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2025 | 211

Application of the Kawasaki green gas engine L30KG for a hybrid propulsion system

System Integration & Hybridization

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ABSTRACT

Kawasaki Heavy Industries, Ltd (KHI) has supplied the gas engine hybrid propulsion system to a limestone carrier which went into service in March 2024. This vessel is the first bulk carrier in the world that applies a hybrid propulsion system combining a gas engine and batteries. The vessel is operated on a regular line under severe oceanographic conditions almost every day with a limited number of people on board. Therefore, as well as strong reliability and high environment performance, easy operation was one of the challenges of this project.

In this hybrid propulsion system, KHI supplied the gas engine, batteries, power conversion module, controllable pitch propeller (CPP), fuel gas supply system, propulsion control system (PCS) and other relevant equipment.

KHI developed the marine green gas engine L30KG fueled only by natural gas to provide an innovative solution to the shipping industry, where the momentum of decarbonization is growing worldwide. Extensive experience accumulated over many years manufacturing marine machineries with high environmental performance, and delivery references of more than 200 sets of KHI original designed V-type engines for power generation plants on land was the key factor of the success. By using the pure gas engine 8L30KG as the main propulsion, the system cuts down CO2 emissions during operation by more than 23% compared with a conventional heavy-fuel-oil engine used in the same vessel type. It also achieves significant reductions in SOx and NOx.

In order to improve the performance of the L30KG, KHI as a systems integrator, also developed the propulsion control system (PCS) as the core component of the hybrid propulsion system. PCS enables seamless and automatic switching during the change of various ship operation modes. During the voyage at sea, 8L30KG will supply propulsion power, onboard electric power and charge the batteries depending on the navigating condition with minimum emission. Also, during entering and leaving port in harbors, 8L30KG is automatically stopped and the system can operate in electric propulsion mode using the batteries to achieve navigation with zero greenhouse gas emissions. In addition, the PCS automatically adjust the battery charging/discharging amount by the motor/generator during navigation and allows the batteries to absorb the load fluctuation of the propulsion. This peak-shaving feature will stabilize the gas engine load and suppress the fuel consumption degradation during rough sea conditions. Since the PCS will integrally control all relative equipment automatically depending on the operation mode, the crew can maneuver the vessel with a handle same as conventional vessels. KHI's PCS can realize highly efficient energy usage with safe and easy vessel operation.

This paper presents the equipment configuration of the gas engine hybrid propulsion system and reports the improvement effect of environment performance compared with a conventional ship since the expected results have been confirmed in actual operation.

1 INTRODUCTION

To mitigate global warming, the International Maritime Organization (IMO) has been strengthening exhaust gas regulations for CO2, NOx, and other emissions in marine transport. Notably, the GHG reduction strategy was revised in 2023 from "the target of at least 50% reduction by 2050" to "net zero emissions by 2050." Against this backdrop, efforts to improve the environmental performance of Japanese domestic vessels have intensified. Additionally, manpower shortages and the aging of crews have become significant issues. Therefore, a propulsion system that achieves both high environmental performance and ease of handling is required.

Kawasaki Heavy Industries, Ltd. (hereinafter KHI), as a system integrator, is responsible for many of the devices that make up the propulsion system, including the main engine and propellers, to enhance customer satisfaction. KHI aims to realize high environmental performance without requiring complicated additional operations by crews by collectively controlling propulsion electric power equipment and onboard electric equipment.

This paper reports on the Shimokita-maru, to which KHI collectively delivered propulsion and power supply systems such as a marine gas-only firing engine (gas engine), controllable pitch propeller (CPP), shaft generator and motor (M/G), lithium-ion battery (battery), and fuel gas supply system. The equipment composition and CO2 reduction effects obtained from actual operation data to date are presented.

2 OUTLINE OF THE HYBRID PROPULSION SHIP

Shimokita-maru was built by Tsuneishi Shipbuilding Co., Ltd. and entered service in March 2024. The vessel is owned and operated by NS United Naiko Kaiun Kaisha, Ltd. It carries limestone from Shiriya-misaki port in Aomori Prefecture to Nippon Steel Muroran Works in Hokkaido, navigating across the Tsugaru Strait almost every day throughout the year. This route is known as one of the roughest sea areas in Japan.

