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Decarbonizing Short-Sea Shipping: A Comparative Analysis of Diesel-Mechanical, Diesel-Electric, and Hybrid Propulsion Systems

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Abstract—Short-sea shipping (SSS) plays a vital role in regional logistics and coastal transportation; however, growing pressure from the International Maritime Organization (IMO) decarbonization mandates—particularly the Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII)—demands urgent adoption of cleaner and more energy-efficient propulsion solutions for this sector. This study aims to conduct a comprehensive techno-economic and environmental comparison of three propulsion architectures—Diesel-Mechanical (DM), Diesel-Electric (DE), and Parallel Hybrid (PH)—for a 5,000 GT Ro-Ro passenger ferry operating on a typical short-sea route. A simulation framework was developed in MATLAB/Simulink using high-resolution operational profiles derived from Automatic Identification System (AIS) data from the Marine Cadastre national archive. Fuel consumption, atmospheric emissions (CO_2, NO_x, and SO_x), and life-cycle cost (LCC) were computed over a 20-year planning horizon using a rule-based Energy Management Strategy (EMS) for the hybrid configuration. The results show that the PH system reduces annual fuel consumption and CO_2 emissions by 25.0% relative to the DM baseline and by 14.3% relative to the DE system. Despite requiring 31% higher initial capital expenditure (CAPEX) than the DM system, the PH system achieves the lowest 20-year LCC of $11.85 million and a payback period of approximately 2.15 years through significant annual operating cost savings of $174,375. These findings confirm that parallel hybrid propulsion is a technically sound, economically viable, and environmentally superior solution for decarbonizing short-sea shipping fleets under current IMO regulatory frameworks.

Keywords— short-sea shipping; hybrid propulsion; techno-economic analysis; decarbonization; life-cycle cost; energy management strategy; AIS data; emissions

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I. INTRODUCTION

Short Sea Shipping (SSS) is an integral part of the worldwide and regional transport network. SSS serves as a sustainable alternative to road transport, alleviating highway congestion and enabling lower greenhouse gas (GHG) emissions per ton-mile compared to land-based freight modes [1]. The shipping industry contributes approximately 2.5–3% of global anthropogenic CO_2 emissions, while also being a significant source of NO_x and SO_x pollutants that adversely affect air quality in coastal regions [2]. In response, the IMO has progressively tightened its climate framework, establishing a target for net-zero GHG emissions from shipping by or around 2050 [3].

Since January 2023, short-term regulatory measures—specifically the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII)—have been mandated to accelerate progress toward these targets [4]. These regulations place direct operational and compliance pressure on fleet owners, creating an urgent need to transition from conventional to energy-efficient propulsion solutions. However, the SSS sector faces significant challenges in selecting the optimal propulsion technology given the trade-offs between capital investment, operational complexity, environmental performance, and regulatory compliance.

Problem Statement. The primary problem addressed in this paper is the absence of a comprehensive, data-driven comparative framework for evaluating propulsion system alternatives for short-sea Ro-Ro ferries under realistic operational conditions. Existing research largely relies on simplified or static operational profiles that fail to capture the high variability characteristic of Ro-Ro ferry operations. Furthermore, few studies integrate high-resolution AIS-based operational data, multi-pollutant emissions modeling, and full life-cycle economic analysis simultaneously.

The novelty of this work lies in three key contributions: (1) the use of real-world, high-resolution

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AIS operational profiles from the Marine Cadastre national archive to construct a 24-hour duty cycle for a 5,000 GT Ro-Ro ferry; (2) the development of a unified MATLAB/Simulink simulation framework enabling simultaneous evaluation of DM, DE, and PH propulsion architectures under identical operational conditions across technical, environmental (CO_2, NO_x, SO_x, PM), and economic (CAPEX, OPEX, LCC, payback period) dimensions; and (3) the design and validation of a rule-based Energy Management Strategy (EMS) for the parallel hybrid system that enables zero-emission port operations and peak shaving, directly targeting IMO CII compliance.

