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Full-Voyage Operational Validation of a Load Optimization Strategy for a Dual-Fuel Diesel-Electric LNG Propulsion System

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Abstract

This study presents a full-voyage operational validation of a load optimization strategy applied to a Dual-Fuel Diesel-Electric (DFDE) liquefied natural gas (LNG) propulsion system. The proposed approach was evaluated onboard an LNG carrier equipped with five four-stroke dual-fuel engines. The operational validation was conducted exclusively with the generator engines operating in LNG (gas) mode, while operation on conventional liquid fuels was outside the scope of this study. A complete 26-day voyage cycle, including cargo loading, loaded passage, cargo discharge, and ballast passage, was defined. Representative steady-state operating intervals for each operational mode were analyzed under both conventional Power Management System (PMS) load distribution and optimized load allocation. Real-time manual redistribution of engine loads was performed to validate the proposed load optimization strategy under real operating conditions. The results show consistent fuel savings across all operating modes, with the highest reduction observed during ballast passage (1.51%), followed by loaded passage (0.74%). A voyage-scale analysis reveals cumulative fuel savings exceeding 22 metric tons per operational cycle, equivalent to annual reductions of more than 300 metric tons under typical service conditions. These savings consistently reduce both carbon dioxide (CO_2) and nitrogen oxides (NO_x) emissions across all operating modes. Ultimately, the proposed load optimization strategy demonstrated stable performance under the investigated steady-state operating conditions and provides a practical approach to improving ship energy efficiency. The results support the potential application of the proposed strategy in existing ship energy management systems, while further validation under long-term and transient operating conditions is recommended.

Keywords: DFDE propulsion; LNG carrier; load distribution optimization; operational validation; voyage-scale analysis

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1. Introduction

Improving the energy efficiency of ship propulsion systems has become a major challenge for the maritime industry. With rising fuel costs, ship operators are increasingly required to comply with environmental regulations aimed at reducing greenhouse gas emissions and improving carbon efficiency [1]. Recent regulatory measures introduced by the International Maritime Organization (IMO), including the Energy Efficiency Existing Ship Index (EEXI) [2] and the Carbon Intensity Indicator (CII) [3], as well as regional initiatives such as FuelEU Maritime [4], have increased the need for practical solutions to reduce fuel consumption and exhaust emissions in daily ship operations.

Dual-Fuel Diesel-Electric (DFDE) propulsion systems have become one of the most widely adopted propulsion concepts for modern LNG carriers because of their operational flexibility, redundancy, and ability to operate on both liquefied natural gas (LNG) and conventional marine fuels [5–7]. In addition to enabling compliance with increasingly stringent emission requirements, DFDE power plants provide an effective means of utilizing boil-off gas generated during cargo transportation [5,6]. However, despite these advantages, the overall efficiency of DFDE systems remains strongly influenced by the operating strategy applied to the onboard power plant, particularly regarding generator loading and power distribution among running engines.

In DFDE power plants, power generation is usually controlled by an on-board power management system (PMS), which determines the number of generators in operation and distributes the electrical load among the running engines. Under normal operating conditions, the PMS load distribution algorithms are primarily designed to ensure system stability, operational reliability, and sufficient reserve capacity [8–10]. Consequently, the electrical load is usually distributed evenly among all connected generators. While this approach simplifies system management and ensures robust operation, it does not necessarily achieve the optimal operating point for fuel consumption and exhaust emissions. Because the specific fuel consumption and emission characteristics of dual-fuel engines vary with engine load, alternative load distribution strategies may improve the overall efficiency of the power plant [10,11].

Extensive research demonstrates that optimization-based power management strategies can improve the operational efficiency of marine electric propulsion systems [11–15]. Research has addressed generator scheduling, optimal load allocation, and energy management techniques aimed at reducing fuel consumption while maintaining system reliability and operational constraints. These methods have been applied to all-electric ships, integrated electric propulsion systems, and diesel-electric power plants, consistently demonstrating that significant efficiency improvements can be achieved through more effective distribution of electrical loads among operating generators. More recent studies have also incorporated environmental objectives, such as greenhouse gas emission reduction and emission-aware power management, highlighting the growing importance of integrated energy and environmental performance optimization in modern ship power systems [14–16]. Recent studies have also examined the broader transition from conventional diesel-powered fleets to alternative-fuel solutions, highlighting LNG as an important transitional fuel while emphasizing that future decarbonization will likely rely on a combination of different fuel technologies [17].

While the benefits of optimization-based power management are well-documented for marine electric propulsion, fewer studies focus on the practical implementation within DFDE LNG plants under dynamic, real-world operating conditions. To address this gap, Martinić-Cezar et al. [18] developed a load optimization model for a DFDE LNG power plant and applied it using operational data from an LNG carrier. The model identified operating conditions where alternative engine load distributions could reduce fuel consumption while maintaining the same total power demand and operational requirements.

In a subsequent study, this framework was expanded to incorporate exhaust emissions, allowing combined assessment of fuel consumption, NO_x emissions, and CO_2 emissions under different engine loading scenarios [19]. The results showed that optimized load allocation can simultaneously reduce fuel consumption and emissions compared with the conventional equal-load distribution typically applied by the PMS.

Despite promising results reported for individual operating conditions, the overall impact of load optimization across an entire LNG carrier voyage remains insufficiently explored. In practice, LNG carriers operate in several distinct modes, including cargo loading, loaded passage, cargo discharge, and ballast passage, each with different power demands and engine loading profiles. Therefore, the cumulative benefits of load optimization cannot be reliably assessed from individual operating conditions alone. A comprehensive voyage-scale evaluation is required to determine the practical applicability of the optimization strategy and to quantify its overall operational and environmental benefits under realistic service conditions.

The primary objective of this study is to extend the previously developed load optimization framework [18,19] from model-based assessment of individual operating conditions to shipboard operational validation and voyage-scale performance assessment. Unlike the authors' previous studies, which developed and evaluated the optimization framework using operational data for selected engine operating conditions, the present study physically implements optimized generator load allocations through the vessel's PMS interface and evaluates their performance under representative steady-state operating conditions onboard an LNG carrier. Four characteristic voyage operating modes— cargo loading, loaded passage, cargo discharge, and ballast passage—are considered. For each mode, the optimized load allocation is directly compared with the conventional equal-load distribution applied by the PMS under an equivalent total power demand. Experimentally determined fuel consumption and emission performance under these representative operating conditions are subsequently used to quantify the cumulative effects of load optimization over a representative 26-day voyage cycle. In this way, the study provides an operational assessment of the practical applicability and the potential energy and environmental benefits of the proposed optimization strategy under realistic shipboard conditions.