In replacing the previous Shimokita-maru, which entered service in 1994, there was a strong request from the shipper for the new vessel to be more environmentally considerate. The owner also requested that the cargo hold volume be maintained and that the vessel have good maneuverability with a low labor load for the crew.

Kawasaki Heavy Industries, Ltd. (KHI), as a system integrator, proposed a hybrid propulsion and power supply system combining a gas engine and batteries. Environmental performance was improved by drastically reducing heavy oil consumption and substituting LNG and electric energy for energy supply. The LNG tank and batteries, which were added from the conventional vessel, were placed inboard, while maintaining the same cargo hold capacity as the conventional vessel. Despite the increase in the number of devices such as the LNG tank, M/G, and reduction gear, we were able to keep the width almost the same as conventional vessels by optimizing the arrangement.

This vessel is the first bulk carrier in the world to be equipped with a hybrid propulsion and feed system using a gas-only engine as the main engine.

Table 1. Characteristics of Shimokita-maru

Gross tonnage	5154 ton
Deadweight tonnage	5646 ton
Length overall	93.78 m
Breadth	18.2 m
Depth	9.9 m
Speed (C.S.O)	12.3 kt
Regular line	Shiriya-misaki - Muroran
Cargo	Limestone

Figure 1. Overview of Shimokita-maru

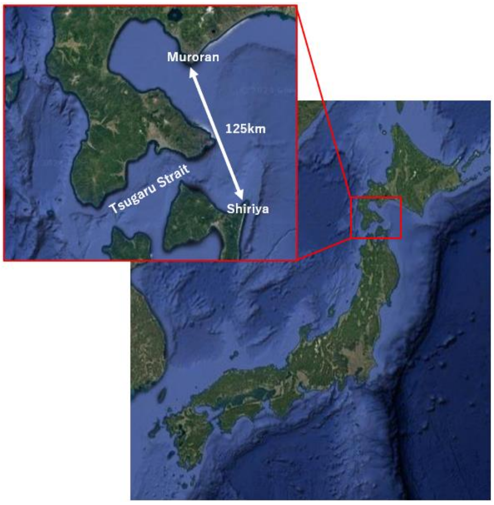

Figure 2. Main route of Shimokita-maru

3 SYSTEM CONFIGURATION

3.1 Outline of system

In the gas engine hybrid propulsion system, the gas engine and M/G are connected to the CPP through a reduction gear in the propulsion system. The M/G and battery are connected to the onboard electric power system through a power conversion module (PCM) in the electric power system. Each piece of equipment is integrally controlled by the propulsion and power control system (PCS), and the maximization of energy efficiency is attempted in proportion to the propulsion load and onboard electric power demand. The features of this system are described below.

