speed of Mach 6.7 at an altitude of 107960m. The temperature was very low at an altitude of 100,000 meters, and it is assumed that the fact that ammonia does not solidify at low temperatures was the reason it was chosen as fuel.

5. Conclusion

CO_2-free fuel is strictly intended to prevent global warming. In order to achieve the target of +2°C or lower based on the Paris Agreement, global CO_2 emissions must be reduced to 1/2 by 2050, and advanced countries must reduce CO_2 emissions by 80%. To that end, CO_2-free fuel that can be used everywhere will become more important. MHIENG has already established commercial CO_2-free ammonia production technology and is ready to provide it at any time.

However, ammonia is more expensive than coal or LNG on the basis of its calorific value, and it is more expensive than even crude oil. For ammonia to be widely used as CO_2-free fuel, it seems that some political incentive is necessary in the early stages of introduction.

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