CO_2 Reduction by Gas Engine Cogeneration System (Combined Heat and Power)

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The global movement towards achieving a low-carbon or decarbonized society is accelerating. Being able to supply both heat and power, gas cogeneration systems are a distributed energy system with energy conservation features. Gas engines are part of the equipment used for electricity generation in gas cogeneration systems. Mitsubishi Heavy Industries Engine & Turbocharger Co., Ltd. (MHIET) offers a lineup of gas engines covering the range of 315 kW to 5,750 kW per unit, and can therefore provide products for use as small-scale distributed power sources, cogeneration systems for facilities, factories and such, or power generation for utility supplies using multiple units. This report presents MHIET's gas engine product lineup and the characteristics, CO_2 reduction effects, and the prospect of technological advancement.

1. Introduction

In light of the global trend towards decarbonization and growing tensions over global energy security, the "6th Strategic Energy Plan" was formulated by the Japanese government in October 2021. It aims to achieve carbon neutrality by 2050, and sets a target of 46% reduction in greenhouse gas emissions by 2030 relative to the 2013 baseline levels.

City gas, which is the fuel for gas engines, is produced from natural gas. As shown in **Figure 1**, natural gas emits less CO_2 than any other fossil fuels. Switching the fuel to natural gas from other types leads to low carbon used in generating heat and power. In the future when technologies such as methanation to synthesize methane from hydrogen and CO_2 are established, gas engines will also be able to be fired with carbon-neutral synthetic methane. In recent years, gas engines in which hydrogen is co-fired for the period of fuel transition or hydrogen is exclusively fired for carbon-neutral have been in development. The gas engine technologies using hydrogen as fuel have nearly been established.

In a cogeneration system, heat is generated together with power. It is a system enabling the most effective utilization of energy through simultaneous use of heat and power, and also show superior energy conservation performance. Being laid underground, the gas pipeline in Japan is less affected by wind and rain and is earthquake-proof in most part. For this reason, it is considered that there is a low risk of the gas supply being interrupted in the event of natural disasters. The gas engine cogeneration systems operable during power outages can continuously supply power and heat in a stable manner even in such emergencies.

As described, gas engine cogeneration systems can support fuel transition towards the goal of carbon neutrality by 2050, and they are expected to have a part to play in the distributed energy systems that contribute to strengthening resilience and improving energy conservation.

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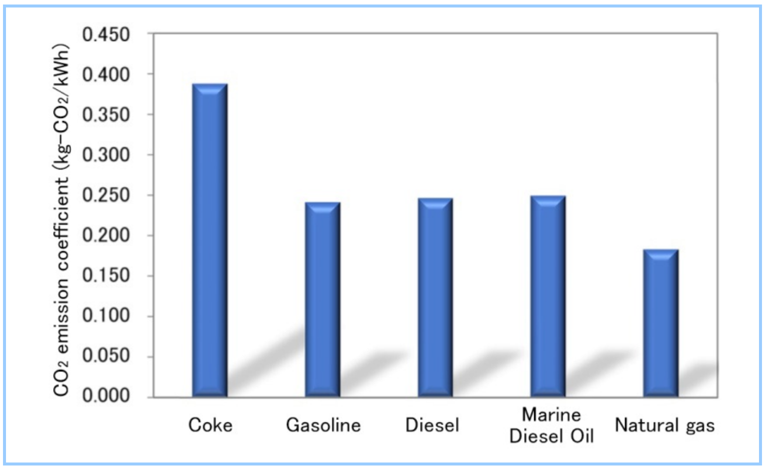

Figure 1 Fuel type and CO_2 emission coefficient

2. Product lineup and characteristics

Since the early 1990s, MHIET has been developing gas engines, which are the electricity generation equipment in gas cogeneration systems, and has delivered them as a distributed cogeneration system to many customers. MHIET's gas engine lineup includes the high-speed gas engine GSR series covering the power output range of 315 kW to 1,500 kW, the space-saving GNB with an output of 2,000 kW and a higher power generation efficiency than GSR series, and the medium-speed gas engine KU30GSI series covering the range of 3,650 kW to 5,750 kW. Our products can be adapted for use as small-scale distributed power sources, cogeneration systems for facilities, factories and such, or power generation systems for utility supplies. **Table 1** lists the principal specifications of MHIET gas engines, while **Figure 2** shows photographs of their exterior views.