2. Case Study and Methodology

This section describes the LNG carrier and the Dual-Fuel Diesel-Electric (DFDE) propulsion plant investigated in this study, outlines the load optimization strategy, and presents the methodology implemented for the voyage-scale operational validation. Furthermore, it details the operational profile of the analyzed voyage cycle and the formal procedure adopted to evaluate the cumulative effects of load optimization.

2.1. LNG Carrier and DFDE Power Plant Description

The vessel under consideration is a liquefied natural gas (LNG) carrier equipped with a Dual-Fuel Diesel-Electric (DFDE) propulsion system comprising five MAN 8L51/60DF medium-speed generating sets. Each engine has a Maximum Continuous Rating (MCR) of 8000 kW, providing a total installed electrical power of 40 MW. The engines are designed to operate on LNG, marine diesel oil (MDO), and heavy fuel oil (HFO), with LNG serving as the primary fuel during normal service. Although the investigated DFDE generator sets can operate on both gaseous and liquid fuels, all operating conditions analyzed in this study correspond exclusively to LNG (gas) mode. Consequently, the optimization results and the subsequent voyage-scale assessment reported here are specific to LNG-mode operation and should not be directly extrapolated to liquid-fuel operation, for which the engine load-dependent fuel consumption and emission characteristics may differ. The LNG used during the investigated operating period originated from a consistent supply source. According to the corresponding cargo quality certificate, the LNG composition was 99.81 mol% methane, 0.02 mol% ethane, and 0.17 mol% nitrogen, with a gross heating value of 55.4089 MJ/kg.

As illustrated in Figure 1, the propulsion plant is based on an integrated electric power system architecture where all generating sets are connected to a common high-voltage distribution network via two 6.6 kV main switchboards. Electrical power is distributed to both the propulsion motors and auxiliary consumers according to the vessel's instantaneous operational requirements. This configuration offers an exceptional degree of operational flexibility and redundancy, enabling various combinations of generating sets to be online under fluctuating power demands.

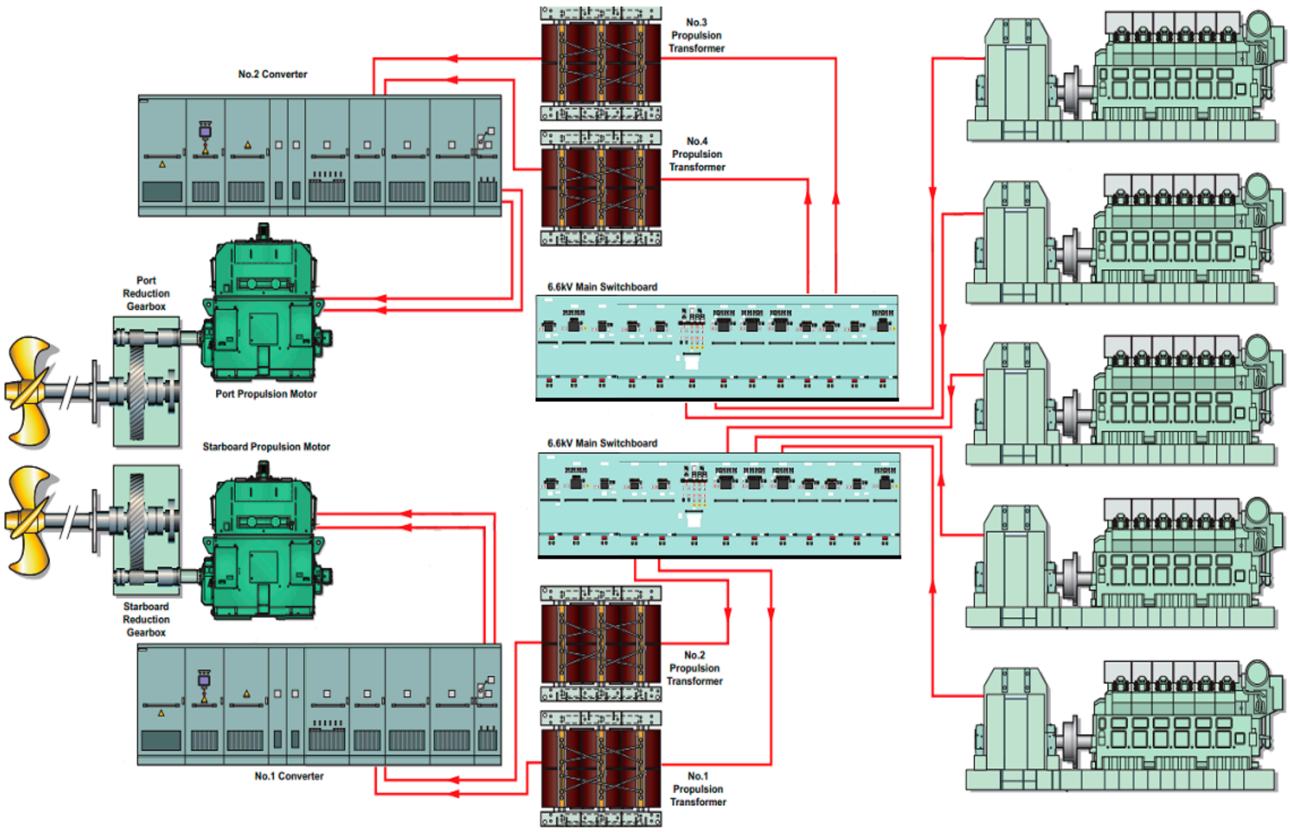

Figure 1. Simplified configuration of the DFDE propulsion system comprising five MAN 8L51/60DF generator sets, propulsion motors, transformers, and main switchboards.

The primary technical specifications of the MAN 8L51/60DF engine are summarized in Table 1. The operation of the power plant is coordinated by the vessel's onboard Power Management System (PMS), which automatically governs generator synchronization, start–stop sequences, protection functions, and equal load sharing among all connected generators. This conventional PMS operating mode is used as the benchmark throughout the present study. Although this strategy ensures grid stability and operational reliability, it does not necessarily correspond to the operating point with minimum fuel consumption, thereby creating an opportunity for performance enhancement through optimized load allocation strategies.

Table 1. Main specification of the MAN 8L51/60DF dual-fuel engine.

