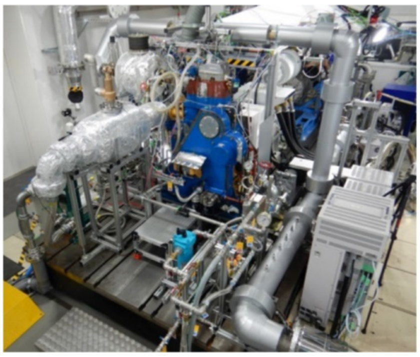
New Engine Products for a Decarbonized Society



Mitsubishi Heavy Industries Engine & Turbocharger, Ltd.
Engine & Energy Division

There is an urgent challenge to reduce CO_2 emissions for a carbon-neutral society and this requires reciprocating engines to adapt accordingly. Mitsubishi Heavy Industries Engine & Turbocharger, Ltd. (MHIET) has been working on various technologies and products to reduce CO_2 emissions from its engines to meet this goal.

1. Making carbon neutrality a reality

Engines can achieve carbon neutrality in two different ways. One is to mainly use carbon-neutral fuels and the other is to capture CO_2 from the exhaust gas. Because the latter is unrealistic due to the difficulty of downsizing CO_2 capture facilities while keeping costs low, using alternative fuels is the most efficient option.

Engines can use two types of carbon neutral fuels; biofuels and hydrogen. **Figure 1** shows different kinds of hydrogen-based fuels. Carbon-neutral hydrogen can be produced primarily by either producing hydrogen through steam methane reforming and then capturing and storing the CO_2 (Blue Hydrogen), or, using renewable energy to extract hydrogen from water through hydrolysis (Green Hydrogen).

As shown in Figure 1, the hydrogen produced by these methods can be both used as-is, or converted into various other fuels depending on the purpose or transportation. Reciprocating engines have the advantage of being able to use a wide range of fuels by optimizing combustion without significantly changing their basic structure and requiring less fuel purity than fuel cells.

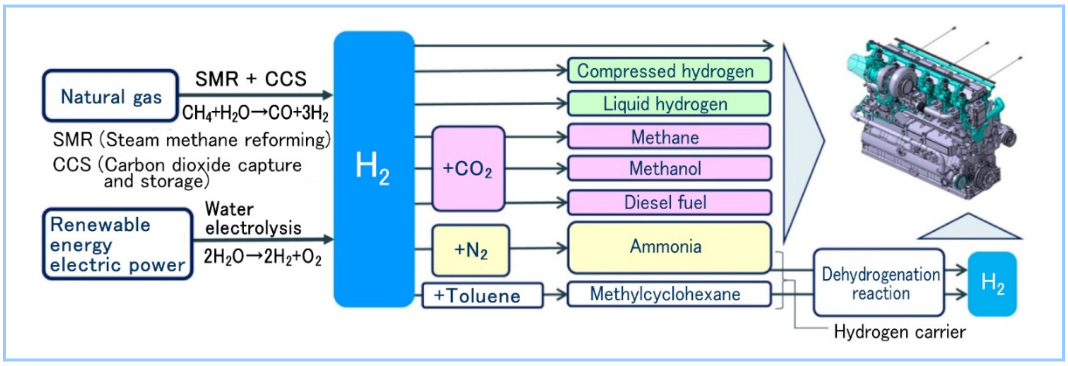


Figure 1 Various types of hydrogen-based fuels

Figure 2 shows the possibilities for power-generating engines to achieve carbon neutrality. It is expected that at first, they will use hydrogen-mixed natural gas, then they will increase the ratio of hydrogen gradually until it is 100% hydrogen based. Although not included in Figure 2, marine engines may use ammonia as a promising alternative since it is unlikely to install hydrogen on ships due to the large volume per calorific value. Currently, marine engines mainly use diesel fuel. However, they are expected to shift to natural gas toward 2030 followed by gradually shifting to ammonia.