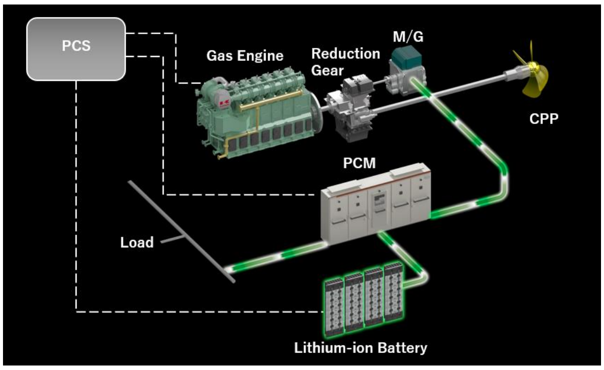

Figure 3. System configuration

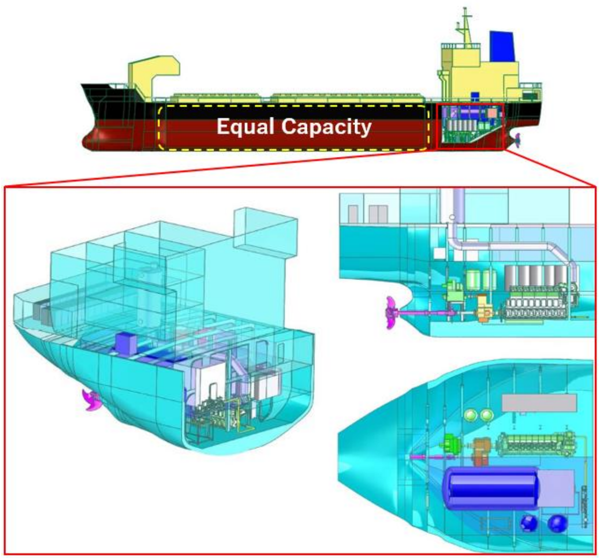

Figure 4. Compact Propulsion System Layout

1 Simple maneuverability

To avoid complicated operation of the propulsion system, operation mode transitions can be automatically and seamlessly carried out by the PCS. The crew only needs to order the ship speed by telegraph, which is almost the same as on conventional vessels.

2 Environmental performance (outside the harbor)

When navigating at a certain speed or higher (Fig. 6), the CPP is operated by the gas engine via the reduction gear. At the same time, the M/G is operated as a generator by the gas engine's surplus output to supply onboard electric power and charge the battery. The roles of the main engine and the main generator of conventional ships are concentrated in the gas engine, and energy savings for the entire vessel are achieved by operating the gas engine in the high output band with high thermal efficiency.

3 Environmental performance (Harbor)

When the demand for propulsion force is low (Fig. 5), the gas engine is stopped, and the vessel operates with zero emissions. The M/G is driven as an electric motor by electric power charged to the battery during navigation, and at the same time, onboard electric power is supplied. This improves the working environment for the crew and reduces noise in the region around the port.

4 Navigational Stability

This vessel navigates back and forth in the Tsugaru Strait throughout the year and is required to maintain stable operation even in stormy weather. When sudden changes in propulsion force occur in stormy weather, the PCS adjusts the amount of M/G power generation and the amount of battery charge to maintain the gas engine's shaft-end output constant. Multiple supply modes were set for fuel gas supply, considering the effect of sloshing due to hull swing. These settings enable gas engine operation with high thermal efficiency regardless of sea conditions.

5 Redundancy

Navigation is possible using either the gas engine or the M/G, providing excellent redundancy for propulsion. The onboard electric power supply system is also made redundant by multiple groups of batteries in parallel, significantly reducing the possibility of a blackout.