Engine Parameters	Specifications
Cylinder No (-)	8
Cylinder diameter (mm)	510
Stroke (mm)	600
Compression ratio (-)	13.3
Speed (rpm/min)	514
MCR-Power (kW)	8000
Fire order (-)	1-4-7-6-8-5-2-3
Mean effective pressure (bar)	19
Ignition pressure (bar)	190

2.2. Load Optimization Strategy

The load optimization strategy implemented in this study was originally developed and validated in previous investigations focusing on the same DFDE propulsion plant [18,19]. Consequently, only a concise overview of the optimization architecture is provided here, while the complete mathematical formulation, engine performance model, boundary conditions and model validation procedures are presented in the referenced publications. Accordingly, the novelty of the present study lies not in the development of a new optimization algorithm, but in the full-scale operational implementation and full-voyage validation of the previously developed optimization framework under real shipboard operating conditions.

Under conventional PMS operation, the instantaneous electrical demand is distributed equally among all active generators. In contrast, the proposed optimization strategy uses the load-dependent fuel consumption and emission characteristics of individual engines to determine the generator load allocation that minimizes fuel consumption while meeting the required power demand and operational constraints. The empirical engine performance datasets were obtained from onboard measurements on the investigated LNG carrier and processed using cubic spline interpolation, as described in [18,19].

The optimization procedure evaluates alternative generator load allocation scenarios for a specified power demand and number of operating generators using experimentally derived engine performance functions. In the extended version of the model presented in [19], exhaust emission characteristics were incorporated along with fuel consumption, enabling simultaneous assessment of both energy efficiency and environmental performance. For each operating condition, the optimization algorithm identifies the generator load distribution that minimizes the selected objective function while satisfying all operational constraints.

For the optimization strategy applied in the present study, the objective is to minimize total fuel consumption (TFC) for the required power demand, subject to the admissible generator operating range. To provide a fully transparent analytical formulation, the mathematical structure of the optimization problem is defined as follows:

$$\min TFC = \sum_{i=1}^{N} \dot{m}_{f,i}(L_i) \cdot P_{MCR,i}, \tag{1}$$

subject to the following equality and inequality constraints:

$$\sum_{i=1}^{N} L_i \cdot P_{MCR,i} = P_{demand}, \tag{2}$$

$$\min TFC(P_{demand}), \qquad 20\% \leq L \leq 90\%, \qquad i = 1, \ldots, N, \tag{3}$$

where TFC represents the total fuel consumption of the power plant (kg/h), \(N\) is the number of active generators, L_i denotes the fractional load of generator i ($0 \leq L_i \leq 1$), $P_{MCR,i}$ is the Maximum Continuous Rating of engine i (8000 kW), $\dot{m}_{f,i}(L_i)$ represents the load-dependent specific fuel consumption function derived experimentally via cubic spline interpolation, and P_{demand} is the instantaneous total electrical power demand required by the vessel. The constrained optimization problem is solved using the MATLAB R2024a fmincon algorithm utilizing the sequential quadratic programming (SQP) method, as described in detail in [18,19].

In this study, the optimization results are compared with the conventional PMS load-sharing strategy, in which the electrical demand is distributed equally among all operating generators. Figure 2 shows the general workflow of the previously developed load optimization framework, which can consider different fuel modes [18,19]. In the present operational validation, however, the framework was applied exclusively to the LNG (gas) mode.

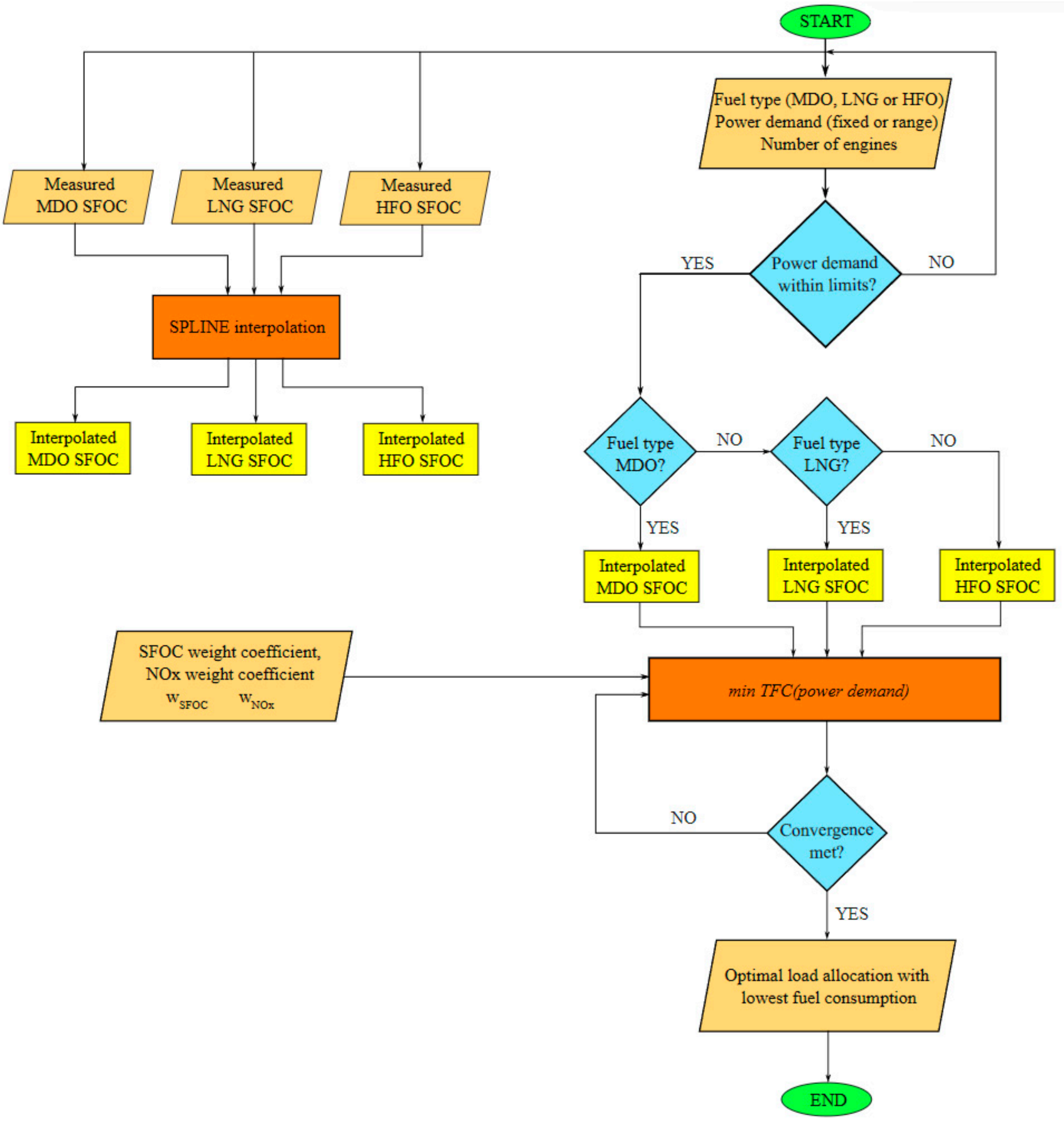

Figure 2. Simplified workflow of the load optimization procedure.

