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Original Paper

A study on ship design modifications for preparing the sea trial demonstration of a thermoelectric generator system

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Abstract: This paper presents the ship design modifications implemented to prepare for the sea trial demonstration of a newly developed 100 kW-class thermoelectric generator (TEG) system aboard KOMERI1, a multi-purpose offshore demonstration vessel. Since the TEG was developed under a separate program based on the exhaust gas conditions of a land-based engine, the scope of this study is limited to the ship-side measures required to accommodate its requirements; the power generation performance will be evaluated during the planned 1,000-hour sea trial. The operational requirements of the TEG were compared with the utilities available on the vessel under a single design basis of 100% SMCR. As a result, the main exhaust gas line was branched with interlocked fail-open dampers, an exhaust fan was installed to secure a back pressure margin of 12.3% in TEG mode, the funnel was extended by 2,750 mm, and a cooling system with a dedicated overboard discharge line was configured and verified by a heat balance analysis. A load bank was selected as an independent power consumer through a DC/AC conversion system, and a fail-safe interlock philosophy was established. These measures were reflected at the newbuilding stage, and classification approval was obtained in a “Ready for TEG system” configuration. The review process is summarized as a ship-side checklist that can serve as a practical reference for preparing future sea trial demonstrations of eco-friendly marine equipment.

Keywords: Waste heat recovery, Thermoelectric generator, Cooling system, Power consumption, Sea trial preparation

1. Introduction

In accordance with the International Maritime Organization (IMO)'s 2050 net-zero emissions strategy, the maritime industry is facing the significant challenge of achieving net-zero carbon emissions by 2050. To achieve this goal, various Energy-Saving Device (ESD) technologies have been proposed to improve the energy efficiency of ships and reduce greenhouse gas (GHG) emissions **[1]-[2].** As one of the world's leading shipbuilding and maritime nations, South Korea has also been actively conducting research and development on various technologies to enhance ship energy efficiency and reduce carbon emissions **[3]-[5].** ESD technologies can generally be categorized into three areas according to their application and operating principles: navigation, hull, and engine systems. Among these, technologies for engine systems have attracted considerable attention because of their potential to minimize energy losses from the main engine and recover otherwise wasted energy.

In particular, the exhaust gas discharged from a ship's main engine contains a considerable amount of high-temperature thermal energy. Recovering this waste heat and converting it into useful energy can improve the overall energy efficiency of the ship while reducing fuel consumption and GHG emissions. Conventional marine waste heat recovery systems include steam-based systems, exhaust gas power turbines, organic Rankine cycles, and other thermodynamic cycles. Although these systems can achieve relatively high energy recovery under suitable operating conditions, their application to ships may be constrained by system complexity, installation space,

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maintenance requirements, and operational variability **[6]**. Accordingly, thermoelectric generator (TEG) technology has attracted increasing attention as a waste heat recovery technology for marine applications because it can directly convert thermal energy into electrical energy without requiring mechanical moving components.

A thermoelectric generation system converts thermal energy directly into electrical energy through the thermoelectric effect induced by a temperature difference. The system can utilize the high-temperature waste heat continuously generated by the exhaust gas of a ship's main engine as an energy source. In addition, the absence of rotating components and working fluids enables a relatively simple system configuration and facilitates maintenance. The modular characteristics of TEG systems also provide potential advantages for integration with existing shipboard systems. Based on these characteristics, a 100 kW-class marine thermoelectric generation system was developed in this study to generate electrical power by utilizing the high-temperature exhaust gas discharged from a ship's main engine as a heat source.

However, for a newly developed TEG system to be installed and operated aboard an actual vessel for sea trial demonstration, it is not sufficient to secure only the power generation performance of the system itself. The operational requirements of the TEG system — including the exhaust gas flow rate and temperature available from the main engine, the cooling water capacity required to maintain the temperature difference across the thermoelectric modules, the installation space for the system and its auxiliary equipment, and a means of consuming the generated electrical power — must be carefully compared against the utilities and structural conditions that the demonstration vessel can actually provide. Where a mismatch exists between these requirements and the vessel's available utilities, corresponding ship design modifications must be identified and reflected in the vessel's design and classification approval before the system can be installed.

Accordingly, in preparation for the sea trial demonstration, this study analyzes the operational requirements of the developed 100 kW-class TEG system in relation to the utilities and design constraints of *KOMERI1*, a multi-purpose offshore demonstration vessel, under a single design basis, and presents the ship design modifications implemented to enable the stable installation and operation of the TEG system. Since the TEG was developed under a separate program based on the exhaust gas conditions of a land-based engine, the scope of this study is limited to the ship-side measures required to accommodate its requirements, and its power generation performance will be evaluated during the planned sea trial. These modifications include the branching of the main exhaust gas line with interlocked damper valves, compensation of the exhaust back pressure margin through an auxiliary exhaust fan, extension of the funnel to secure installation space, and the configuration of the cooling system with a dedicated overboard discharge line, as well as the selection of a load bank as an independent power consumption device for the generated electricity and the establishment of a fail-safe interlock philosophy. This design was fully reflected during the newbuilding stage, and classification approval was obtained in a "Ready for TEG system" configuration, enabling immediate installation of the TEG system upon its completion. The review process is summarized as a ship-side checklist, which is expected to serve as a practical reference for identifying the ship-side design considerations required when preparing future sea trial demonstrations of eco-friendly marine equipment.

2. Ship and Equipment Information

2.1 *KOMERI1* Ship for Offshore Demonstration

KOMERI1 is a 17,000 DWT-class bulk carrier compliant with IMO regulations, capable of both domestic and international voyages. With a single bunkering, the vessel can sail more than 10,000 nautical miles, making it suitable for demonstration on long-distance routes. It is also an eco-friendly vessel equipped with a dual-fuel engine, offering the advantage of operating on either LNG or diesel. The vessel comprises three cargo holds, which can also serve as demonstration spaces depending on the intended use. To facilitate understanding of the vessel configuration, an excerpt from the General Arrangement (GA) is presented in **Figure 1 [7]**, and the principal particulars are summarized in **Table 1 [8]**.