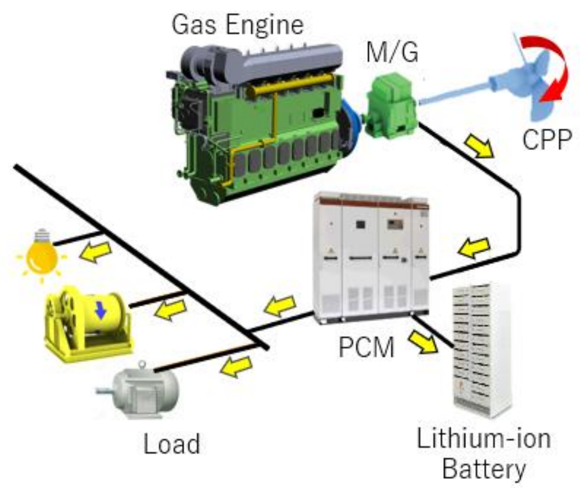

Figure 5. Navigation by gas engine

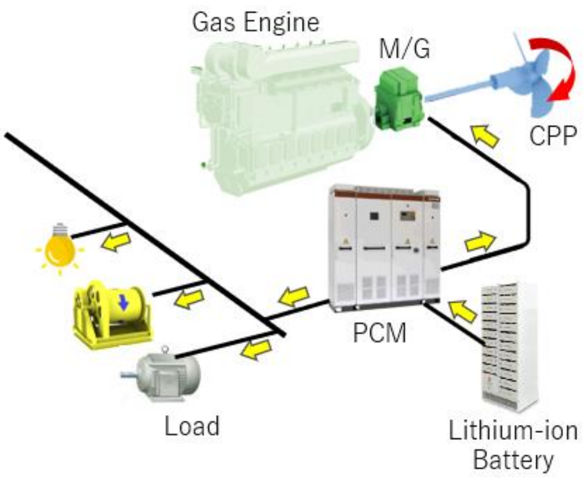

Figure 6. Entering/Departing port by battery

3.2 Primary components

3.2.1 Marine gas engine

The gas engine 8L30KG installed on this vessel is an engine with improved followability to fuel property changes and sudden load fluctuations, based on the gas engine delivered in over 200 units for land power generation. This engine adopts a prechamber spark ignition type lean burn system (Fig. 7). Since it uses a spark plug for ignition and does not require the injection of any liquid fuel as pilot fuel like dual-fuel engines, operation with only natural gas fuel is possible across the entire operational range. Additionally, cylinder pressure sensors are installed in all eight cylinders to monitor cylinder conditions every cycle, and ignition timing and fuel injection quantity are precisely adjusted to achieve the highest level of fuel efficiency in its class.

CO_2 emissions can be reduced by about 25% with natural gas compared to fuel oil. NOx emissions can be kept to less than half of the IMO NOx Tier III limit without aftertreatment equipment. Since LNG does not contain sulfur, SOx emissions are almost negligible.

Table 1. Characteristics of 8L30KG

Bore	300 mm
Stroke	480 mm
Speed	750 min^{-1}
Power	3560 kW

Figure 7. Marine gas engine

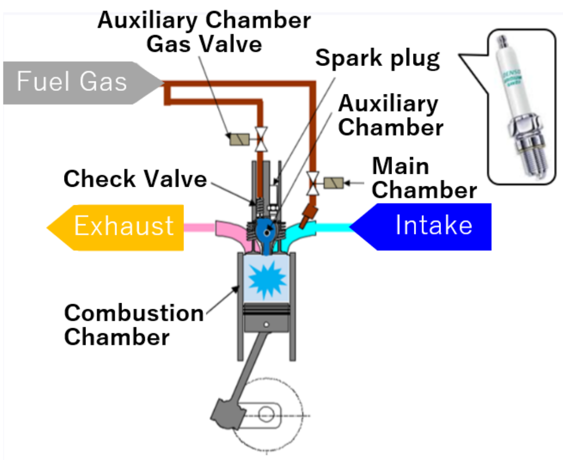

Figure 8. Detail of combustion chamber

3.2.2 Lithium-ion battery

A lithium-ion battery is installed to charge the surplus electric power generated by the M/G during navigation and to enable zero-emission operation when entering and departing ports. Based on the vessel's operation profile, the optimum battery capacity was determined to be 2.8 MWh, which is sufficient to cover zero-emission operation during port entry and departure, as well as onboard electric power needs while anchoring. The gas engine can be operated stably with high thermal efficiency by adjusting the battery's charging and discharging amounts as needed by the PCS.

Regarding safety, a risk assessment was conducted using HAZID (Hazard Identification Study) with concerned parties such as NK Consulting, the shipowner, the shipyard, and main suppliers during the basic design stage of this vessel. The assessment confirmed that there are no issues.

Figure 9. Lithium-ion battery room

3.2.3 LNG tank

The LNG tank is a type C vacuum double-shell thermal insulation structure, with its capacity set considering bunkering frequency. To secure the same cargo hold capacity as a conventional vessel and avoid obstructing cargo handling work, it was installed in the engine room instead of on the deck. "7% nickel-added steel for LNG tank," developed by Nippon Steel Corporation, was adopted for the tank's steel material. It has been confirmed to have safety equivalent to 9% nickel-added steel, which NK approves for use under the IGF code, while suppressing the use of expensive nickel. This material was adopted for the first time as a marine tank in this vessel.

Figure 10. LNG tank

3.2.4 Propulsion and power control system (PCS)

The PCS manages the energy and power flow of the onboard electric power system in addition to the propulsion system. As the propulsion controller, the PCS controls the propeller angle, torque, rotational speed, and clutch engagement/disengagement of the reduction gear based on telegraph operations. To reduce load fluctuations of the gas engine, the battery charge/discharge quantity and M/G output are controlled.

In energy and power flow management, the output of electric power sources (battery, M/G, main generator) is integrally controlled based on ship handling conditions and the state of charge of the battery to appropriately supply onboard electric power and propulsion. The output of each device related to propulsion and power supply, as well as the battery capacity, are displayed on monitors installed on the bridge and in the control room, allowing all statuses to be grasped briefly.