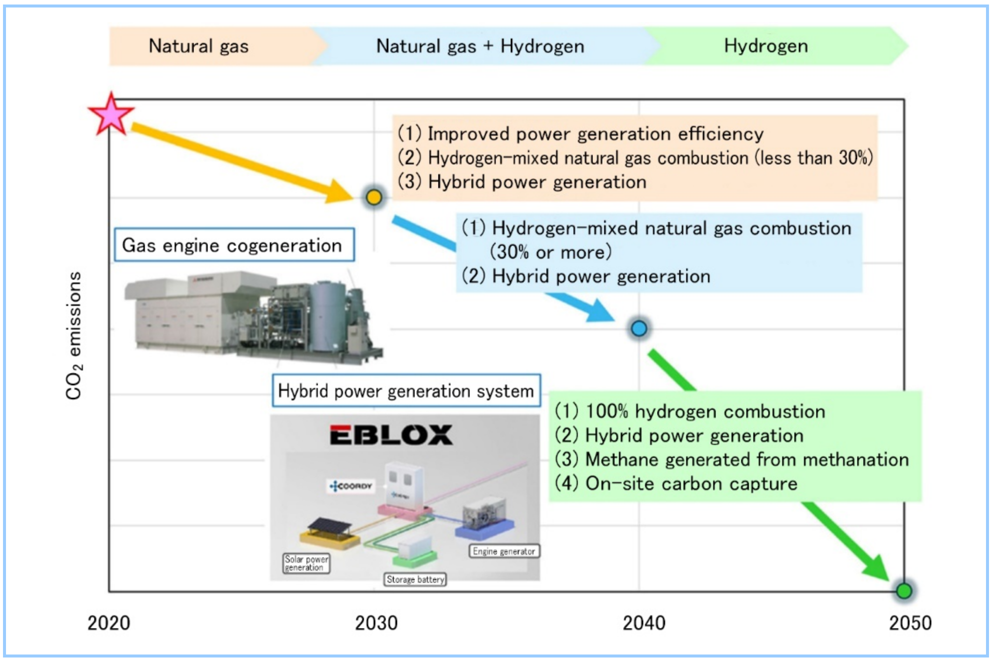
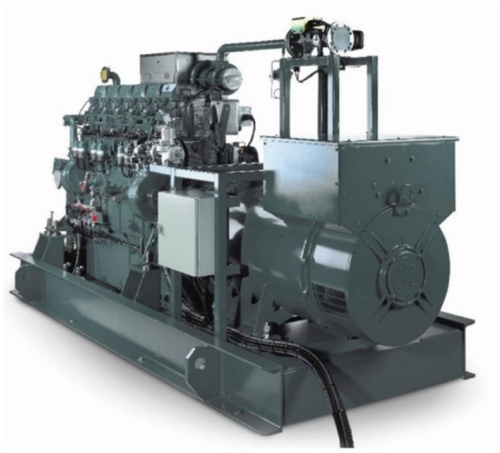


Figure 2 Possible scenarios to achieve carbon neutrality with power-generating engines

2. The shift from diesel to natural gas in marine engines

Shifting from diesel to natural gas means an increased hydrogen ratio in the fuel and thereby a 20% decrease in CO_2 emissions. Since marine engines still primarily use diesel, a major change to natural gas is expected.

In response, MHIET has modified its pre-chamber lean-burn gas engines used in genset to be used as marine engines. **Figure 3** shows the exterior view of a gas engine generator set used on ship (auxiliary genset) and its primary specifications. We have already sold more than 40 units in Europe and plan to expand our product lineup for these engines along with this shift to natural gas.



Item	Unit	Detail
Number of cylinders	–	6
Cylinder bore x stroke	mm	Φ170 x 220
Rated output	kW	380
Engine speed	min^{-1}	1,200
Ignition method	–	Spark ignition
Combustion method	–	Lean-burn

Figure 3 Exterior view of marine gas engine generator set and its primary specifications

3. Going hybrid with renewable energy

The output of renewables such as solar or wind power fluctuates depending on the environment. This makes achieving a stable power supply to meet demand a challenge to this day. Options for their application are quite limited, particularly in off-grid areas where there is no grid-connected power. To meet such demands, MHIET developed EBLOX, a hybrid power generation system that combines a storage battery and an engine generator with a renewable energy source. EBLOX's configuration and its demonstration facility are illustrated in **Figure 4**. This new power generation system is capable of independent operation by optimally controlling three power sources, i.e., the engine generator, renewable energy, and storage battery, with its control system COORDY. The individual functions of the system have been developed, tested, and verified at the demonstration facility within the premises where both MHIET and MHI Sagamihara Machinery Works are located. There, it was shown to be applicable industrially and to be a independent power generating system in off-grid areas. MHIET is planning to promote the product heavily to contribute to sustainable energy, and further down the road, plans to replace the engine generator with a hydrogen engine for an independent power generating system with zero CO_2 emissions. This will be a major advancement for both the realization of a decarbonized society and stable energy generation.