Table 1 Gas engine production lineup

<table>
<tr><td colspan="2">Engine type</td><td></td><td colspan="2">GS6R2</td><td>GS12R</td><td colspan="2">GS16R</td><td colspan="2">GS16R2</td><td>G16NB</td><td>12KU 30GSI</td><td>14KU 30GSI</td><td>16KU 30GSI</td><td>18KU 30GSI</td></tr>
<tr><td colspan="2">Bore/stroke</td><td>mm</td><td colspan="2">170/220</td><td colspan="3">170/180</td><td colspan="3">170/220</td><td colspan="4">300/380</td></tr>
<tr><td rowspan="2">50 Hz</td><td>Power output</td><td>kW</td><td>315</td><td>500</td><td>700</td><td>930</td><td>N/A</td><td>1, 000</td><td>1,500</td><td>2,000</td><td>3,800</td><td>4,450</td><td>5,100</td><td>5,750</td></tr>
<tr><td>Engine speed</td><td>min⁻¹</td><td>1,000</td><td colspan="3">1,500</td><td>N/A</td><td>1,000</td><td colspan="2">1,500</td><td colspan="4">750</td></tr>
<tr><td rowspan="2">60 Hz</td><td>Power output</td><td>kW</td><td>380</td><td>450</td><td>610</td><td>815</td><td>850</td><td>1,000</td><td>1,200</td><td>N/A</td><td>3,650</td><td>4,250</td><td>4,900</td><td>5,500</td></tr>
<tr><td>Engine speed</td><td>min⁻¹</td><td colspan="7">1,200</td><td>N/A</td><td colspan="4">720</td></tr>
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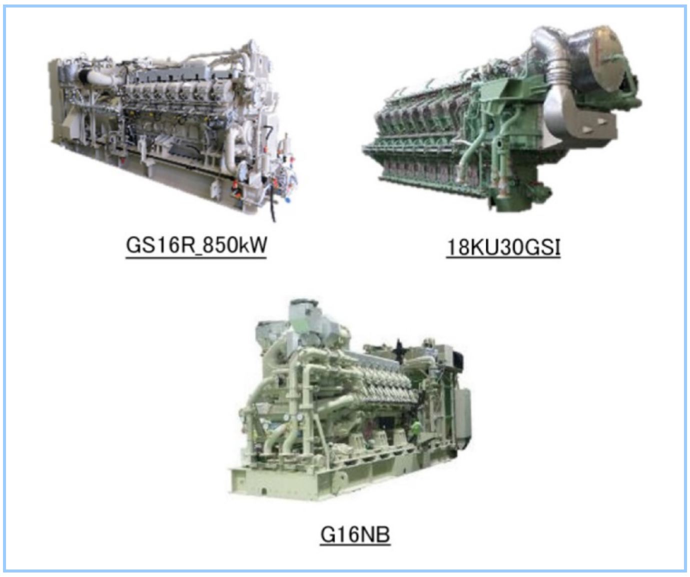

Figure 2 Exterior views of our gas engines

In gas cogeneration system, the equipment used for power generation may be gas turbines, gas engines, or in more recent cases, fuel cells. Among them, gas engines are often used at sites with a power output range between several hundred kW and several tens of MW using multiple units. Gas engines have high starting performance enabling them to reach the rated output within a few minutes, and high load-following capabilities with a flexible response to the power required to be supplied. In recent years, the demand for gas engines as a regulated power supply for renewable energy is also growing. Moreover, the drop in power generation efficiency at partial load is small. Especially at a plant in which multiple units are in operation, it is possible to keep the power generation efficiency high by adjusting the number of units in operation and the resulting output, as shown in **Figure 3**.