A. Literature Review

The technical, environmental, and economic performance of marine propulsion systems has received considerable scholarly attention. Talluri et al. [6] conducted a techno-economic and environmental assessment of wind-assisted marine propulsion systems, demonstrating the effectiveness of harnessing alternative energy sources. Doulgeris et al. [7] proposed a computational framework for techno-economic and environmental risk assessment of advanced marine propulsion systems, establishing a methodological precedent for integrated multi-criteria evaluation.

Korberg et al. [8] assessed the potential of advanced renewable fuels across various propulsion architectures for future fossil-free ships, highlighting the transitional role of hybrid systems. Jeong et al. [9] performed a multi-criteria decision-making analysis comparing hybrid, diesel-electric, and diesel-mechanical systems, concluding that hybrid systems offer the best overall economic performance under variable load conditions—a finding that motivates the present study's focus on the parallel hybrid configuration. Tang et al. [10] developed a large-scale global optimization-based energy management strategy for maritime hybrid energy systems, underscoring the critical role of EMS in realizing fuel savings potential.

He et al. [11] and Akbarzadeh et al. [12] examined battery energy storage system (BESS) applications in marine contexts, demonstrating that BESS can effectively optimize engine efficiency through peak shaving and load leveling. Kim and Jeon [15] provided a comparative analysis of AC and DC distribution systems for electric propulsion ships, informing the electrical architecture assumptions of the DE and PH models. Recent work by Tu et al. [18] confirmed the cost-effectiveness of energy efficiency measures for shipping decarbonization, while Animah et al. [20] demonstrated techno-economic feasibility assessment methodologies for hybrid systems in patrol boat applications.

A critical gap persists in the literature: existing research predominantly employs static or simplified operational profiles that do not accurately reflect real-world SSS operations. There is a shortage of studies that simultaneously integrate high-resolution AIS-derived operational data, multi-pollutant emissions calculation, and comprehensive life-cycle cost analysis specifically for SSS Ro-Ro ferries. The present study addresses this gap directly.

B. Paper Structure

Section II describes the methodology, including case study definition, operational profile construction, propulsion system modeling, EMS design, and evaluation metrics. Section III presents and discusses the simulation results. Section IV states the conclusions and recommends future research directions.

II. METHODOLOGY

The study employs a four-phase methodology: (1) case study definition and operational profile construction from AIS data; (2) modular modeling of the three propulsion architectures; (3) design and implementation of a rule-based EMS for the parallel hybrid system; and (4) comparative evaluation using technical, environmental, and economic performance metrics. The simulation framework was implemented in MATLAB/Simulink, operating on a time-step basis of $\Delta t = 1$ s over a 24-hour operational cycle, then scaled to annual performance figures (330 operating days, 365 voyages per year).

A. Case Study Definition and Operational Profile

The vessel selected is a roll-on/roll-off (Ro-Ro) passenger ferry of 5,000 GT capacity. Key particulars: length overall (LOA) = 130 m, beam = 24 m, design draft = 4.5 m, design speed = 20 knots. Ro-Ro ferries are well-suited as a case study for hybrid propulsion research due to their highly variable operational profiles—characterized by frequent port calls, extensive maneuvering phases, and significant variation in propulsion power demand [13].

The operational profile was constructed using historical AIS data from the Marine Cadastre national AIS archive (marinecadastre.gov), managed by NOAA and BOEM [21]. After screening, cleaning, and compressing the raw AIS records, representative 24-hour speed-time profiles for short-sea Ro-Ro ferries were synthesized. The resulting operational cycle comprises three phases: (1) high-speed cruising at 18–20 knots (~60% of daily time); (2) low-speed maneuvering at 2–5 knots during port approach and departure (~10% of daily time); and (3) port stay at zero speed requiring auxiliary hotel load (~30% of daily time).