Figure 11. PCS installed on bridge console

3.2.5 Motor/Generator (M/G) and Power conversion module (PCM)

The M/G is driven by the gas engine as a generator during navigation, supplying electric power for onboard systems and battery charging. It is driven by electric power from the lithium-ion battery and functions as an electric motor when entering and departing ports.

The PCM is equipped with an inverter for driving the M/G, a DC/DC converter for charging and discharging the battery, and an AC/DC converter for supplying power to the AC bus. Through the PCM, the vessel's power system, including the battery and propulsion system, is collectively controlled, allowing for efficient use of the entire system.

3.2.6 Condition monitoring system (CMS)

All data about the propulsion and power supply systems of this vessel are transmitted and stored in a shore data server by the CMS. By monitoring the conditions of the propulsion and power supply systems and accurately grasping the conditions of each piece of equipment, KHI will propose appropriate maintenance and operation improvement methods to reduce fuel consumption.

4 OPERATION MODE

The PCS automatically switches the propulsion power source and the electric power source, minimizing the crew's operation for changing the operating mode.

4.1 Navigation

The operation mode during navigation is roughly divided into two types: hybrid propulsion mode and battery propulsion mode. These mode transitions are automatically and seamlessly executed by the operation of the telegraph without any special actions required from the crew. The PCS controls the starting and stopping of the gas engine and the switching operation of the reduction gear clutch, based on commands from the telegraph.

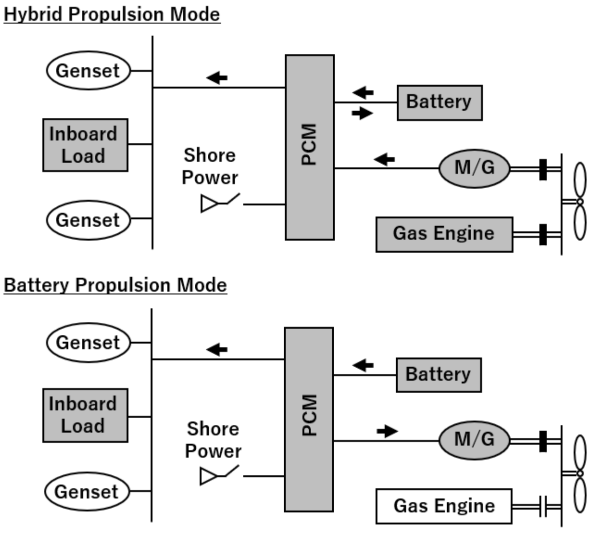

Figure 12. Operation mode in Navigation

4.2 Anchorage

There are two anchorage modes: battery anchorage mode, in which onboard electric power is supplied by the battery while at anchor, and shore power anchorage mode, in which onboard electric power is supplied from a shore power source and the battery is charged. In the operation of this vessel, there are cases where land electric facilities are available at the quay and cases where they are not, and the appropriate mode is used accordingly. This vessel is also equipped with main generators for redundancy to enable the supply of onboard electric power even when the vessel is anchored for a long time in battery anchorage mode or when land power, batteries, and PCM are not available. The PCS monitors the onboard electric power demand, battery charge level, and equipment conditions, and automatically starts and stops the main generator when necessary.

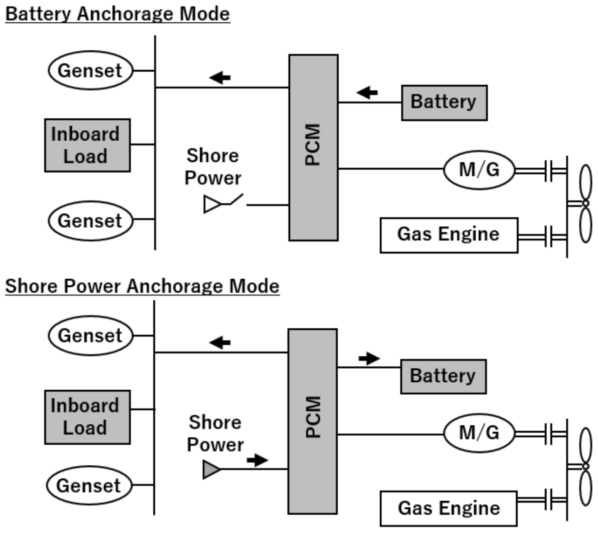

Figure 13. Operation mode in anchorage

5 VERIFIED RESULT OF OPERATION

The reliability of the propulsion system was confirmed through HILS, combination tests on actual machines in our factory before installation, and sea trials. This chapter presents some operational data from the sea trials and actual operation.