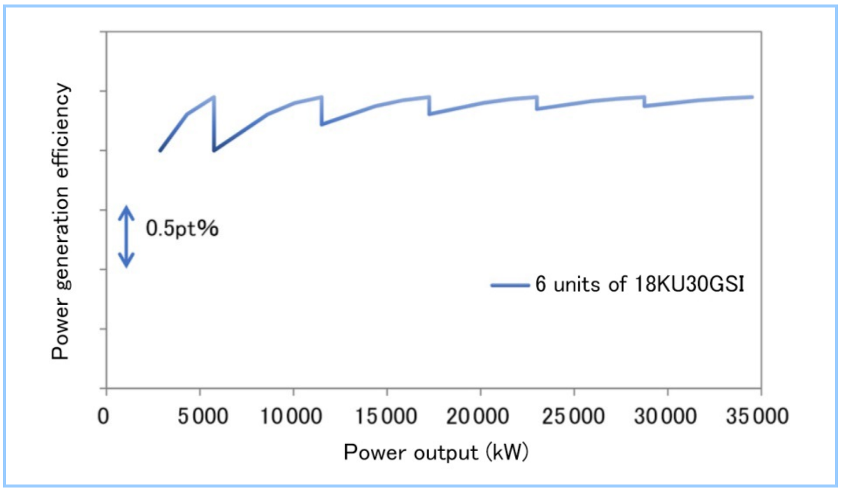

Figure 3 Power generation efficiency with use of multiple units

2.1 High-speed gas engines

Since their market release in 1991, the high-speed gas engine “GSR” series have enhanced the reliability and the efficiency in production and parts supply by making about 80% of the parts used be the same as the diesel engine that serves as the base of the GSR products. The power output per unit ranges from 315 kW to 1,500 kW. The application of the Miller cycle has helped realize the highest power generation efficiencies in the same output classes. Furthermore, as the GSR series feature superior load input performance and black out start (BOS), they are also used as equipment that can satisfy the needs for power supply security in times of emergency. A radiator version of the GSR lineup has also been made available to meet business continuity plan (BCP) needs, and demand is growing after the Great East Japan Earthquake. The other GSR applications include the use as a normal power source for high-rise buildings, factories, commercial facilities, hospitals and such, and a regulated power supply during peak-cut operation.

“GNB” is a high-speed gas engine with an output of 2,000 kW. It was developed based on the well-proven GSR series as a high-output and high-efficiency model. It features a two-stage turbocharger system, which is the world’s first as a gas engine of the same output class. As a result, the output per engine displacement volume or speed has been increased by 33%, while the power generation efficiency has been improved by approximately 9% (3.6 pt%) from the GS16R2 model with the same engine speed. The power generation efficiency is one of the world’s highest among the high-speed engines of the same class. When it comes to utilization of heat, the energy use efficiency can be further elevated by combining with the recovery of not only steam and high-temperature water but also warm (medium-temperature) water with the aim of supplying hot water. The installation area required for a power generation package can be reduced by about 40%, when compared with a 2,000 kW power generation facility in which two 1,000 kW units of the existing models are operated. Energy supply therefore becomes possible in places with a limited installation area such as the inside of buildings and commercial facilities. The GNB model can contribute to improving power supply security as well as energy conservation thanks to features such as high power generation efficiency, superior load input performance and the BOS function like the GSR series.

2.2 Medium-speed gas engines

The medium-speed gas engine “KU30GSI” series achieve the world’s highest levels of efficiency in terms of the total efficiency of power generation and steam, enabled by increasing the power generation efficiency and the exhaust gas temperature. The KU30GSI, the maximum power output of which is 5,750 kW/unit, is used in various applications, such as CHP, private power generation in factories, and PPS (Power Producer and Supplier) with multiple units, because of high starting performance and load following capability.

In Japan, there are some cases in which waste hot water from private power generation systems cannot be utilized effectively. Therefore, in the KU30GSI series, the outlet temperature of engine cooling water was raised to 120°C, which can serve as a stable source of heat to produce a low-pressure steam. The obtained saturated steam is compressed to add to the steam produced by other components such as the exhaust gas boiler. This established “cogeneration system (CGS) with all steam recovery” has been commercially available since May 2015. In the 18KU30GSI model (50 Hz), the amount of steam produced has been increased roughly by a factor of 1.5 from about 3.4 tons/h to about 5.1 tons/h, realizing the world’s highest “power generation and steam-combined” efficiencies of 70% or higher. In the existing gas engines, it was difficult to improve both efficiencies in power generation and steam. However, our CGS with all steam recovery has achieved a heat and power energy balance that could not have been possible before, and the amount of steam produced is now comparable to the lower limit of small gas turbines.

Although the KU30GSI series employ a spark plug ignition system, about 80% of the parts used are the same as the previous gas engine KU30GA, a previous micro pilot ignition gas engine with a different ignition system, and KU30A diesel engine, on which the KU30GA was based. The KU30GA model that is currently in operation can therefore be remodeled to the latest KU30GSI model, enabling full use of the existing facilities and effectively extending the life of field operating engines.

The GSR, GNB and KU30GSI models make it possible for a plant to be operated with high efficiency and energy conservation according to the demand for power and heat. These models can also contribute to enhancing energy security, because off-the-grid power supply to important equipment is possible even when the power supply from the grid is interrupted.