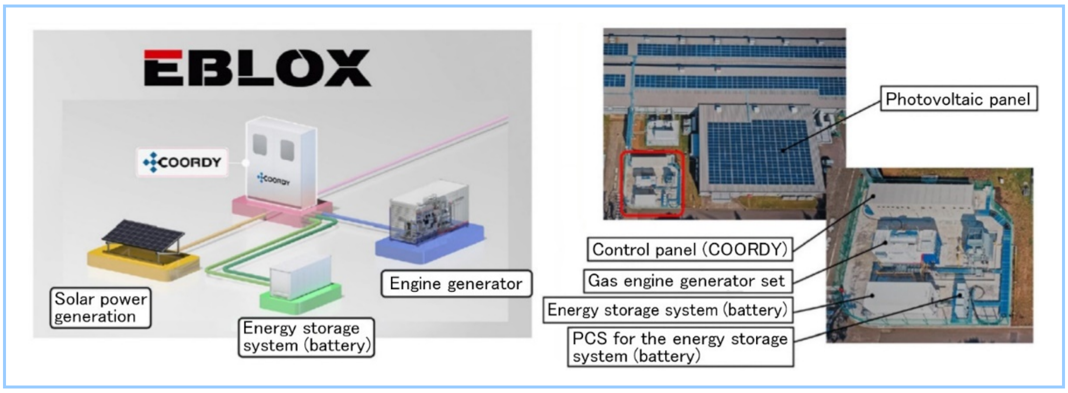


Figure 4 EBLOX configuration and demonstration facility

4. Hydrogen engine

4-1. Projected widespread use of hydrogen engines

Hydrogen will have to become more economically efficient than natural gas to reach widespread use. The current price of hydrogen is approximately 100 yen/Nm^3, which is more than six times that of natural gas per calorific value. It is essential that the price of hydrogen decreases, but another key element will be carbon pricing. The carbon price has not been fixed, but **Figure 5** shows a comparison we conducted between hydrogen and natural gas in terms of economic efficiency supposing it fluctuates within the range of 0 to 250USD/t-CO_2. The hydrogen price is shown on the horizontal axis and the values obtained by dividing its price per calorific value by that of natural gas on the vertical axis. The natural gas price includes the carbon price. Hydrogen exceeds natural gas in economic efficiency when the values on the vertical axis fall below 1. Accordingly, if the carbon price is 250USD/t-CO_2, the maximum threshold hydrogen price for its widespread use would be 30 yen/Nm^3, whereas if the carbon price remains at around 50USD/t-CO_2, the hydrogen price would need to be lower than 20 yen/Nm^3. Since the Ministry of Economy, Trade and Industry aims to achieve a hydrogen price of 30 yen/Nm^3 in 2030 and 20 yen/Nm^3 in 2050, the widespread use of hydrogen cannot be expected until after 2030.