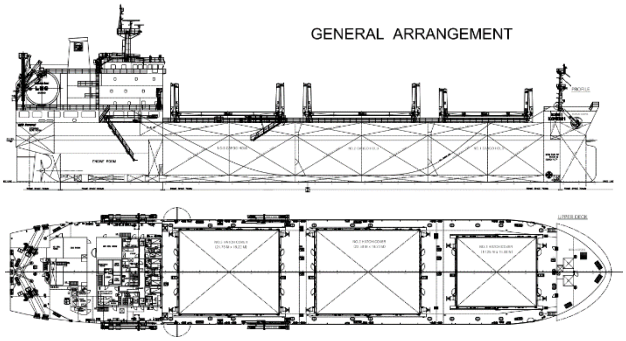


Figure 1: General Arrangement of *KOMERI1*

Table 1: Specification for *KOMERI1*

General Information	Ship	*KOMERI1*
	Type	17,000 DWT Bulk Carrier
	IMO No.	9985899
Principal Dimension	Length Overall	132.0 m
	Length between perpendiculars	126.0 m
	Breadth	23.0 m
	Depth	13.5 m
	Designed draft	9.5 m
Main Engine	Type	MAN 6S35ME-C9.7-GI
	SMCR	3,150 kW × 124.0 rpm
	NCR 90%	2,835 kW × 119.7 rpm

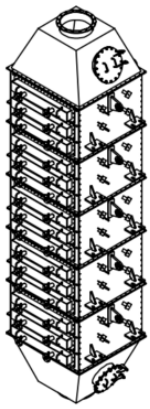


Figure 2: Schematic of 100 kW-class TEG

Table 2: Specification for TEG

Principal Dimension	Length	2,030 mm
	Breadth	2,072 mm
	Height	7,515 mm
Total Weight	Dry	Abt. 16,420 kg
	Wet	Abt. 17,250 kg

2.2 100 kW-Class TEG

The thermoelectric generator (TEG) refers to a device equipped with thermoelectric modules that convert thermal energy into electrical energy. A single stage has a rated output of 20 kW, and this system is applied to the main engine exhaust gas line of *KOMERI1*. It is configured with five stages arranged sequentially along the exhaust gas flow. **Figure 2** illustrates the system configuration and **Table 2** summarizes the basic specifications.

Since power is generated by the temperature difference across the thermoelectric modules, a cooling system is required. The cooling system consists of a unit that directly cools the thermoelectric modules (direct cooling) and a unit that cools the coolant (indirect cooling). This cooling system was installed during the shipbuilding stage through design modifications. The vessel has obtained classification approval in a "Ready for TEG system" configuration, so that the developed TEG can be installed on board immediately after undergoing the inspection procedures of the Korean Register (KR).

3. TEG System Configuration and Design Implementation

For *KOMERI1* to realize the performance of the TEG, the following information must be provided: 1) the exhaust gas flow rate and temperature of the main engine, 2) the cooling capacity, and 3) the installation space. To this end, additional utility configurations are required on the vessel, and the corresponding measures are introduced in this section.

3.1 Exhaust Gas Design of *KOMERI1*

3.1.1 Main Engine Exhaust Gas Information

The exhaust gas generation rate of *KOMERI1*'s main engine was determined based on the engine manufacturer's NOx Technical File and CEAS Engine Data Report. The exhaust gas generation rate for each fuel type and engine load, calculated according to Equation (1), is presented in **Table 3 [9], [10]**.

$$\text{Exh. Gas amount}(kg/h) = \text{Exh. Gas Flow Rate}(kg/kWh) \times \text{Engine Power(kW)} \quad (1)$$

To ensure consistency throughout the analysis, a single design basis was defined for the TEG system, as summarized in **Table 4**. The operating condition of the TEG system was set at 100% SMCR, which yields the maximum exhaust gas flow rate and therefore represents the most severe case for the back pressure of the main engine exhaust gas line. The sea trial demonstration of the TEG will be conducted in LSFO mode, the default fuel of *KOMERI1*. Since the TEG is installed downstream of the composite boiler, the boiler outlet temperature calculated by the boiler manufacturer under the specified ambient condition **[11]**

Table 3: Exhaust Gas Emission by Engine Load and Fuel Mode

Engine load (%)	Engine power (kW)	Diesel mode (kg/h)	LNG mode (kg/h)
100%	3,150	23,694.3	24,973.2
75%	2,363	19,121.4	20,543.9
50%	1,575	12,916.6	14,159.3
25%	788	7,992.7	9,145.5

Table 4: Design Basis Exhaust Gas Conditions of *KOMERI1* Compared with the TEG Reference Engine

Item	TEG design reference engine (Land-based test engine of KR)	*KOMERI1* (design basis)
Engine	2-stroke, 7,400 kW × 129 rpm	MAN 6S35ME-C9.7-GI, 3,150 kW × 124.0 rpm
Engine load	100%	100% SMCR
Fuel	Bunker A (S 0.24%)	LSFO
Exhaust gas flow (kg/h)	63,486	24,120
Composite boiler inlet temp. (°C)	– (no boiler)	222
TEG inlet gas temp. (°C)	255.9	194.1
Ratio to reference (flow / temp.)	1.00 / 1.00	0.38 / 0.76

was adopted as the TEG inlet gas temperature. The exhaust gas flow rate in the design basis differs from that in **Table 3** by approximately 2% owing to the difference in calculation sources, which does not affect the conclusions of this study. For comparison**, Table 4** also presents the exhaust gas conditions of the 7,400 kW land-based engine on which the design of the TEG system was based **[12]**; the exhaust gas flow rate and TEG inlet gas temperature available on *KOMERI1* correspond to approximately 38% and 76% of those of the reference engine, respectively. All subsequent analyses in this paper are based on this design basis.