3. Reduction in CO_2 emissions

As carbon dioxide (CO_2) is one of the greenhouse gases that contribute to global warming, the importance of reducing CO_2 emissions is rapidly increasing when promoting low-carbonization and decarbonization towards the achievement of a carbon-neutral society.

In a gas cogeneration system, energy can be utilized most effectively through simultaneous supply of heat and power. While the system features superior energy conservation performance, this chapter describes its CO_2 emission reduction effect in particular.

As shown in **Figure 4**, the CO_2 emission coefficient for power generation in Japan shows a downward trend from the 1970s level of 0.60 kg-CO_2/kWh. Although it increased to 0.57 kg-CO_2/kWh in 2013 mainly because of the long-term shutdowns of nuclear power plants in the aftermath of the Great East Japan Earthquake in 2011, it dropped to about 0.44 kg-CO_2/kWh in 2020[2].

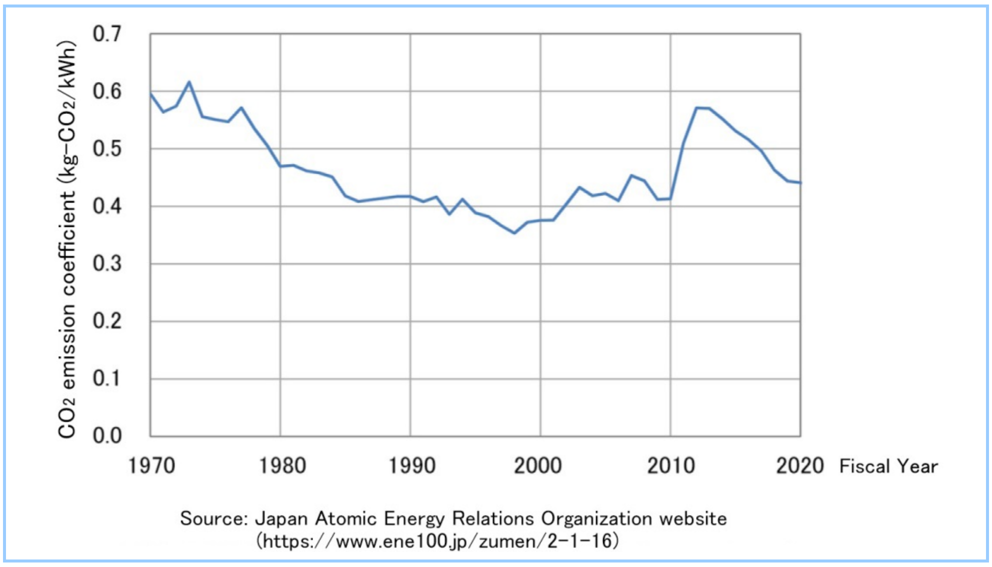

Figure 4 Temporal change in CO_2 emission coefficient for power generation in Japan

In the gas engine cogeneration system, energy can be effectively utilized by recovering the waste heat produced in the process of power generation by gas engine, in addition to the generated power itself. Waste heat can be recovered in the form of steam in the boiler using the exhaust gas heat from the gas engine, or as hot water from the engine's cooling water. **Figure 5** compares CO_2 emissions between the gas engine cogeneration system and the grid power supply combined with the city-gas boiler, when the demand for heat and power is the same. As shown in the figure, when power is provided by the grid and heat supply relies on the boiler or water heater, CO_2 is emitted from each source. In contrast, the gas engine cogeneration system's simultaneous supply of heat and power can reduce CO_2. **Figure 6** shows the results of CO_2 emission coefficient estimation for MHIET gas engines, based on the concept shown in Figure 5. In our gas engine cogeneration system, the CO_2 emission coefficient for power generation and steam roughly ranges from 0.27-0.34 kg-CO_2/kWh. If all the hot water is also recovered, it can fall as low as 0.23-0.27 kg-CO_2/kWh. Suppose that all the energy that can be produced from power generation and waste heat is supplied by the grid (Tokyo Electric Power Company Holdings, Incorporated: 0.452 kg-CO_2/kWh in 2021[(3)]) and the city-gas boiler. When compared with the obtained CO_2 emission coefficient, the CO_2 reduction rates by the cogeneration system are 8% to 23% in the case of power generation and steam, and 21% to 32% in the case of hot water recovery included, respectively. The CO_2 emission coefficient for power generation in 2013 was 0.57 kg-CO_2/kWh in Japan. The reduction effect becomes 34% to 43% in this case.