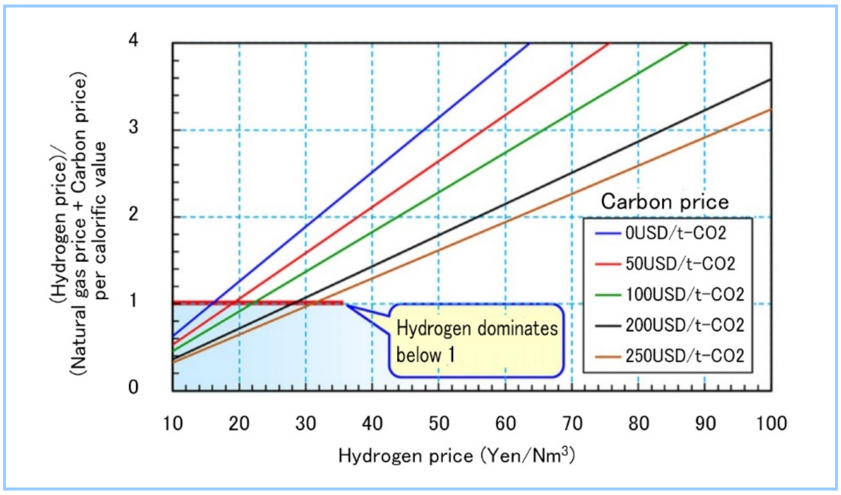


Figure 5 Conditions for widespread use of hydrogen

4-2. The technical challenges of hydrogen

Utilizing hydrogen in reciprocating engines poses a significant challenge, in part because hydrogen is prone to abnormal combustion. A comparison of hydrogen and methane combustion is shown in **Figure 6**. Hydrogen has a wider flammability range, lower minimum ignition energy, and higher combustion wave propagation velocity than methane, and this is likely to cause various issues such as backfire, premature ignition, and knocking when used in engines. Avoiding these issues requires that we optimize the air-fuel mixture and combustion considering the position the hydrogen is supplied, ignition method, compression ratio, and air excess ratio. Using hydrogen poses other major problems in addition to its combustion properties, such as how it is handled.

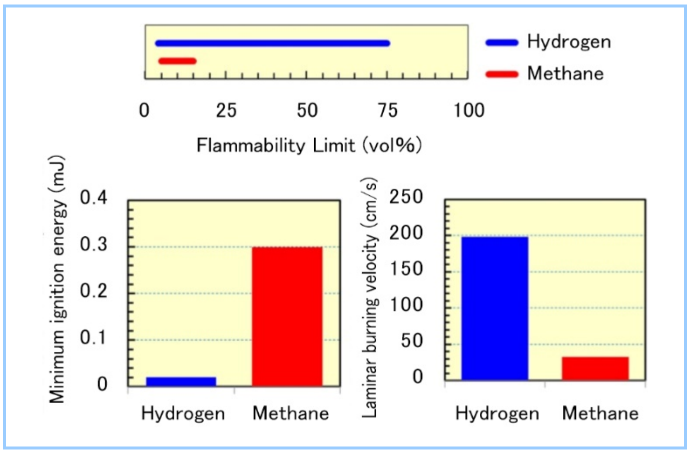


Figure 6 Comparison of combustion characteristics between hydrogen and methane

4-3. A test run

MHIET conducted a test run of a hydrogen engine in a joint research effort with the National Institute of Advanced Industrial Science and Technology (AIST).

A single-cylinder engine (bore 170mm × stroke 220mm), an modified model of MHIET’s 4-stroke reciprocating gas engine “GS6R2-GS16R2” series, was installed at the AIST Fukushima Renewable Energy Institute (Koriyama, Fukushima Prefecture) where a 100%-hydrogen combustion test was carried out. **Figure 7** shows the exterior view of the test engine and its primary specifications. The test was carried out while reviewing the hydrogen fuel supply method, ignition method, and timing of intake air valve closing, in accordance with the hydrogen combustion characteristics. Although some premature ignition and minor backfires occurred while improving output, we were able to gradually increase the output while adjusting the combustion parameters such as the excess air ratio and ignition timing. As a result, we successfully increased the output up to 920kW using 100% hydrogen in a 16-cylinder engine. Moving forward, we will continue to optimize the engine and its combustion to reach an output of 1,000kW. This will allow us to collect and accumulate test data for the eventual development of the next-phase multi-cylinder test engine.

Item	Unit	Detail
Number of cylinders	–	1
Cylinder bore x stroke	mm	Φ170 x 220
Target output (based on 16-cylinder)	kW	1,000
Engine speed	min^{-1}	1,500
Ignition method	–	Spark ignition
Combustion method	–	Lean-burn

Figure 7 Hydrogen engine test device

5. Further development

The fuels used for reciprocating engines have already started to shift from diesel to natural gas, and this will accelerate with the recent low-carbon trend. The widespread use of engines combining natural gas and hydrogen, as well as hybrid power generation systems, is expected as the world moves toward decarbonization. Carbon-free fuels such as hydrogen and ammonia will be vital to our coming society. MHIET will continue researching and developing hydrogen mixed natural gas combustion engines, hydrogen engines, ammonia engines, and more in order to market engine products along with fuel availability and each stage of decarbonization. In the future, MHIET intends to market 6-, 12- and 16-cylinder engines to cover the range of 350kW to 1,000kW with hydrogen engines. These products are planned to be launched in the 2030s when hydrogen is expected to be more widely used.