3.1.2 Allowable Back Pressure Information

If the engine's back pressure increases, the continuous combustion cycle is disrupted, leading to problems such as reduced power output, engine overheating, component damage, and deteriorated fuel efficiency **[13]**. Therefore, the back pressure must not exceed the allowable back pressure of the main engine, and this is an essential factor that must be considered during the design stage. In general, back pressure is primarily caused by structures that obstruct fluid flow, with the length and shape of the piping also acting as contributing factors. Considering these factors, the total back pressure is calculated according to **Equations (2), (3), and (4).**

$$\Delta P_{total} = \Delta P_{pipe} + \Delta P_{fittings} + \Delta P_{equipment} \quad (2)$$

Here, ΔP_{pipe} denotes the frictional pressure loss in the piping, which is calculated based on the Darcy–Weisbach equation, as expressed below.

$$\Delta P_{pipe} = f \cdot \frac{L}{D} \cdot \frac{\rho v^2}{2} \quad (3)$$

Here,

f : Friction factor

L : Length of the pipe (m)

D : Internal diameter of the pipe (m)

ρ : Exhaust gas density (kg/m^3)

v : Exhaust gas velocity (m/s)

In addition, $\Delta P_{fittings}$ represents the pressure loss at pipe fittings, which is calculated using the Equivalent Length Method or the resistance coefficient (K), as expressed by the following equation.

$$\Delta P_{fittings} = \sum K \cdot \frac{\rho v^2}{2} \quad (4)$$

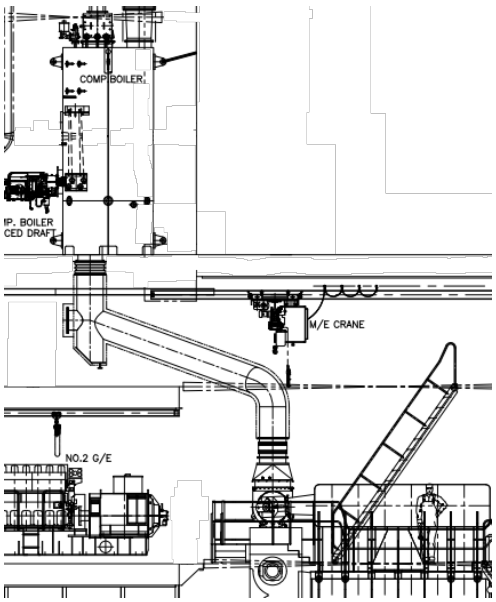


Figure 3: Piping Arrangement of Main Engine Exhaust Gas Line

Table 5: Back Pressure Calculation and Margin of Main Engine Exhaust Line

Factor		Value	Unit
Back Pressure Calculation	Pipe Pressure Loss	27.11	mmAq
	Fitting Pressure Loss	27.23	mmAq
	Equipment Pressure Loss	150	mmAq
	Total Back Pressure	204.34	mmAq
Margin Calculation	Main Engine Allowable Back Pressure	300	mmAq
	Back Pressure Margin	95.66	mmAq
	Margin Ratio	31.89	%

Finally, $\Delta P_{equipment}$ was calculated by incorporating the differential pressure value of 150 mmAq obtained from the Composite Boiler manufacturer. The piping arrangement of the main engine of *KOMERI1* is shown in **Figure 3**, and the calculated results, based on the Main Engine CEAS report, Machinery Arrangement, and Composite Boiler specification, are presented in **Table 5 [10]**.

3.2 Design of Cooling Capacity

As shown in **Figure 4**, the TEG cooling system consists of a Fresh Water (F.W) line, which exchanges heat directly with the thermoelectric modules to form the temperature difference required for power generation, and a Sea Water (S.W) line, which absorbs heat from the F.W line—after it has taken up heat from the TEG—and ultimately rejects it. Heat exchange between the two lines takes place through the Central Fresh Water Cooler (C.F.W Cooler) **[14]**.

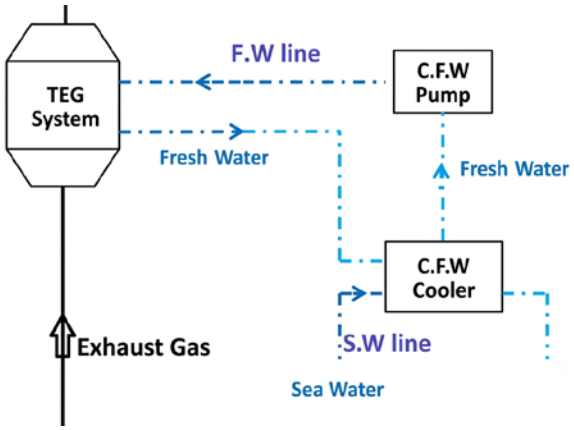


Figure 4: Schematic Diagram of TEG Cooling System

The F.W line was newly installed as a closed loop, while the seawater for the S.W line is supplied from the vessel's fire, bilge and G.S. pumps (Section 4.4). To determine the required cooling water flow rates, a HYSYS model was established, as shown in **Figure 5 [15]**, using the CFD analysis results provided by Gachon University, the joint research and development institution **[16]**. The CFD analysis indicated that the design-point power generation of the TEG is achieved when the cooling water velocity is 0.5 m/s or higher and the heat removal rate is 630 kW or higher; this heat removal rate corresponds to the rated design condition of the TEG. Based on this, a case study was conducted by varying the coolant outlet temperature and heat exchange rate, and the results (**Figure 6**) showed that an F.W flow rate of 200–250 ton/h would require an S.W flow rate of 150–200 ton/h. However, securing such a seawater flow rate would have required an additional sea chest and large-diameter seawater piping, entailing hull structural modifications that were not feasible **[12]**. Consequently, the S.W flow rate was set at 100 m³/h, which can be allocated from the G.S. pump, and the C.F.W pump was selected with a capacity of 120 m³/h × 45 mTH.

To verify that the final design flow rates can still remove the required heat, a simplified heat balance analysis based on the log-mean temperature difference (LMTD) was performed, as summarized in **Table 6**. With the F.W supply temperature controlled at 36 °C by a three-way temperature control valve and a design seawater temperature of 32 °C, the heat duty of 630 kW results in temperature rises of 4.5 K on the F.W side and 5.5 K on

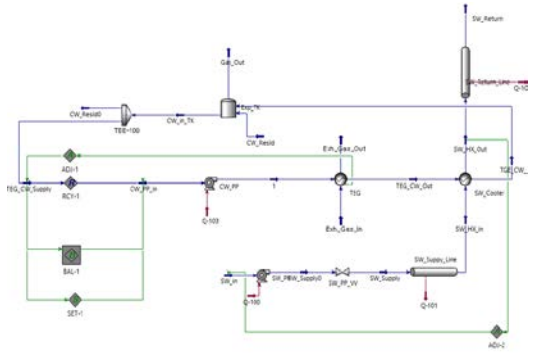
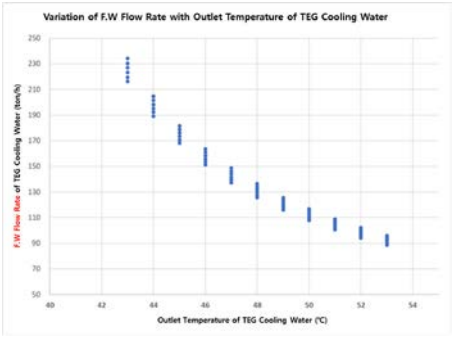