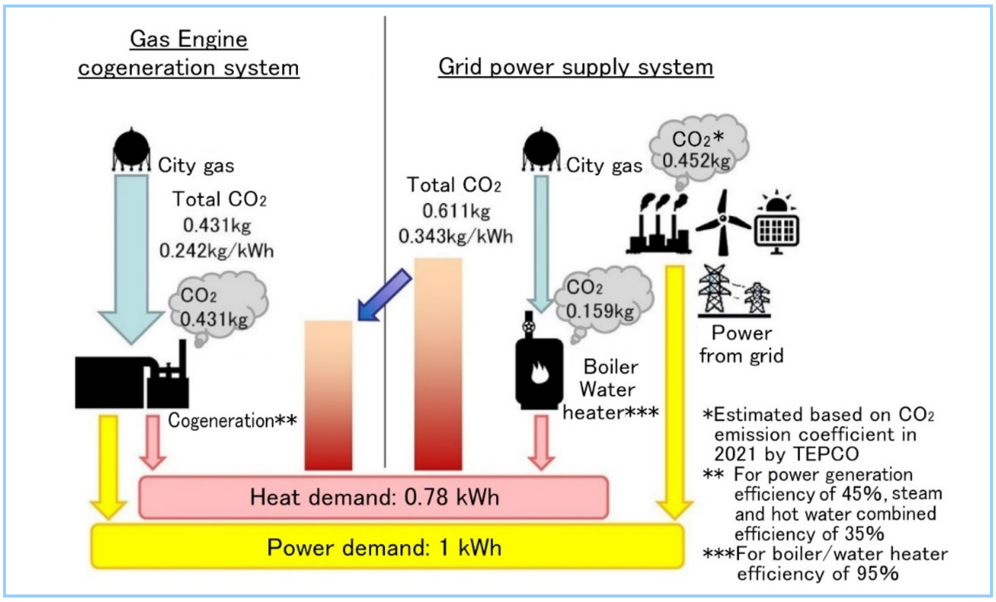

Figure 5 Comparison between gas engine cogeneration system and grid power supply system

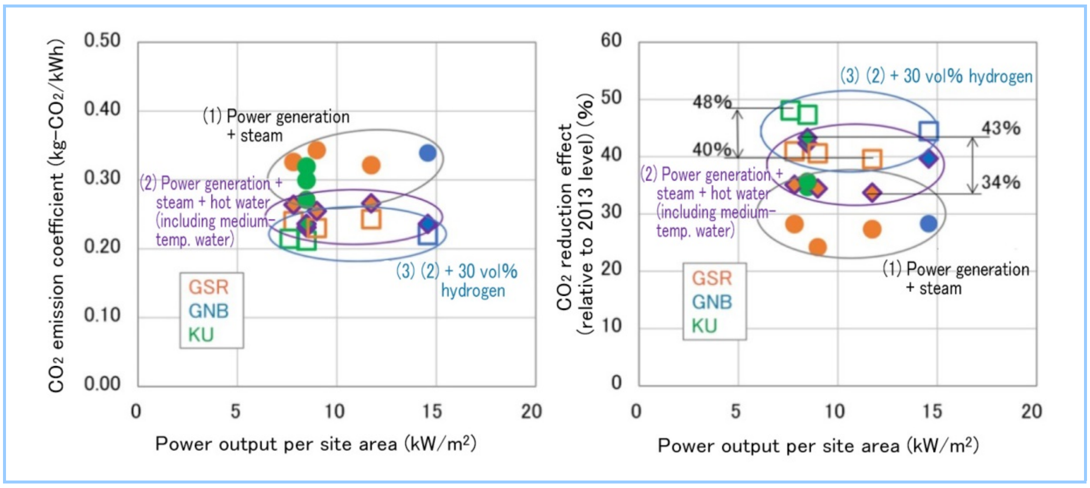

Figure 6 Estimates of CO_2 emission coefficient and reduction rate (relative to 2013 level)

Furthermore, as hydrogen blended gas in which hydrogen is blended with city gas may be used in the period of fuel transition until carbon-neutral synthetic methane or 100% hydrogen is used, the hydrogen co-firing technology for gas engines is also in the process of being established. If 30 vol% of hydrogen is co-fired, the CO_2 reduction rate from the current grid power and city-gas boiler system can be in the neighborhood of 28% to 38% considering power generation and recovery of steam, high-temperature water and medium-temperature water. The reduction rate may become as large as around 40% to 48% when compared with the 2013 levels.