2.3. Voyage Operational Profile

The operational validation was performed utilizing high-fidelity data extracted from the vessel's official logbooks and onboard automation monitoring systems during a representative voyage cycle. Operating under a long-term charter agreement, the vessel follows a well-defined, repetitive trading pattern that includes cargo loading, loaded passage, cargo discharge, and ballast passage. These distinct operating modes are characterized by highly variable power demands, engine loading profiles, and operational durations, making them ideal for evaluating the practical effectiveness of the load optimization strategy under realistic service conditions.

For this voyage-scale assessment, a complete operational cycle spanning exactly 26.0 days was analyzed. Based on historical operational records, the cycle comprised

1.5 days of cargo loading, 10.0 days of loaded passage, 1.5 days of cargo discharge, and 13.0 days of ballast passage. This timeline represents a standard, real-world voyage profile for this category of LNG carrier and serves as the baseline for estimating cumulative fuel savings and emission reductions resulting from the optimized engine load allocation. Table 2 summarizes the operational breakdown used as the boundary condition in this study.

Table 2. Operational profile of the analysed voyage cycle.

Operating Mode	Duration (Days)
Cargo loading	1.5
Loaded passage	10.0
Cargo discharge	1.5
Ballast passage	13.0
Total voyage duration	26.0

These four operating modes differ fundamentally in terms of electrical power demand and generator utilization. Cargo handling operations (loading and discharging) require relatively low power, primarily driven by auxiliary cargo machinery, such as high-duty compressors for boil-off gas (BOG) management and ballast pumping systems. Conversely, the loaded and ballast passages demand continuous, high-load electrical power for the electric propulsion motors. Consequently, the generating sets operate across a broad load spectrum throughout the voyage, presenting diverse opportunities to improve overall thermal efficiency through strategic, asymmetric load allocation. The proposed optimization strategy is formulated as a function of the required electrical power demand rather than vessel speed. Vessel speed indirectly affects the optimization only through its influence on the propulsion power demand and the resulting electrical load on the generating plant. The operational validation was conducted during an actual commercial voyage under naturally occurring environmental conditions. Consequently, the measured electrical power demand inherently includes the combined effects of the weather and sea-state conditions experienced during the voyage under investigation.

2.4. Validation Procedure

The operational validation protocol relied on high-fidelity data from representative, steady-state operating intervals carefully selected from each voyage mode. To ensure a scientifically rigorous benchmark, these intervals were isolated only after the total electrical power demand, thermal parameters, and engine operating conditions had completely stabilized. For each baseline condition, the actual equal-load distribution governed by the conventional onboard Power Management System (PMS) was comprehensively logged, establishing a precise datum for total power demand, fuel mass flow rates, and secondary engine parameters.

The developed load optimization model was subsequently executed under identical boundary conditions to compute the optimal asymmetric engine load allocation. To verify the empirical viability of these theoretical outputs under real-world maritime conditions, the ship's crew manually adjusted the generator load setpoints via the PMS interface to match the exact allocation vectors recommended by the optimization model. Once the plant re-stabilized under the optimized configuration, the resulting fuel consumption and thermodynamic parameters were measured and directly cross-referenced with both the conventional PMS baseline and the initial model predictions.

The optimized load allocation was implemented manually through the PMS human–machine interface by adjusting the generator load setpoints to the values determined by the optimization model. The adjustments were performed progressively, while the actual generator loads and relevant operating parameters were continuously monitored through the onboard automation system. After each load redistribution, the generating sets were maintained at the prescribed operating condition for at least 10 min, and measurements were recorded only once the generator loads and monitored engine parameters had stabilized. Minor deviations between the target and actual generator loads could occur due to the resolution and regulation characteristics of the onboard PMS; however, no systematic quantitative assessment of these deviations was performed. Consequently, the present procedure validates the practical feasibility of the optimized load allocation under stabilized operating conditions but does not represent the response accuracy or speed achievable with an automated closed-loop implementation.

This physical validation procedure was systematically executed across distinct operating intervals corresponding to cargo loading, loaded passage, cargo discharge, and ballast passage. The empirically verified fuel savings for each discrete mode were then integrated over the respective temporal durations presented in Table 2, enabling an accurate, voyage-scale estimation of cumulative fuel savings and net emission mitigation potential.

Representative operating intervals were selected only after power demand and engine operating conditions stabilized to ensure meaningful comparison between conventional and optimized load allocation. Fuel consumption and exhaust emission data were obtained using the vessel's onboard monitoring and automation systems. In the present study, CO_2 emissions are reported as directly measured exhaust gas concentrations (%). As exhaust gas mass flow was not measured during the onboard validation tests, the measured CO_2 concentrations cannot be directly converted into absolute CO_2 mass emission rates (kg/h) without introducing additional assumptions. Therefore, CO_2 results are presented as measured concentrations, while fuel consumption is reported separately as mass flow (kg/h). The measurement procedures and instrumentation for data acquisition are described in detail in the authors' previous studies [18,19] and are not repeated here. For each operating condition investigated, data acquisition was carried out only after the generating sets had reached stable steady-state operation. After each adjustment of the generator load distribution, the engines were held at the prescribed operating point for at least 10 min to ensure stable steady-state conditions before the corresponding fuel consumption and emission measurements were recorded. A single set of readings was taken at each stabilized operating point; therefore, the reported steady-state values represent instantaneous measurements obtained under stable operating conditions rather than time-averaged data from continuous sampling. The associated measurement uncertainty is primarily determined by the accuracy and calibration characteristics of the measurement instrumentation, as detailed in [18]. Only validated operational data corresponding to steady-state operating conditions were considered in this analysis.

3. Results and Discussion

This section presents the results of the operational validation conducted under representative voyage operating conditions. The thermodynamic and environmental impacts of the optimized engine load allocation framework are first evaluated aggregately across all operating modes and subsequently analyzed in technical detail for each distinct voyage phase.