Figure 5: HYSYS Model of the Cooling System for the TEG System



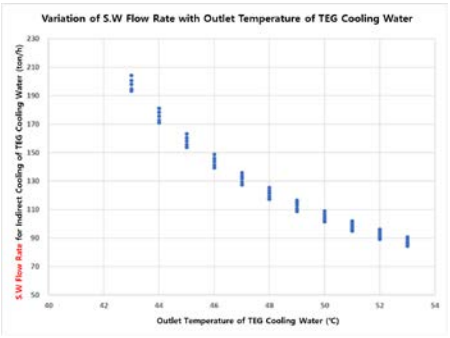


Figure 6: Variation of F.W and S.W Flow Rates with Outlet Temperature of TEG Cooling Water

Table 6: Design Conditions and Heat Balance of the TEG Cooling System

	Value	Basis
Heat duty	630 kW	Cooling capacity required by the TEG at its rated design condition
F.W flow / supply temp.	120 m³/h / 36.0 °C	Pump rating / 3-way valve setting
F.W return temp. (TEG outlet)	40.5 °C	Heat balance (ΔT 4.5 K)
S.W flow / inlet temp.	100 m³/h / 32.0 °C	Allocated G.S. pump capacity / design seawater temp.
S.W outlet temp.	37.5 °C	Heat balance (ΔT 5.5 K)
Cooler approach temp. (hot / cold end)	3.0 K / 4.0 K	–
LMTD / required UA (at rated heat duty)	3.5 K / approx. 181 kW/K	Requirement for the cooler; to be verified during the sea trial
F.W line design temp.	50 °C	Piping specification
Pump head	F.W 45 mTH (closed loop), S.W 30 mTH	Pump ratings

the S.W side. The resulting F.W return temperature of 40.5 °C is below the design temperature of the cooling F.W line (50 °C), and the required overall heat transfer coefficient–area product (UA) of the cooler is approximately 181 kW/K at the rated heat duty. Since the actual heat duty on *KOMERI1* is expected to be smaller than 630 kW owing to the lower exhaust gas conditions (**Table 4**), and the required UA decreases approximately in proportion to the heat duty, this value represents a conservative requirement. The actual performance of the cooler will be verified by measuring the inlet and outlet temperatures and flow rates of both the F.W and S.W lines during the sea trial; if the cooler performance is insufficient, the F.W supply temperature will rise slightly above the set point, resulting in a minor reduction in the TEG output rather than a safety concern. Since the F.W line is a closed loop with an expansion tank located at the compass deck, the static head is balanced, and the pump head of 45 mTH is used to overcome the frictional losses of the piping, the TEG cooling jackets, and the cooler.

Regarding the effect of the reduced cooling water flow rate on the TEG output, the analyses performed during the development of the TEG showed that the power generation converges at a cooling water flow rate of approximately 100 ton/h and that reducing the cooling water flow rate to one-tenth decreases the power generation by only about 10% **[12]**. Therefore, the effect of the final F.W flow rate of 120 m³/h on the TEG output is expected to be limited. Moreover, since the exhaust gas conditions of *KOMERI1* are lower than the rated design condition of the TEG (**Table 4**), the actual heat duty will be smaller than 630 kW, and the cooling system design is therefore conservative.

3.3 Design of Power Consumption Plan

3.3.1 Onboard Power Analysis

Table 7: Summary of Electric Load in *KOMERI1*

NO.	NAME OF CONSUMER GROUP	AT SEA				DEPARTURE AND ARRIVAL				UNLOADING /LOADING		AT HARBOUR	
		NORMAL SEA GOING		WITH BWTS		WITH B/T		WITHOUT B/T					
		C.L	I.L	C.L	I.L	C.L	I.L	C.L	I.L	C.L	I.L	C.L	I.L
1	MAIN ENGINE AUXILIARIES	60.4	0.4	60.4	0.0	126.9	0.6	126.9	0.6	3.1	4.4	14.9	2.8
2	ENGINE ROOM AUXILIARIES	86.5	114.1	206.5	115.6	197.7	118.3	197.7	116.8	159.3	115.2	39.2	128.8
3	BOILER PLANT	2.9	0.9	2.9	0.0	16.5	0.0	16.5	0.0	16.5	0.0	16.5	0.0
4	CARGO HANDLING PLANT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	62.0	0.0	0.0
5	DECK MACHINERY	104.3	0.0	104.3	0.0	644.4	0.0	173.8	0.0	65.4	13.1	0.0	13.1
6	AIR-COND. PLANT	19.2	63.5	19.2	63.5	19.2	63.5	19.2	63.5	19.2	63.5	19.2	63.5
7	VENT FANS	48.4	5.7	48.4	5.7	48.4	5.7	48.4	5.7	44.5	5.7	23.8	5.7
8	GALLEY & LAUNDRY EQUIPMENT	4.8	29.3	4.8	29.3	4.8	29.3	4.8	29.3	4.8	29.3	4.8	25.1
9	LIGHTING, NAV. & COMM.	102.4	0.0	102.4	0.0	102.4	0.0	102.4	0.0	102.4	0.0	81.9	0.0
10	MISCELLANEOUS	0.8	0.0	0.8	0.0	0.8	2.1	0.8	2.1	0.8	14.2	0.8	25.3
	TOTAL LOAD	**429.7**	**212.5**	**549.7**	**214.1**	**1161.1**	**219.5**	**690.5**	**218.0**	**416.0**	**307.5**	**201.1**	**263.3**
	TOTAL LOAD OF CONTINUOUS LOAD	429.7		549.7		1161.1		690.5		416.0		201.1	
	TOTAL LOAD OF INTERMITTENT LOAD	212.5		214.1		219.5		218.0		307.5		263.8	
	DIVERSITY FACTOR(%)	40		40		40		40		40		40	
	ACTUAL LOAD OF INTERMITTENT LOAD	85.0		85.6		87.8		87.2		123.0		105.5	
	TOTAL LOAD(KW)	514.7		635.5		1248.9		777.7		539.0		306.6	
	CAPACITY OF GENERATOR(KW)	**680.0**		**680.0**		**680.0**		**680.0**		**680.0**		**680.0**	
	NUMBER OF WORKING GENERATOR	**1**		**2**		**3**		**2**		**1**		**1**	
	GENERATOR LOAD FACTOR(%)	**75.7**		**46.7**		**61.2**		**57.2**		**79.3**		**45.1**	