As described, the gas engine cogeneration systems can have a large CO_2 reduction effect while making use of the existing systems.

4. Prospect of technological advancement

According to the Strategic Energy Plan[1] in Japan, hydrogen is expected to makes various contributions to achieving a carbon-neutral society, including decarbonization of heat utilization for which electrification is difficult, zero emissions from power sources, and decarbonization in the industrial sector. The aim is to increase the hydrogen supply to a maximum of 3 million tons/y by 2030 and about 20 million tons/y by 2050. The hydrogen supply cost will be reduced to 30 JPY/Nm^3 (CIF price) by 2030 and 20 JPY/Nm^3 or below by 2050. The cost is expected to become nearly as low as fossil fuel in the long term.

Although it is necessary to use hydrogen as fuel in gas engines as well for the achievement of a carbon-neutral society, one of the technical challenges in using hydrogen lies in its combustion characteristics. When compared with city gas, hydrogen is broader in the flammability range, faster in the burning velocity, and lower in the minimum ignition energy. Therefore, when used in an engine, it is prone to abnormal combustion such as knocking, pre-ignition and backfiring.

Having a pre-chamber, MHIET's gas engines realize high efficiency combustion. This is realized by stable ignition by making the ratio of air to combustion gas in the pre-chamber almost the same as the theoretical amount of air required for complete combustion, while increasing the excess air ratio in the main combustion chamber to approximately 2 for ultra-lean combustion with reduced emissions of NOx and such. **Figure 7** shows a conceptual diagram of excess air ratio and laminar burning velocity. As hydrogen is characterized by the fast burning velocity, burning in the main combustion chamber is considered to get too quick to control if the gas engine has a pre-chamber. Although the burning velocity can be controlled by increasing the excess air ratio, the output or co-firing ratio may be limited depending on the turbocharger's performance because the amount of air required is increased. As such, the technology enabling the turbocharger to achieve higher pressure is expected to be applied more widely for the use of hydrogen in the future.

When it comes to combustion systems, the burning velocity can be reduced by adopting a single-chamber configuration instead of a pre-chamber. Especially in the case of 100% hydrogen firing, the performance will be optimized according to the turbocharger's performance after adopting a single-chamber combustion system, so that stable operation becomes possible. When pure hydrogen is fired, in addition to the aforementioned configuration change, it becomes necessary to have an appropriate combustion control system for optimizing the specifications related to the formation of air-fuel mixture and the combustion conditions such as the positioning of hydrogen supply into the engine, the compression ratio and the air-to-fuel ratio, as well as for monitoring the combustion. Based on these characteristics of hydrogen, MHIET has used a single-cylinder test engine for evaluation, and are currently verifying the specifications suitable for 100% hydrogen firing.