3.1. Comparative Performance Across Voyage Operating Modes

For each specific boundary condition, the performance of the optimized asymmetric load allocation was directly benchmarked against the baseline equal-load sharing strategy executed by the conventional onboard PMS. The quantified fuel mass flow reductions and environmental benefits are synthesized in Table 3.

Table 3. Summary of optimization performance across voyage operating modes.

Operating Mode	Power Demand (kW)	Active Engines	PMS Fuel Rate (kg/h)	Optimized Fuel Rate (kg/h)	Fuel Savings (%)	Phase Fuel Saving (t)	NO_x Emission Reduction (%)
Cargo loading	4000	2	800.0	787.2	1.60	0.46	10.18
Cargo discharge	8000	2	1398.4	1381.2	1.23	0.62	23.35
Loaded passage	24,000	4	4108.1	4077.7	0.74	7.30	11.87
Ballast passage	17,500	3	3021.0	2975.9	1.51	14.07	4.70

Table 3 shows that optimized engine load allocation resulted in measurable fuel savings under all operating conditions considered. The highest relative reduction in fuel consumption was achieved during cargo loading (1.60%), closely followed by ballast passage (1.51%). Although loaded passage had the lowest percentage reduction (0.74%), the high propulsion power demand and extended operating duration led to substantial cumulative fuel savings of approximately 7.3 t per voyage phase. The largest cumulative fuel savings were achieved during ballast passage, amounting to approximately 14.07 t over the corresponding voyage phase. Significant reductions in NO_x emissions were also observed across all operating modes, with the most pronounced improvement during cargo discharge, where optimized load allocation reduced NO_x emissions approximately 23%.

3.2. Loaded Passage Operation

The loaded passage represents one of the most energy-intensive operating regimes of the investigated LNG carrier. Throughout this phase, the electrical demand is heavily dominated by the steady-state load requirements of the electric propulsion motors, maintaining high and stable generator utility profiles. For the specific steady-state interval analyzed, the total electrical load on the high-voltage busbar was approximately 24 MW, sustained by four generator sets operating primarily in LNG fuel mode.

Under conventional PMS operation, the total electrical demand was distributed equally among the four operating generators (Figure 3). The optimization model redistributed the load by increasing the operating load of two generators to approximately 83% and reducing the remaining two generators to approximately 72%, thereby maintaining the same total power output. This redistribution shifted engine operation toward more favorable specific fuel consumption regions without affecting the power supplied to the propulsion system and auxiliary consumers.

The optimized load allocation reduced fuel consumption by approximately 30.4 kg/h, corresponding to a fuel saving of 0.74% compared to conventional PMS operation. Although the percentage reduction was lower than those achieved in other operating modes, the long duration of loaded passage operations resulted in substantial cumulative savings. For a typical 10-day loaded passage, the reduction in fuel consumption corresponds to approximately 7.3 t of LNG fuel.

In addition to fuel savings, the optimized load distribution reduced NO_x emissions by 11.87%. The results indicate that measurable efficiency improvements can be achieved even under high propulsion power demand, where generator operating points are already relatively close to their optimum efficiency region. This finding is particularly important because loaded passage represents one of the longest and most energy-intensive phases of the voyage cycle.

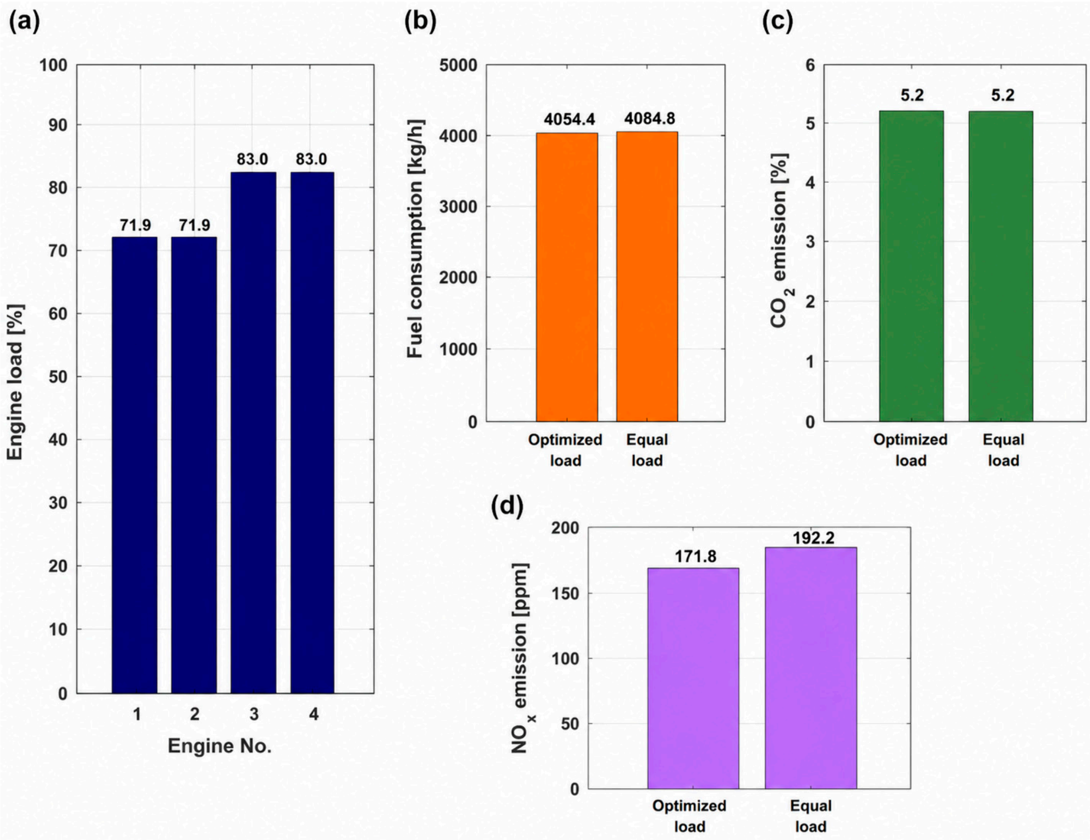

Figure 3. Comparison of optimized and conventional PMS load allocation for loaded passage operation (24 MW total power demand, four generators in operation): (**a**) engine load distribution; (**b**) fuel consumption; (**c**) CO_2 emissions; and (**d**) NO_x emissions.