Table 8: Review Results of the Vessel's Electrical Load Analysis (ELA)

No.	System	C.L (kW)	I.L (kW)	Applicability
1	Main Engine Auxiliary Machinery	60.4	0.0	Not applicable (Inability to ensure supply stability)
2	Engine Room Auxiliary Machinery	86.5	114.1	Not applicable (Inability to ensure supply stability)
3	Boiler	2.9	0.0	Not applicable (Low power demand)
4	Cargo Handling Equipment	0.0	*0.0*	Not applicable *(Out of service during sailing)*
5	Deck Machinery	104.3	0.0	Not applicable (Power demand exceeded)
6	Air Conditioning System	19.2	63.5	Not applicable (Large power fluctuation)
7	Vent Fan	48.4	5.7	Not applicable (Low power demand) *Candidate for future review
8	Galley and Laundry Room Equipment	4.8	29.3	Not applicable (Low power demand)
9	Lighting, Steering, and Communication	102.4	0.0	Not applicable (Power demand exceeded)
10	Miscellaneous	0.8	0.0	Not applicable (Low power demand)

The consumption plan within *KOMERI1* for the power generated through the TEG demonstration was considered. First, an Electrical Load Analysis (ELA) of *KOMERI1* was conducted. To examine whether the required power amount and generator capacity are sufficient for each operating condition of the vessel, the systems were classified into 10 categories, and the power consumption composition by operating condition and the total required power for each condition were identified by dividing them into Continuous Load (C.L) and Intermittent Load (I.L), as presented in **Table 7**.

3.3.2 Review of the Feasibility of Power Linkage with Onboard Systems

Considering that the TEG system operates while the vessel is under way, the Normal Sea Going condition was applied, and a standalone operating scheme was selected. The review results are summarized in **Table 8**. As shown in **Table 8**, none of the systems was found suitable for immediate connection to the TEG: the main engine and engine room auxiliary machinery were excluded because they are critical to ship operation and require a continuous and stable power supply; the deck machinery and the lighting, steering, and communication systems were excluded because their power demand exceeds the TEG output; the air conditioning system was excluded because of its large load fluctuation; and the remaining systems were excluded because of their low power demand or because they are out of service during sailing. Among these, the vent fans, whose continuous load is not critical to ship operation, were identified as a candidate for future review.

3.3.3 Independent Power Consumption Device

Connecting the power generated by the TEG system to the switchboards of each individual system and configuring it in parallel with the ship's main power system to serve as an auxiliary shipboard power system for the continuous and intermittent loads required during ship cruising was confirmed to be difficult to apply. Therefore, independent power consumption devices that do not affect onboard systems (an Energy Storage System (ESS) and a load bank) were reviewed.

In the case of an ESS, since the power generated by the TEG is stored in a battery and discharged as needed, it can serve as a buffer that absorbs fluctuations in TEG output caused by variations in exhaust gas temperature and flow rate, and by supplying the stored power to actual onboard loads, it enables securing a demonstration case in which the generated power is utilized. However, batteries are subject to separate safety standards under the IGF Code and KR classification rules (containment spaces for fire/explosion risk response, ventilation, battery management system (BMS) fire-extinguishing equipment, etc.), making the certification process demanding **[17]**. In addition, a bidirectional battery power conversion system (PCS) and BMS are required in addition to the DC-DC converter and inverter common to both options, which increases system complexity and initial investment cost, and there is a burden of design changes and classification approval reflecting the above considerations.

In the case of a load bank, since the generated power is

dissipated as heat through resistors, it can be utilized to verify the power generation performance of the TEG (output, voltage/frequency stability, load response characteristics, etc.) rather than for actual power utilization. In addition, its structure is simple and does not require separate battery safety standards, resulting in a lower certification burden and cost, and its installation is also relatively easy. However, unlike an ESS, it cannot actually utilize the generated power, meaning that a practical energy utilization effect cannot be demonstrated.

The review results for the ESS and load bank as independent power consumption devices are summarized in **Table 9**, and the load bank was selected in order to determine, at the early stage of demonstration, whether the TEG generates power stably and whether it satisfies the electrical characteristics (voltage, frequency, etc.) required by the classification society. Accordingly, the appearance and specifications of the 100 kW-class load bank constructed for this purpose are presented in **Figure 7** and **Table 10.**

Table 9: Comparison of Applicability between ESS and Load Bank

Item	ESS	Load Bank
Purpose	Actual use/storage of generated power (demonstration of energy-saving effect)	Verification of TEG power generation performance (confirmation of electrical characteristics)
Classification Approval / Safety	Battery safety standards (IGF Code, etc.) apply	Relatively low burden
System Complexity	Additional equipment required (battery, PCS, BMS, etc.)	Simple resistive load
Cost	High	Low
Space / Weight	Additional requirements such as containment space; significant burden	Relatively small
Applicable Stage	Later stage of demonstration (verification of effectiveness)	Early stage of demonstration (basic performance verification)
Power Conversion	DC-DC converter and DC-AC inverter (common), plus bidirectional battery PCS	DC-DC converter and DC-AC inverter (common)



Figure 7: 105 kW AC Load Bank

Table 10: Specification of Load Bank for TEG System

Model	105 kW AC load bank							
Rated Capacity	105 kW							
Rated Voltage	3Ø 440 V, 60 Hz (Control AC 220 V)							
Cooling Method	Forced air cooling							
Capacity Configuration								
Capacity(kW)	1	2	4	8	10	20	30	105
Current(A)	1.31	2.62	5.25	10.5	13.12	26.24	39.4	137.8
Resistance(Ω)	193.6	96.8	48.4	24.2	19.36	9.68	6.45	1.85
Unit	1	1	1	1	1	1	2	8