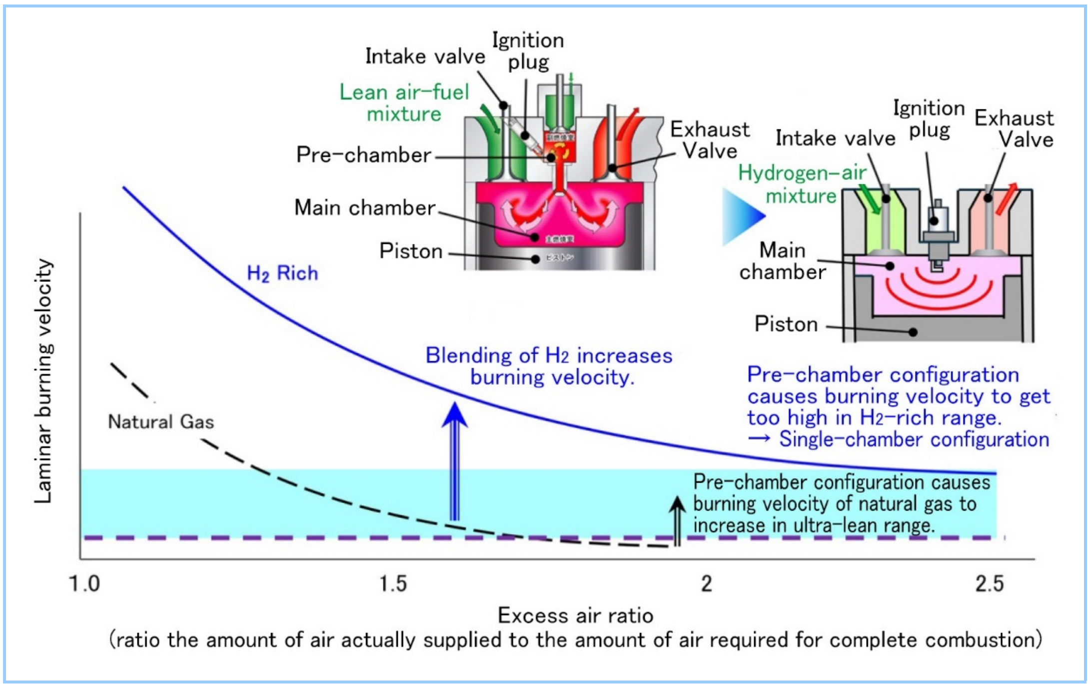

Figure 7 Conceptual diagram of air-to-fuel ratio and laminar burning velocity

Let us next consider the technological outlook for 2030. According to the breakdown of power sources projected for 2030, fossil fuels such as oil, coal and LNG will be reduced to about 41%; nuclear power and renewable energy will be increased to 20% to 22% and 36% to 38%, respectively; and hydrogen and ammonia will be around 1%[(1)]. To enable social implementation of hydrogen, it has to be supplied in a cost-competitive manner compared to other energy sources throughout the supply chain from production to transport/storage to use. Although large-scale utilization in areas such as coasts, and self-consumption and peripheral utilization/applications using equipment such as electrolyzers are being promoted as implementation models, the optimal supply chain for hydrogen has not been defined unambiguously. The current stage is to continue discussing how to minimize the cost for hydrogen supply through developing a social implementation model.

In order to realize a hydrogen society, it is considered necessary to promote the development of a large-scale hydrogen supply chain and the creation of demand in an integrated manner. For the use of hydrogen in the power generation sector, new combustion equipment enabling 30 vol% hydrogen co-firing has been developed, which requires only minimum remodeling for introduction even in the latest large gas turbines (gas turbine combined cycle or GTCC), and the research is under way to increase the co-firing ratio with a view to achieving 100% hydrogen firing[(4)]. Even in gas engines, hydrogen co-firing within a range that does not involve extensive remodeling is considered to support power generation demand. As indicated by the regional development of hydrogen supply chains, the realization of hydrogen co-fired power generation using a gas engine cogeneration system with high power generation efficiency may be seen in relatively small-scale power generation systems.

The shift to natural gas and the introduction of gas engine cogeneration are expected to be promoted during the transition period until a hydrogen society is realized. When it comes to the use of fossil fuels, it is believed carbon storage and reuse through carbon dioxide capture, utilization and storage (CCUS) are expected to promote. Mitsubishi Heavy Industries, Ltd. (MHI) has delivered its own CO_2 capture process called KM CDR Process™ * to coal-fired power plants and chemical plants. Their scale has reached 500 t-CO_2/day or more. To make this technology address the reduction needs at small-scale sources of CO_2, we are developing compact CO_2 capture equipment[(5)]. A demonstration test using MHIET's GS16R2 gas engine with a power output of 1,500 kW, which is combined with the compact CO_2 capture equipment, is under way at MHI Sagamihara Machinery Works. **Figure 8** shows the exterior view of the CO_2 capture equipment used in the demonstration test.

* KM CDR Process™ is a registered trademark of Mitsubishi Heavy Industries, Ltd. in Japan and other countries and a registered trademark of Kansai Electric Power Co., Inc. in Japan, the European Community (CTM), Norway, Russia and Australia.

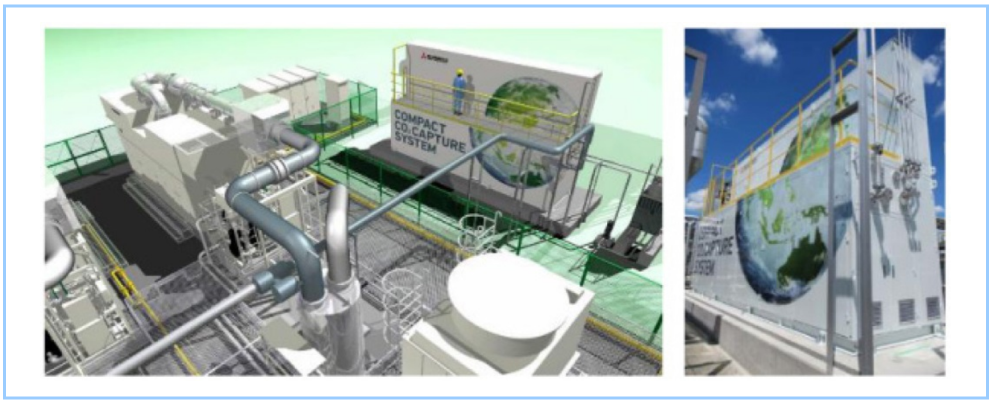

Figure 8 1,500kW power generation system using GS16R2 and compact CO_2 capture system