The instantaneous propulsion power demand is calculated from the dynamic speed profile using the Holtrop–Mennen semi-empirical resistance method [14]. The total hull resistance is expressed as:

$$R\_T = R\_F(1+k_1) + R\_APP + R\_W + R\_B + R\_TR + R\_A \quad (1)$$

where RF is the frictional resistance (ITTC-1957); $(1+k_1)$ is the form factor; RAPP, RW, RB, RTR, RA are the appendage, wave-making, bulbous bow, transom, and correlation resistances, respectively. The effective power is:

$$P\_E = R\_T \times V \quad (2)$$

where V is the ship speed (m/s). The shaft power delivered to the propeller is:

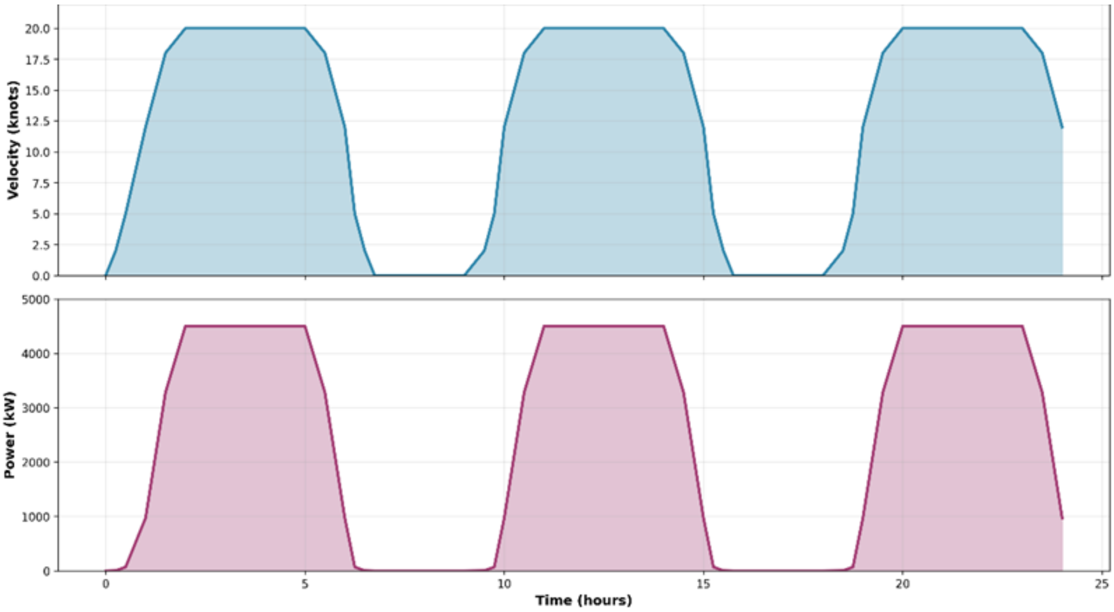

Figure 1. Operational profile of the Ro-Ro ferry over 24 hours. Upper: vessel speed (knots); lower: propulsion power demand (kW).

$$P\_shaft = P\_E / \eta\_total \quad (3)$$

where $\eta total = \eta O \times \eta H \times \eta R \times \eta S$ is the total propulsive efficiency, incorporating propeller open-water, hull, relative rotative, and shaft mechanical efficiencies.

B. Propulsion System Modeling

1) Diesel-Mechanical (DM) System

The DM system couples the main diesel engine directly to the propeller shaft through a reduction gearbox. The instantaneous fuel consumption rate (g/s) is:

$$FC(t) = SFOC(P\_load) \times P\_engine(t) \quad (4)$$

where SFOC(Pload) is the specific fuel oil consumption (g/kWh) as a function of engine load fraction, and Pengine(t) is the instantaneous engine output power (kW). The SFOC curve has a minimum at approximately 75–85% of MCR [23]. The DM system suffers ~30% SFOC penalties above optimum at low maneuvering loads.

2) Diesel-Electric (DE) System

The DE system replaces direct mechanical coupling with an electrical power generation and distribution architecture. Diesel generator sets supply power to a medium-voltage AC switchboard, from which propulsion motors are driven via frequency converters. The total power conversion efficiency of the DE chain is:

$$\eta\_DE = \eta\_gen \times \eta\_sw \times \eta\_conv \times \eta\_mot \quad (5)$$

where $\eta gen = 0.96$, $\eta sw = 0.99$, $\eta conv = 0.97$, and $\eta mot = 0.95$, yielding overall $\eta DE \approx 0.874$. The electrical transmission losses (~12.6%) partially offset the benefit of improved engine load management compared to the DM system.