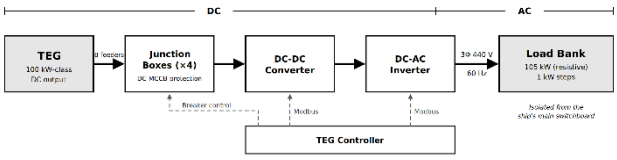


Figure 8: Single-Line Diagram of the Electrical Interface between the TEG and the Load Bank

The electrical configuration between the TEG and the load bank is shown in **Figure 8**. The DC output of the TEG is collected through eight feeders into four junction boxes (JB#1–JB#4), each equipped with two DC molded-case circuit breakers (250AF/160AT) with a shunt-trip function. The collected DC power is conditioned by a DC-DC converter and converted by a DC-AC inverter into three-phase 440 V, 60 Hz AC power, which is supplied to the load bank. The load bank consists of eight resistor units (1–30 kW) that can be switched in combination, allowing the load to be adjusted in 1 kW steps up to 105 kW according to the TEG output. The TEG controller monitors the output power via RS-485, communicates with the converter and inverter via Modbus, and controls the circuit breakers, the C.F.W

pump, the exhaust fan, and the solenoid valves of the intake and bypass dampers, while transmitting status and alarm signals to the vessel's alarm monitoring system (AMS). The TEG power circuit is electrically isolated from the ship's main switchboard; the vessel supplies only the auxiliary and control power (AC 440 V and AC 220 V).

Although the generated power is dissipated in the load bank during the present demonstration, the fuel savings and CO_2 reductions achievable through the utilization of the TEG output can be evaluated according to **Equations (5) and (6)**.

$$\Delta FC = (P_{TEG} - P_{aux}) \cdot t \cdot SFOC_{DG} \times 10^{-6} \quad (5)$$

$$\Delta CO_2 = \Delta FC \cdot C_F \quad (6)$$

Here,

ΔFC : Fuel saving (t)

ΔCO_2 : CO_2 reduction (t)

P_{TEG} : Output of the TEG (kW)

P_{aux} : Power consumption of the auxiliary equipment (kW)

t : Operating time (h)

$SFOC_{DG}$: Specific fuel oil consumption of the diesel generator per unit electrical output (g/kWh)

C_F : CO_2 conversion factor (t-CO_2/t-fuel)

For *KOMERI1*, the specific fuel oil consumption of the diesel generator engine is 193 g/kWh at the rated output of 745 kW, which corresponds to approximately 211 g/kWh of electrical output based on the rated generator output of 680 kW. With a CO_2 conversion factor of 3.206 t-CO_2/t-fuel for diesel/gas oil **[18]**, each kWh of net electrical output would therefore save approximately 211 g of fuel and 0.68 kg of CO_2. However, the actual TEG output depends on the exhaust gas conditions, which vary with the main engine load under actual sea conditions, and the net output must account for the power consumption of the auxiliary equipment, such as the C.F.W pump and the exhaust fan. Therefore, the fuel savings and CO_2 reductions will be quantified by applying **Equations (5)** and **(6)** to the TEG output, auxiliary power consumption, and engine operating data measured during the 1,000-hour sea trial.

4. Ship Design Modifications for the Installation of the TEG System Onboard

Since *KOMERI1* was under construction, the design modifications related to the TEG system were reflected during the newbuilding stage.

4.1 Funnel Extension

Considering the TEG dimensions (2,030 × 2,072 × 7,515 mm), the funnel length was extended by 2,750 mm, as shown in **Figure 9**, to secure the installation space within the funnel. Since the exhaust gas passing through the TEG experiences a reduction in both temperature and flow velocity, exposing the outlet at a low position could result in flow instability, such as backflow induced by crosswind or the ingress of rainwater and seawater. In addition, the location of the exhaust outlet is determined through the classification approval process to satisfy a number of safety requirements, including the bridge visibility (blind sector) requirements under SOLAS Chapter V, the separation distance

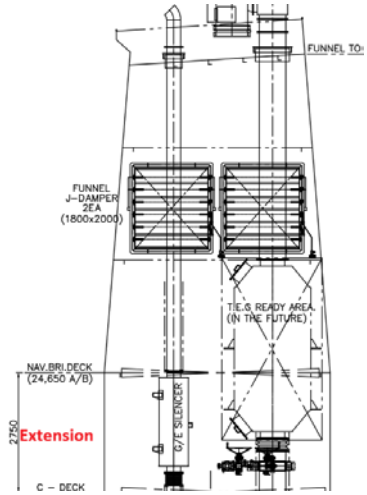


Figure 9: Schematic of Funnel Extension

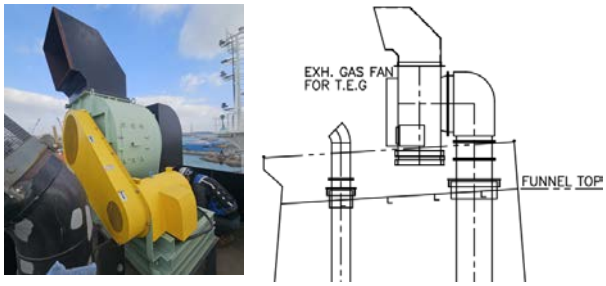


Figure 10: Actual Exhaust Fan (left) and Drawing (right)

Table 11: Specification of Exhaust Fan

Item	Specification
Model	Exhaust Fan
Power supply	AC 220 V, 60 Hz, 3Ø, 4-pole (4p)
Performance	495 m³/min × 60 mmAq

from accommodation and engine room air intakes, and the safety distance from life-saving appliances; the vessel already has a funnel structure that reflects these requirements from the newbuilding stage. Accordingly, in this study, the exhaust line downstream of the TEG was extended in accordance with the existing funnel arrangement requirements.

4.2 Installation of Exhaust Fan

According to **Table 5** in Section 3.1.2, the back pressure margin of the main engine exhaust gas line is 95.66 mmAq. Since the pressure drop across the TEG, including its inlet and outlet hoods, is approximately 120 mmAq according to the analysis performed during the development of the TEG system **[12]**, this margin alone is insufficient for TEG operation. Therefore, an exhaust fan (**Figure 10**) with a rated performance of 495 m³/min × 60 mmAq (**Table 11**) was installed at the outlet of the TEG line to compensate for the additional pressure drop.