Figure 14. Combination test in our factory

5.1 Mode transition in navigation

Fig. 15 shows the behavior of the mode transition from battery propulsion to hybrid propulsion. The mode transition is initiated by a command from the telegraph handle. First, the gas engine starts, and the clutch on the gas engine side engages when it reaches the specified rotational speed. Next, the load is shifted from the M/G to the gas engine, the gas engine's rotational speed is increased, and the M/G transitions to hybrid propulsion by switching from electric motor to generator.

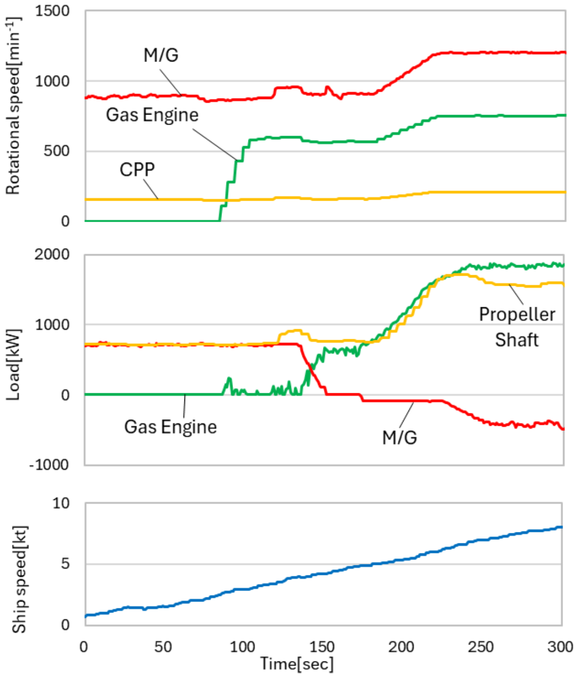

Figure 15. Propulsion mode transition

5.2 Peak shaving

In this propulsion system, a peak shaving function that keeps the load of the gas engine constant is equipped. Fig. 16 shows the output of each machinery when peak shaving is applied during hybrid propulsion. It can be seen that the shaft-end output of the gas engine is kept constant by adjusting the power generation of the M/G, even if the load on the propeller shaft fluctuates due to the peak shaving function.

In winter, when sea conditions deteriorate, thermal efficiency tends to decrease because the main engine operates at low power. However, on this vessel, the gas engine can be operated continuously in the high load range, as indicated by the above results. Therefore, it is expected to maintain high efficiency throughout the year.

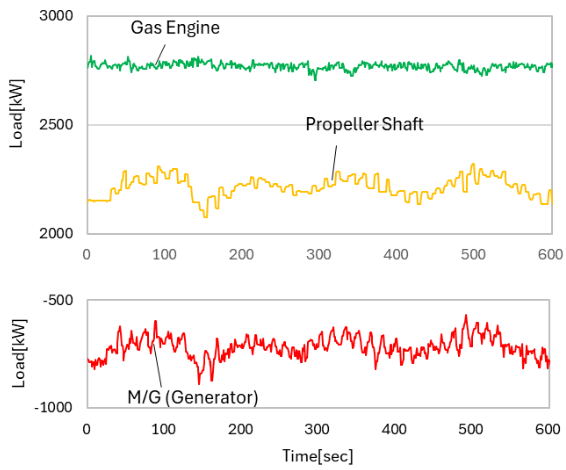

Figure 16. Peak shaving

5.3 Mode transition in emergency

This propulsion system is equipped with a gas engine and M/G as propulsion power sources. Typically, in hybrid propulsion, the CPP is driven by the gas engine, and the M/G operates as a generator to supply onboard electric power and charge the batteries. If a fault occurs in the gas engine and it stops, the M/G automatically switches to the electric motor, allowing propulsion to continue.