3) Parallel Hybrid (PH) System

The PH system integrates a reduced-size main diesel engine with an electric motor/generator (PTI/PTO) coupled to a lithium-ion BESS through a common reduction gearbox. The BESS is sized at 1,500 kWh gross (1,200 kWh usable at 80% DoD), with energy density ~200 Wh/kg, round-trip efficiency of 90%, and cycle life of 3,000 cycles [11]. The electric motor/generator rating is 2,000 kW. The architecture supports four operating modes: diesel-only, electric-only, boost (peak shaving), and PTO charging (regeneration).

C. Energy Management Strategy (EMS)

A rule-based EMS was implemented for the PH system to optimize the power split between the diesel engine and BESS. Three hierarchical rules govern the EMS:

Zero-emission mode: if power demand P*demand*(t) < P*low* (20% MCR), the diesel engine is shut down and the BESS supplies all power through the electric motor. This applies during all maneuvering and port stays.

Optimal-load charging rule: when P*low* ≤ P*demand*(t) ≤ P*opt* (~80% MCR), the diesel directly serves the propulsion demand. If SOC < SOC*min*, the engine load is elevated to P*opt* and excess power charges the BESS in PTO mode.

Peak-shaving rule: when P*demand*(t) > P*max* (engine MCR), the diesel operates at MCR and the BESS provides the deficit power via PTI. The instantaneous power balance is:

$$P\_demand(t) = P\_engine(t) + P\_battery(t) \times \eta\_PTI \quad (6)$$

where ηPTI is the power take-in efficiency of the electric motor drive. SOC is maintained within a 20–90% operating window. The BESS is sized for approximately 2.5 hours of zero-emission maneuvering/port power (400–500 kW).

D. Evaluation Metrics

1) Technical and Environmental Metrics

Annual fuel consumption is computed by integrating the instantaneous fuel consumption rate over the full annual operating profile. Annual pollutant emissions for each species i are calculated as:

$$E\_i = FC\_annual \times EF\_i \quad (7)$$

where Ei is the annual emission of species i (tons); FC*annual* is total annual fuel consumption (tons); and EFi is the IMO emission factor per species [17]. Applied values: EFCO_2 = 3.206, EFNO_x = 0.0185, EFSO_x = 0.0025, EFPM = 0.0008 (all in t-pollutant/t-fuel).

2) Economic Metrics

Life-cycle cost (LCC) analysis was performed over a 20-year planning horizon. LCC is calculated as:

$$LCC = CAPEX + \Sigma\ [OPEX\_n/(1+r)^n],\ n=1\ to\ N \quad (8)$$

where N = 20 years and r = 5% is the discount rate. The incremental payback period (PBP) of the PH system relative to the DM baseline is:

$$PBP = \Delta CAPEX\ /\ \Delta OPEX\_annual \quad (9)$$

where ΔCAPEX = CAPEX*PH* − CAPEX*DM*, and ΔOPEX*annual* = OPEX*DM* − OPEX*PH*.

III. Results and Discussion

A. Operational Profile Analysis

The synthesized 24-hour operational profile reveals significant variability in speed and propulsion power demand (Figure 1). The vessel cruises at 18–20 knots for approximately 60% of daily time (~5,500 kW peak power demand), maneuvers at 2–5 knots for ~10% of daily time (500–1,200 kW), and stays in port for ~30% of daily time (~400 kW hotel load). The resulting load variation factor exceeds 10:1, substantially higher than the near-constant loads typical of ocean-going cargo vessels. This wide load range is precisely the operational regime where hybrid systems provide the greatest advantage.

Table 1.
Annual Technical and Environmental Performance Comparison

Metric	DM	DE	PH	Reduction (PH vs DM)
Annual Fuel (tons/yr)	1,200	1,050	900	25.0%
CO_2 Emissions (tons/yr)	3,847	3,366	2,885	25.0%
NO_x Emissions (tons/yr)	22.2	19.4	16.7	24.8%
SO_x Emissions (tons/yr)	3.0	2.6	2.3	23.3%
PM Emissions (tons/yr)	0.96	0.84	0.72	25.0%
CII Rating	—	—	A/B	—