The final back pressure balance at the design basis (100% SMCR, **Table 4**) is summarized in **Table 12**. The additional losses of the branch line, dampers, and piping downstream of the branch point were estimated using the same method as **Table 5**, with a loss coefficient of 0.3 assumed for the fully open dampers and a loss coefficient of 0.1 for straight-through flow at the branch. The exit loss was neglected, consistent with **Table 5**, and the gas temperature downstream of the TEG was conservatively assumed to be equal to the TEG inlet temperature (194 °C). As a result, the total back pressure in TEG mode with the exhaust fan running is 263.00 mmAq, corresponding to a margin of 37.00 mmAq (12.3%) with respect to the allowable back pressure of 300 mmAq, which satisfies the reserve margin of 10–20%.

4.3 Branch of Main Exhaust Gas Line

To supply exhaust gas to the TEG system, the main engine exhaust gas line was branched from a point downstream of the Composite Boiler, as shown in **Figure 11**. The left line serves as the bypass flow path used during normal operation, while the right line serves as the flow path used for demonstration purposes. The interlocked damper valves installed on each line operate in conjunction with one another, alternately opening and closing, thereby enabling stable flow path switching and back pressure control.

4.4 Seawater Supply and Dedicated Overboard Line for TEG System Cooling

A dedicated sea chest for the S.W line was initially considered; however, it was excluded because it would have required hull

Table 12: Back Pressure Balance of the Main Engine Exhaust Gas Line in Bypass and TEG Modes

Item	Bypass mode	TEG mode (fan on)
Existing line incl. composite boiler (shipyard calc.)	204.34	204.34
Bypass damper (K = 0.3)	+ 11.51	–
Bypass section downstream of branch (a)	(included)	− 24.29
TEG line: branch, intake damper, piping (b)	–	+ 22.95
TEG pressure drop (incl. inlet/outlet hoods)	–	+ 120.00
Exhaust fan compensation	–	− 60.00
Total back pressure	215.85	263.00
Margin to 300 mmAq (ratio)	84.15 (28.1%)	37.00 (12.3%)

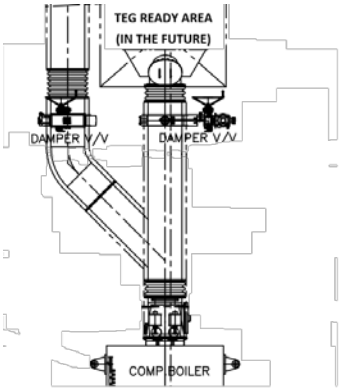


Figure 11: Configuration of the Exhaust Gas Bypass and Demonstration Lines Equipped with Interlocked Damper Valves

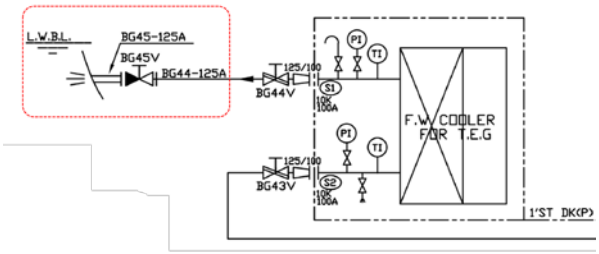


Figure 12: Arrangement of the Dedicated Overboard Discharge Line for the C.F.W Cooler (red dotted line)

structural modifications. Instead, seawater for the S.W line is supplied from the vessel's fire, bilge and G.S. pumps (two sets, 160/90 m³/h × 30/90 mTH each), from which 100 m³/h is allocated to the C.F.W cooler, and a dedicated overboard discharge line (125A) was newly installed for the C.F.W cooler, as shown in **Figure 12**. Since the required seawater flow rate is within the capacity of a single pump, one pump can be assigned to the TEG cooling during the sea trial while the other remains available for fire-fighting and general service. In addition,

Table 13: Interlock Logic and Trigger Bases of the TEG System

Event	Detection	Interlock action	Trigger basis
Exhaust fan stop/trip	Fan run/abnormal signal	Bypass mode; DC breakers trip	Status signal (TEG-mode back pressure without fan ≈ 323 mmAq > 300 mmAq)
C.F.W pump trip	Pump abnormal signal	Bypass mode; DC breakers trip	Status signal
Low F.W expansion tank level	Level switch	Bypass mode; DC breakers trip	Status signal
Loss of cooling / F.W high temperature	F.W temperature sensors	Bypass mode; DC breakers trip	Below the design temperature of the F.W line (50 °C)
Excessive back pressure	Exhaust gas pressure transmitters	Bypass mode	Below the allowable back pressure (300 mmAq)
TEG overtemperature	TEG temperature sensors	Bypass mode; DC breakers trip	Below the allowable module temperature specified by the TEG manufacturer
Damper malfunction	Damper position feedback	Alarm to AMS; intake damper not closed until bypass is confirmed open	Status signal
Loss of control power/air	–	Both dampers spring-return to open	Passive (no set point required)

fluctuations in the seawater supply are absorbed by the three-way temperature control valve on the F.W line, which maintains the F.W supply temperature to the TEG at 36 °C. In the event of a loss of seawater supply, the TEG is switched to bypass mode, as described in Section 4.5.

4.5 Structural and Fail-Safe Considerations

The 2,750 mm extension of the funnel and the TEG installation space were designed by the ship designer in accordance with the KR rules, taking into account the dimensions (2,030 × 2,072 × 7,515 mm) and wet weight (approximately 17.25 t) of the TEG, and the funnel extension was approved by KR. However, the KR approval at this stage covers the “Ready for TEG system” configuration, in which the TEG itself is not yet installed; in accordance with the KR approval conditions, drawings reflecting the installation of the TEG must be submitted to KR for approval prior to installation. Accordingly, the detailed verification of the foundation strength, the design accelerations due to ship motion, the avoidance of resonance with the main excitation frequencies (1st order of 2.07 Hz and 6th order of 12.4 Hz of the main engine at 100% SMCR, and the propeller blade frequency), and the effect of the added weight on stability will be performed at that stage. Since the installation space was secured as a reserved area at the newbuilding stage, the TEG will be fitted to suit the actual site conditions during installation.