Fig. 17 shows the transition in rotational speed and output of each piece of equipment when the gas engine stops during hybrid propulsion. Although the rotational speed of the CPP decreases briefly after the gas engine stops, it is demonstrated that the M/G switches to the motor, enabling continued propulsion by driving the CPP. Additionally, it was confirmed that a blackout did not occur due to the automatic switching of the onboard electric power supply source to the battery.

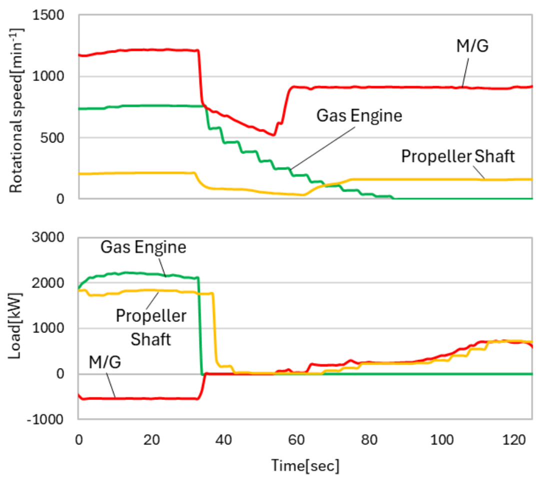

Figure 17. Mode transition in emergency

6 REDUCTION ENVIRONMENTAL LOAD

Fig.18 illustrates the CO2 emissions per voyage for both the old and new Shimokita-maru in June and July 2024, normalized by voyage distance and cargo weight. The average emissions per voyage for the old Shimokita-maru were derived from operational records spanning the past seven years. In comparison, the new Shimokita-maru achieved a CO2 emissions reduction exceeding 30%. The transition from heavy oil to LNG contributed approximately 25% to this reduction, with further significant reductions attributed to the implementation of a high thermal efficiency gas engine and a battery hybrid system.

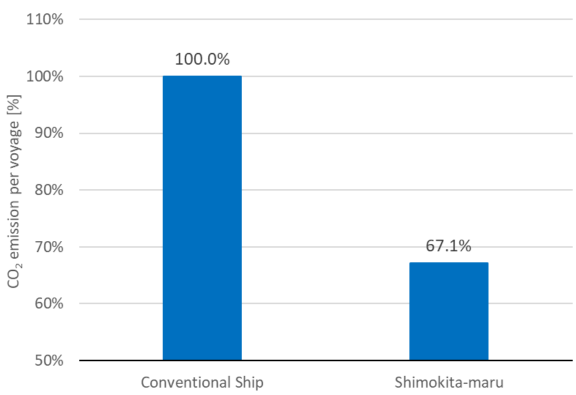

Figure 18. CO_2 emissions reduction

7 CONCLUSION

This paper presents the equipment composition, actual operation results, and environmental load reduction effects of the gas engine hybrid propulsion system of the Shimokita-maru. Our company delivered the propulsion and power supply systems as a batch, acting as the system integrator, and put the vessel into service in March 2024.

The Shimokita-maru has been operating smoothly since its entry into service. As of December 2024, it had carried a total of about 840,000 tons of limestone in 160 voyages (280 miles per voyage). It has achieved an environmental load reduction effect that exceeds the initial CO2 reduction goal. In the future, it is also possible to make LNG carbon neutral through methanation technology, which synthesizes methane from CO2 and hydrogen, a technology that has been developed recently.

KHI, as a system integrator, will continue to provide propulsion systems with excellent environmental performance achieved through optimized combinations of gas engines, propellers, and other core components to reduce environmental impact in the marine shipping industry.

8 DEFINITIONS

LNG: Liquefied Natural Gas

NOx: Nitrogen Oxide

SOx: Sulphur Oxide

IMO: International Marine Organization

NK: Nippon Kaiji kyoukai

HAZID: Hazard Identification Study

CPP: Controllable Pitch Propeller

PCS: Propulsion Control System

PCM: Power Conversion Module

M/G: Motor / Generator

CMS: Condition Monitoring System

HILS: Hardware In the Loop Simulation

9 REFERENCES

[1] Nonaka, Y, Ishii, H, Fujihara, S and Hirayama, T. 2016. Development of Kawasaki Green Gas Engine for marine, L30KG series, *CIMAC Congress 2016*, 159.