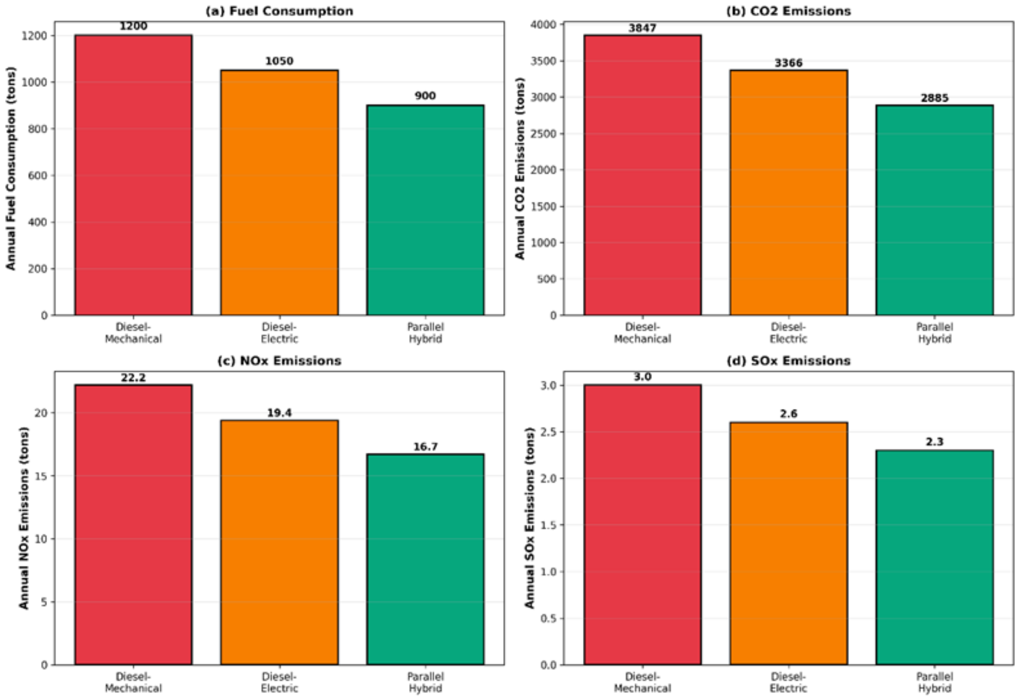

Figure 2. Comparison of (a) annual fuel consumption, (b) CO_2 emissions, (c) NO_x emissions, (d) SO_x emissions for the three propulsion systems.

B. Comparative Technical and Environmental Performance

Table 1 presents the annual technical and environmental performance metrics for the three propulsion architectures.

The PH system achieves a 25.0% reduction in annual fuel consumption relative to DM (1,200 to 900 tons) and a 14.3% reduction relative to DE (1,050 to 900 tons). This superior fuel efficiency is primarily attributable to the EMS, which directs the system into three key operational regimes: (i) zero-emission electric mode for approximately 40% of daily time (all maneuvering and port phases); (ii) diesel-only mode at near-optimal SFOC for approximately 50% of time (steady-state cruising); and (iii) PTO charging mode for approximately 10% of time.

In contrast, the DM system must operate its main engine continuously during all non-port phases, incurring an SFOC penalty of approximately 30% above the optimum during low-load maneuvering. The DE system achieves partial improvement through flexible generator set scheduling but suffers inherent electrical transmission losses of ~12.6% (Equation 5). The corresponding CO_2 emission reductions mirror the fuel savings (25.0% for PH vs. DM; 14.3% for PH vs. DE), directly improving the vessel's CII rating to an estimated A/B band without requiring speed reduction or costly fuel switching.

C. Cost-Effectiveness Analysis

Table 2 presents the life-cycle cost analysis across the three architectures.

The PH system's CAPEX of $1.575 million is 31.3% higher than the DM system ($1.2M), due to the additional BESS (1,500 kWh) and 2,000 kW electric motor/generator. The DE system carries the highest CAPEX at $2.9M, reflecting multiple generator sets, medium-voltage switchboard, and high-power electric propulsion machines.