Since the TEG is not essential to the operation of the vessel, the fail-safe philosophy of the system is to switch to bypass mode and electrically isolate the TEG upon any abnormality, while ensuring that at least one exhaust gas path is always open. This is achieved by both the intake and bypass dampers being of the

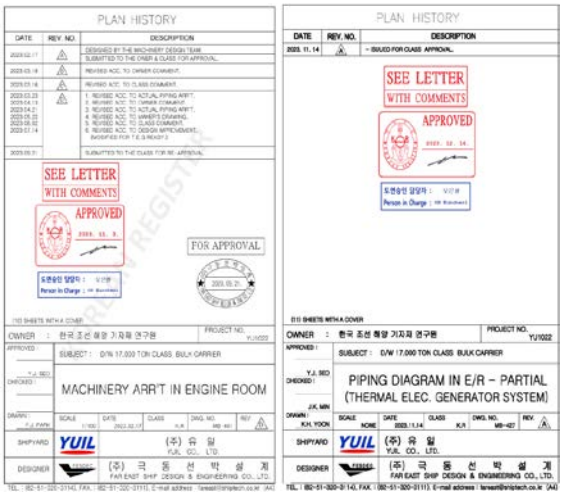


Figure 13: Revised Design Drawing Reflecting the "Ready for TEG system" Configuration

spring-return, fail-open type, and by the operating procedure in which the intake damper is opened before the bypass damper is closed. The TEG controller receives the run and abnormal signals of the exhaust fan and C.F.W pump, the low-level signal of the F.W expansion tank, the damper position feedback, and the signals of the temperature sensors and exhaust gas pressure transmitters, and it can trip the DC circuit breakers of the TEG. The interlock logic for each abnormal event is summarized in **Table 13**. Events detected by status signals, such as an exhaust fan trip, trigger the interlock immediately; in particular, the back pressure in TEG mode without the exhaust fan (approximately 323 mmAq) exceeds the allowable value, so an immediate switch to bypass mode is required. For events detected by measured values, the bases for the trigger conditions are given in **Table 13**, and the final set points will be established in the control narrative

Table 14: Ship-Side Checklist for Preparing the Sea Trial Demonstration of the TEG System

No.	Review item	Equipment requirement to be identified	Ship-side review and measure	Result for *KOMERI1*	Section
1	Design basis	Exhaust gas flow and temperature at the equipment inlet	Define a single operating point; use the boiler outlet condition if installed downstream	100% SMCR, LSFO; 24,120 kg/h, 194.1 °C	3.1.1
2	Back pressure	Pressure drop of the equipment	Back pressure balance including branch, dampers, and piping; compensation if required	Exhaust fan; margin 12.3% (TEG mode), 28.1% (bypass mode)	3.1.2, 4.2
3	Exhaust gas routing	Bypass capability	Branch line with interlocked dampers	Fail-open intake and bypass dampers	4.3
4	Installation space and structure	Dimensions and weight	Funnel extension; structural verification at installation	Funnel extended by 2,750 mm	4.1, 4.5
5	Cooling capacity	Heat duty and coolant flow	Heat balance against available seawater; pump head	630 kW with F.W 120 m³/h and S.W 100 m³/h	3.2
6	Seawater supply and discharge	Seawater flow	Use of existing pumps; dedicated overboard line	G.S. pump (100 m³/h); 125A overboard line	4.4
7	Power consumption	Output and electrical interface	Review of onboard loads; independent consumer	DC/AC conversion; 105 kW load bank	3.3
8	Fail-safe	Abnormal events	Interlock logic and trigger bases	Bypass mode upon any abnormality	4.5
9	Classification	–	Approval at newbuilding; modification approval at installation	“Ready for TEG system” approval	4.6

in cooperation with the TEG manufacturer and the control system supplier and approved by KR prior to the installation of the TEG.

4.6 Classification Approval as "Ready for TEG system"

The revised design drawings incorporating all of the above information have obtained approval from the Korean Register (KR) in the "Ready for TEG system" configuration (Ready status), as shown in **Figure 13.** The vessel has now completed construction and is awaiting delivery.

5. Conclusion

To prepare for the sea trial demonstration of a 100 kW-class TEG system developed under a separate program, the operational requirements of the TEG were compared with the utilities available on *KOMERI1* under a single design basis (100% SMCR, LSFO mode), and the following ship-side measures were reflected in the design.

1) Back pressure: Considering the pressure drop of the TEG (approximately 120 mmAq) and the additional losses of the branch line, dampers, and piping, an exhaust fan was installed at the outlet of the TEG line. The final back pressure margin with respect to the allowable value of 300 mmAq is 12.3% in TEG mode and 28.1% in bypass mode.
2) Installation space and exhaust gas routing: The funnel was extended by 2,750 mm to accommodate the TEG (2,030 × 2,072 × 7,515 mm), and the main exhaust gas line was branched with interlocked fail-open dampers to enable switching between TEG and bypass modes.
3) Cooling system: The TEG cooling system consists of a closed F.W loop (120 m³/h) and an S.W line (100 m³/h) supplied from the existing fire, bilge and G.S. pumps with a dedicated overboard discharge line. A heat balance analysis confirmed that the required heat duty of 630 kW can be removed with an F.W return temperature below the design temperature of the line.
4) Power consumption and safety: A 105 kW load bank was selected as an independent power consumer through a DC/AC conversion system isolated from the ship’s main switchboard, and a fail-safe philosophy of switching to bypass mode upon any abnormality was established.
5) Classification: All of the above measures were reflected at the newbuilding stage, and classification approval was obtained from KR in the “Ready for TEG system” configuration.

The review process is summarized as a ship-side checklist in **Table 14**, which can be applied to the preparation of sea trial demonstrations of other eco-friendly marine equipment. Since the TEG was not designed for the exhaust gas conditions of *KOMERI1*, its output during the sea trial is expected to be lower than the rated value. The power generation performance, the fuel savings and CO_2 reductions, the set points of the interlocks, and the structural verification at installation will be addressed in future work based on the 1,000-hour sea trial.

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Author Contributions

Conceptualization, S. H. Jeong and S. Y. Choi; Methodology, S. H. Jeong and S. Y. Choi; Software, S. Y. Choi; Resources, S. H. Jeong; Writing—Original Draft Preparation, S. H. Jeong; Writing—Review & Editing, M. H. Lee and Y. S. Yun; Supervision, Y. S. Yun; Project Administration, S. Y. Choi; Funding Acquisition, S. H. Jeong and S. Y. Choi.

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