Moreover, as the increased ratio of renewable energy as a power source is aimed at, solar and wind power generation are regarded as important power sources for further decarbonization. On the other hand, renewable energy faces the issue of being unstable power sources with varying amounts of power generated depending on climate and weather conditions. The demand for backup power supply is expected to grow, because it is needed when the amount of power generated by renewable energy is decreased. Featuring high load-following capability and low CO_2 emissions, gas engines are expected to be used more frequently as a backup power source. Furthermore, hybrid power generation in which storage batteries and gas engine cogeneration systems are used in a combined manner can serve as a more stable power source, and this is considered to be one of the solutions to facilitate the use of renewable energy. MHIET has developed and validated a hybrid power generation system called EBLOX, in which the 500kW GS6R2 gas engine, a storage battery facility (500 kW× 0.5 h), and a 311kW solar power generation system are used in a combined manner[(6)]. **Figure 9** shows the exterior view of EBLOX. It is considered that such hybrid power generation systems will also be used as an independent power supply system in off-grid areas.

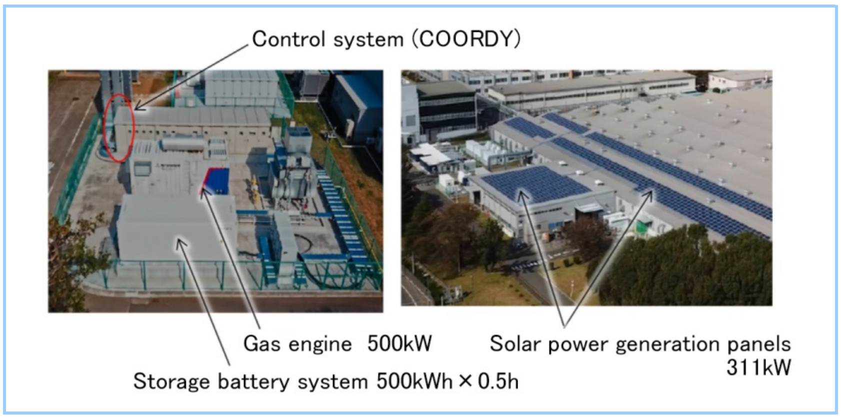

Figure 9 Demonstration facility of hybrid power generation system (EBLOX)

Towards achieving carbon neutrality by 2050, synthetic methane technology is expected to be established in order to make the decarbonization transition smooth. Gas engine cogeneration systems have the potential to be used for any of the following: hydrogen co-firing, 100% hydrogen firing, and synthetic methane. As their hybrid power generation systems with renewable energy have also been in development, they are looked on as being the key system that supports future energy demand as a distributed energy system.

5. Conclusion

Gas engine cogeneration systems are a distributed energy system with energy conservation features. MHIET offers a lineup of these systems with a wide range of outputs. The gas engines have the potential to be fired with pure hydrogen or synthetic methane for the achievement of a carbon-neutral society in the future, and can also be used for hydrogen co-firing during the period of fuel transition. When power generation, steam and hot water (including medium-temperature water) are utilized in a combined manner through MHIET's gas engine cogeneration systems, the CO_2 emission coefficient is expected to be reduced roughly by approximately 34% to 43% from the 2013 levels obtained for the combined use of grid power and city-gas boilers. If 30 vol% of hydrogen is co-fired, the reduction effect will be approximately 40% to 48%. As indicated by the regional development of hydrogen supply chains, the simultaneous supply of heat and power using hydrogen as fuel in a gas engine cogeneration system with high power generation efficiency will be realized first as a distributed energy system in relatively small-scale power generation of several hundred kW to several tens of MW.

Backed by the reliability based on numerous proven records, MHIET's gas engine cogeneration systems are expected to function as the key system that supports energy demand for the achievement of a carbon-neutral society in the future, including during the period of fuel transition.

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