3.3. Ballast Passage Operation

Ballast passage is the longest operating phase of the analyzed voyage cycle. In this mode, the vessel sails without cargo, resulting in lower propulsion power requirements than during the loaded passage. For the analyzed operating condition, the total electrical demand was approximately 17.5 MW, supplied by three generators operating in LNG mode.

Under conventional PMS operation, the total electrical demand was distributed equally among the three operating generators (Figure 4). The optimization model redistributed the load by increasing one generator's load to approximately 83% and reducing the other two generators to approximately 71%. This redistribution maintained the required power output while shifting engine operation to a more fuel-efficient operating region.

The optimized load allocation reduced fuel consumption from 3021 kg/h to 2975.9 kg/h, resulting in a fuel saving of 45.1 kg/h, or 1.51%, compared to conventional PMS operation. Although the percentage reduction was similar to that achieved during cargo loading, the substantially longer duration of ballast passage resulted in the highest cumulative fuel savings among all voyage operating modes. For a typical 13-day ballast passage, this reduction in fuel consumption amounts to approximately 14.07 t of LNG fuel. The optimization strategy also reduced NO_x emissions from 180.2 ppm to 172.1 ppm, a decrease of 4.7%. While the relative reduction in NO_x emissions was lower than that observed during cargo discharge and loaded passage, the combined reduction in fuel consumption and emissions demonstrates the effectiveness of load optimization during prolonged voyage conditions. Given its duration and contribution to total voyage fuel consumption, ballast passage is the operating mode with the greatest overall benefit from optimized engine load allocation.

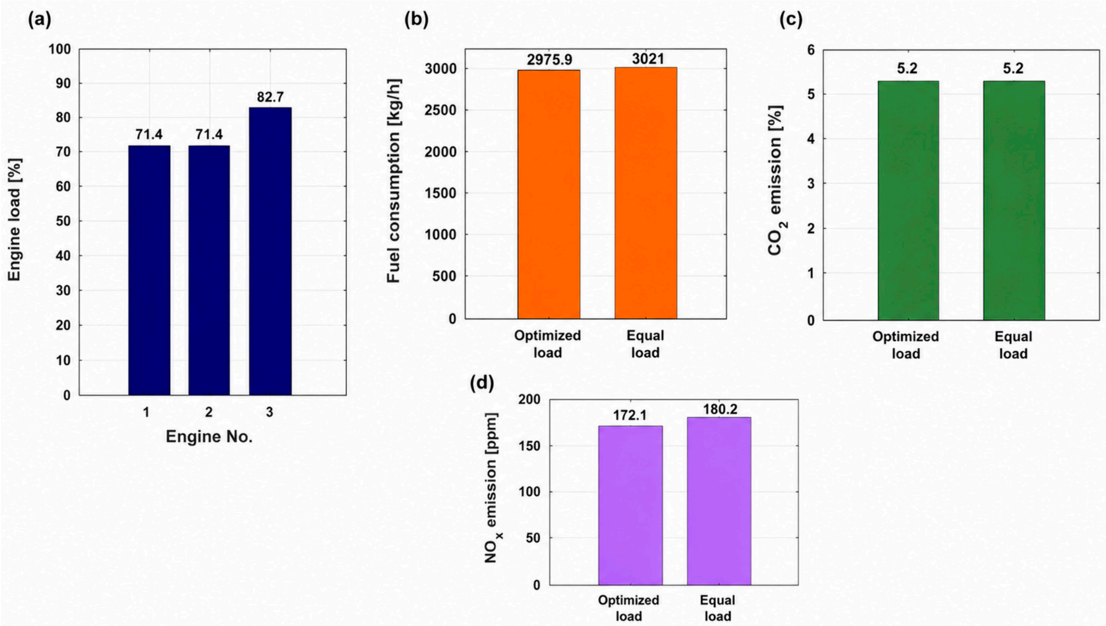

Figure 4. Comparison of optimized and conventional PMS load allocation for ballast passage operation (17.5 MW total power demand, three generators in operation): (**a**) engine load distribution; (**b**) fuel consumption; (**c**) CO_2 emissions; and (**d**) NO_x emissions.

3.4. Cargo Discharge Operation

During cargo discharge, electrical power is primarily required for cargo pumps, ballast pumps, and auxiliary systems. In the analyzed operating condition, the total electrical demand was approximately 8 MW, supplied by two generators operating in LNG mode.

Under conventional PMS operation, the electrical demand was shared equally between the two generators. The optimization model identified a more efficient operating point by concentrating most of the load on one generator. As shown in Figure 5, the optimized solution increased the load of one generator to approximately 82%, while the second generator operated at only 20% load. Despite this uneven load distribution, the total power demand remained unchanged.

The optimized load allocation reduced fuel consumption from 1414.4 kg/h to 1397.2 kg/h, corresponding to a reduction of 17.2 kg/h or 1.23%. Over the 1.5-day cargo discharge period considered in this study, this reduction corresponds to approximately 0.62 t of LNG fuel. The most pronounced effect of optimization was observed in NO_x emissions. While fuel consumption decreased by only 1.23%, NO_x emissions were reduced from 432.5 ppm to 331.5 ppm, corresponding to a reduction of 23.35%. This was the largest relative NO_x reduction achieved among all analysed operating modes. This pronounced reduction results from the nonlinear, load-dependent NO_x emission characteristics of the investigated engines and the redistribution of load between the two operating generator sets. The underlying NO_x–load characteristics were experimentally determined over the 20–90% engine-load range and reported in [18]. For the present cargo discharge condition, the reduction from 432.5 ppm under equal load sharing to 331.5 ppm under optimized load allocation corresponds to 23.35%, which is consistent with the magnitude of NO_x reductions previously obtained using the same load-dependent optimization approach [18].

The result shows that load redistribution can produce a substantially larger relative change in NO_x emissions than in fuel consumption under this specific operating condition. A small reduction in measured CO_2 concentration was also observed, from 5.6% to 5.4%. However, the most important environmental benefit of this operating mode remains the substantial decrease in NO_x emissions achieved without any modification of the propulsion plant or its operating configuration.

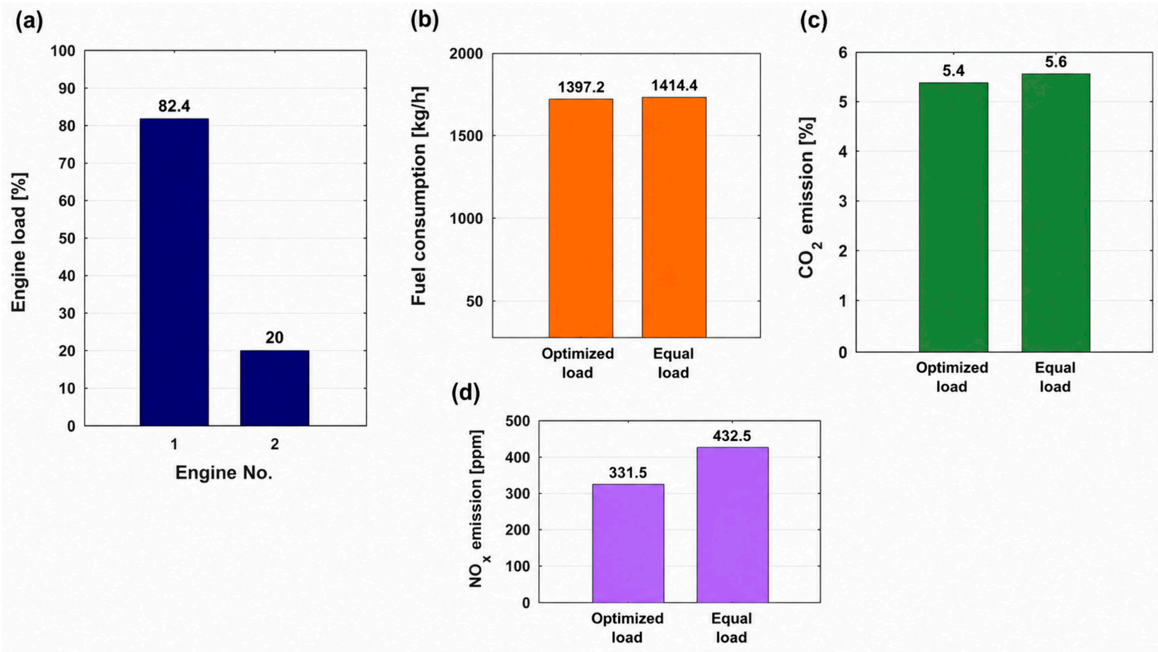

Figure 5. Comparison of optimised and conventional PMS load allocation for cargo discharge operations (8 MW total power demand, two generators in operation): (**a**) engine load distribution; (**b**) fuel consumption; (**c**) CO_2 emissions; and (**d**) NO_x emissions.

3.5. Cargo Loading Operation

During cargo loading operations, the electrical power demand is primarily dictated by the ballast pumps, and essential auxiliary machinery. For the specific operational interval analyzed, the total electrical load on the main switchboards was approximately 4 MW, sustained by two generating sets operating in LNG mode.

As shown in Figure 6, both generators remained in operation despite the relatively low power demand. This operating strategy is commonly used to maintain redundancy and ensure the safe operation of cargo handling systems during port activities. As a result, the optimization model was constrained to redistribute the load between the two running generators rather than concentrating the entire load on a single unit.

Under conventional PMS operation, the electrical demand was distributed equally between the two operating generators. The optimization model identified a more efficient load allocation by increasing the load of one generator to approximately 31% while keeping the second generator at approximately 20% load. Although both generators operated at relatively low load levels, this redistribution improved the overall operating efficiency of the power plant while maintaining the required electrical demand.

The optimized load allocation reduced fuel consumption from 809.4 kg/h to 796.6 kg/h, corresponding to a reduction of 12.8 kg/h or 1.60%. This represents the highest relative fuel saving among all operating modes analyzed in this study. However, due to the relatively short duration of cargo loading operations, the cumulative fuel saving over the 1.5-day loading period was approximately 0.46 t of LNG fuel.

NO_x emissions were reduced from 756.5 ppm to 679.5 ppm, corresponding to a reduction of 10.18%. This reduction demonstrates that load optimization remains beneficial even at relatively low power demands, where generators operate far from their preferred efficiency region. In contrast to the other operating modes, the measured CO_2 concentration remained unchanged at 5.9% for both load allocation strategies.

Although cargo loading contributes only a small fraction of the total voyage fuel consumption, the results confirm that measurable efficiency improvements can be achieved across the full range of operating conditions encountered during LNG carrier operation.

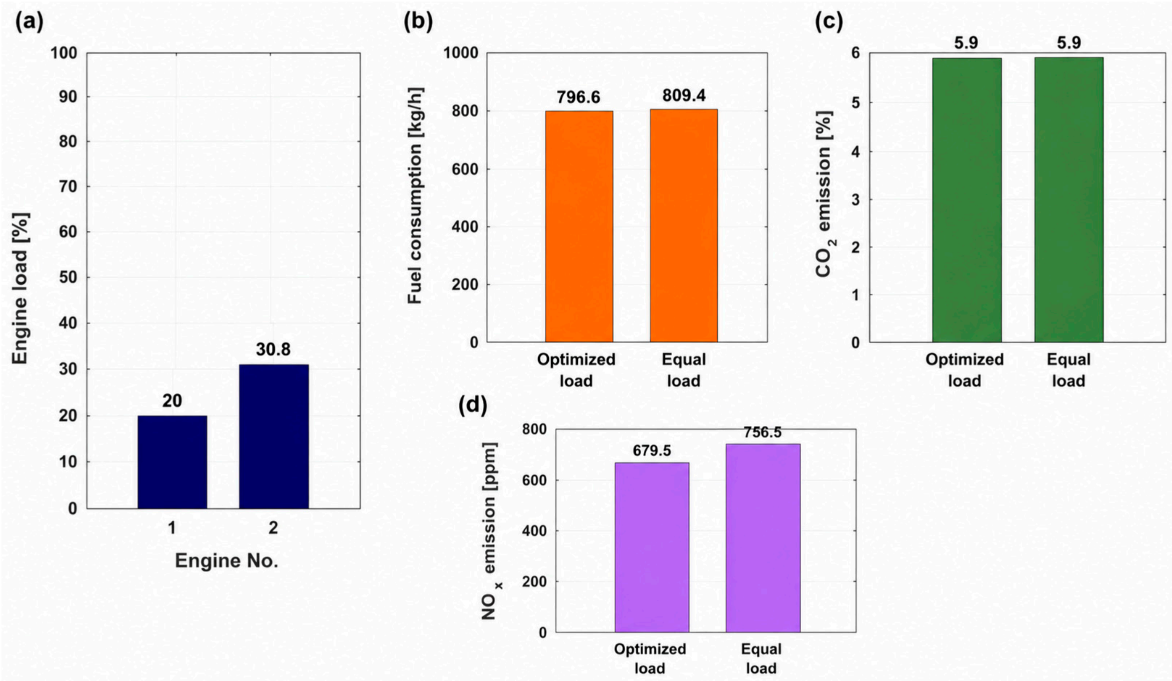

Figure 6. Comparison of optimized and conventional PMS load allocation for cargo loading operations (4 MW total power demand, two generators in operation): (**a**) engine load distribution; (**b**) fuel consumption; (**c**) CO_2 emissions; and (**d**) NO_x emissions.

3.6. Voyage-Scale Assessment and Operational Implications

The previous sections evaluated the effect of load optimization under representative operating conditions for individual voyage phases. However, the practical value of the proposed strategy can be assessed only by considering its cumulative impact over the complete voyage cycle. Because the duration and power demand of each operating mode differ significantly, the contribution of individual modes to the overall fuel-saving potential is not proportional to their relative efficiency improvements.

As shown in Table 4, the contribution of individual operating modes to overall voyage fuel savings was strongly influenced by their duration. Although cargo loading achieved the highest relative fuel saving (1.60%), its contribution to total voyage savings remained limited due to the short duration of loading operations. In contrast, ballast passage accounted for the largest share of total fuel savings. The combination of a 1.51% fuel saving and a 13-day operating period resulted in a cumulative reduction of approximately 14.07 t of LNG fuel, representing more than 60% of the total voyage savings.

Table 4. Fuel savings over the analysed 26-day voyage cycle.

Vessel Operating Regime	Duration (Days)	Fuel Savings (t)
Cargo loading	1.5	0.46
Loaded passage	10	7.30
Cargo discharge	1.5	0.62
Ballast passage	13	14.07
Total voyage saving	26	22.45

When all operating modes are considered together, the optimized load allocation strategy yields an estimated fuel saving of approximately 22.45 t of LNG per voyage cycle. It should be emphasized that this voyage-scale result is an extrapolation of the experimentally validated steady-state fuel savings for each representative operating mode over the corresponding phase durations, rather than a continuous measurement of optimized operation throughout the entire voyage. The results demonstrate that relatively small improvements in generator operating efficiency can accumulate into substantial fuel savings when applied consistently throughout a complete voyage cycle.

An important observation is that the greatest benefits were not necessarily achieved under the highest power demands. Instead, the optimization strategy proved most effective when conventional PMS operation maintained several generators at operating points that were not optimal from a fuel consumption perspective. By selectively redistributing the electrical load among operating generators, the proposed approach shifted engine operation toward more favorable efficiency regions while maintaining the same power demand and operational requirements.

From a practical perspective, the proposed strategy is particularly attractive because it does not require modifications to the propulsion plant configuration or additional hardware installation. The achieved savings are obtained solely through improved generator load allocation and can therefore be implemented using existing power management infrastructure. Assuming approximately 14 similar voyage cycles per year, the estimated annual fuel savings are approximately 314 t of LNG for a single vessel. For fleets comprising multiple sister vessels operating on comparable routes, the cumulative fuel-savings potential becomes even more significant. Beyond the direct reduction in fuel consumption, the proposed optimization strategy may also lower compliance costs under market-based environmental regulations such as the EU Emissions Trading System (EU ETS). As regulatory frameworks increasingly link ship emissions with operating costs, operational measures that improve fuel efficiency without requiring hardware modifications are expected to become more attractive for ship operators [20].

The results indicate that the benefits of load optimization extend beyond the representative operating conditions investigated in this study, and apply over a complete voyage cycle. Consequently, optimized generator load allocation represents a practical operational measure capable of improving both the energy efficiency and environmental performance of DFDE LNG carriers without compromising system reliability or operational safety.

4. Conclusions

This study presented a rigorous, voyage-scale operational validation of an asymmetric load optimization strategy applied to a Dual-Fuel Diesel-Electric (DFDE) LNG carrier power plant. The empirical analysis utilized high-fidelity operational datasets systematically collected onboard an in-service vessel equipped with five four-stroke dual-fuel generating sets. A representative, multi-phase 26.0-day voyage cycle encompassing cargo loading, loaded passage, cargo discharge, and ballast passage was evaluated to quantify the cumulative operational and environmental benefits of optimized generator load allocation under realistic service environments.

The empirical results demonstrate that strategic, asymmetric redistribution of generator loads consistently enhances multi-engine power plant efficiency across all analyzed operational modes. Measurable fuel mass flow reductions were secured under every investigated boundary condition, ranging from a localized saving of 0.74% during the high-power loaded passage to 1.60% during part-load cargo loading operations. Although the highest relative percentage efficiencies were extracted during low-power port modes, the maximum absolute cumulative benefits occurred during the blue-water ballast passage due to its prolonged chronological duration. Macroscopic voyage-scale assessment indicates a total net savings of 22.45 t of LNG per operational cycle, with the ballast transit supplying the dominant contribution (over 60%) to the aggregate result.

Parallel to fuel mass flow mitigation, the optimized load allocation framework systematically suppressed exhaust emissions. The most pronounced environmental milestone was recorded during cargo discharge operations, where raw NO_x emissions plummeted by 23.35% compared to the conventional PMS equal-load baseline. These findings confirm that intelligent generator load redistribution can simultaneously optimize thermal efficiency and environmental performance without compromising grid stability, operational safety margins, or instantaneous power availability.

A highly critical outcome of this research from an industrial perspective is that these performance milestones were extracted entirely without necessitating capital-intensive structural modifications to the propulsion plant architecture or the installation of auxiliary hardware. The optimization strategy relies exclusively on software-based load re-allocation among active units, making it fully deployable within existing power management system (PMS) infrastructures. Projecting these cyclical reductions over 14 standard voyage profiles per annum yields an estimated annual fuel savings exceeding 314 t of LNG for a single vessel, with exponential multiplication factors applicable to sister-ship fleets.

Overall, the findings indicate that voyage-scale generator load optimization is a practical operational approach to improving the energy efficiency of DFDE LNG carriers under representative steady-state operating conditions. Although the proposed strategy was successfully implemented during the investigated voyage using the existing PMS infrastructure, further validation under long-term operation and transient loading conditions is required before broader operational generalization. A limitation of the present study is that the operational validation was restricted to stabilized steady-state conditions and did not explicitly evaluate the dynamic response of the optimization strategy under transient load variations. Future work will focus on the real-time, closed-loop integration of these optimization algorithms directly into onboard integrated automation systems (IAS) and on evaluating framework robustness under fluctuating metocean conditions and diverse marine fuel transitions.

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