TABLE 2.
ECONOMIC EVALUATION AND LIFE-CYCLE COST ANALYSIS (USD)

Cost Component	DM	DE	PH
CAPEX	$1,200,000	$2,900,000	$1,575,000
Annual Fuel Cost	$780,000	$682,500	$585,000
Annual Maintenance	$36,000	$87,000	$47,250
Annual Battery Replacement	$0	$0	$3,750
Annual Crew & Insurance	$183,000	$208,500	$188,625
Total Annual OPEX	$999,000	$978,000	$824,625
LCC (20 Years)	$13,649,788	$15,088,252	$11,852,551

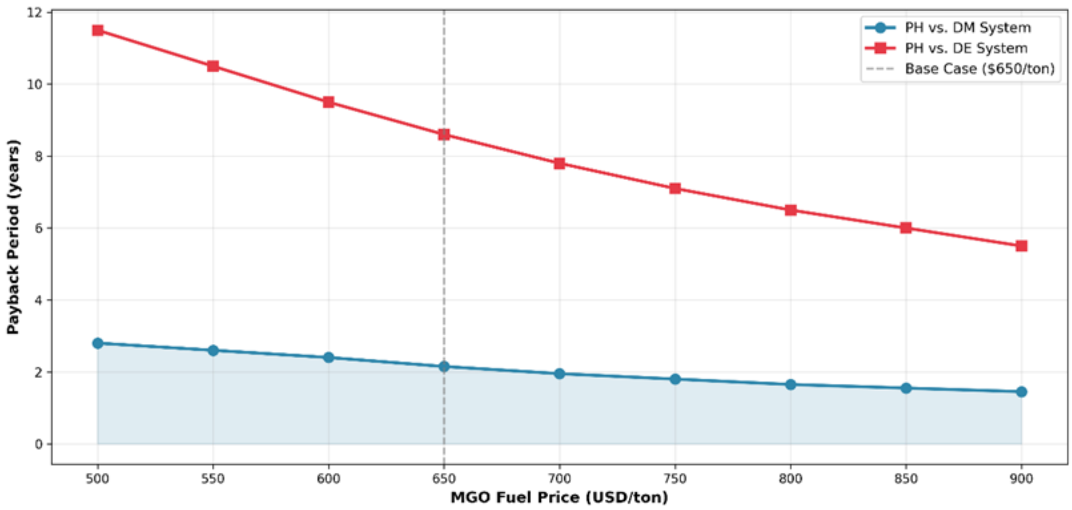

Figure 4. Sensitivity analysis showing the impact of MGO price variations on the payback period of the PH system compared to DM and DE baselines

Despite its higher upfront investment, the PH system emerges as the most cost-effective option over the 20-year analysis period. Total annual OPEX for the PH system is $824,625, representing savings of $174,375/year relative to DM ($999,000/year). The 20-year LCC of the PH system is $11.85M—13.2% lower than DM ($13.65M) and 21.4% lower than DE ($15.09M). The payback period from Equation (9): PBP = $375,000 / $174,375 ≈ 2.15 years—well within typical marine investment thresholds of 5–7 years.

D. Sensitivity Analysis

A sensitivity analysis was conducted on the PH payback period across a range of MGO fuel prices. At base case (MGO = $650/ton), PBP = 2.15 years. At low fuel price (MGO = $500/ton), PBP ≈ 2.8 years. At high fuel price (MGO = $900/ton), PBP ≈ 1.45 years. Across the full range ($500–$900/ton), the PH system's payback period remains well below 3 years, confirming the robustness of the investment case. Additionally, a 20% reduction in battery CAPEX would further lower the investment threshold, and future carbon pricing mechanisms (e.g., EU ETS for shipping) will impose additional financial penalties on higher-emission DM systems [19].

E. Deeper Discussion of Findings and Novelty .

Validation against published results. The 25.0% fuel saving achieved by the PH system exceeds the 15–20% range reported by Jeong et al. [9] for comparable vessel classes. This difference is attributable to: (i) a more aggressive EMS with a 20% MCR zero-emission threshold; and (ii) a larger BESS capacity (1,500 kWh vs. smaller packs in comparable studies), enabling complete diesel shutdown during all port stay and maneuvering phases—the highest-penalty operational segments for the DM system.

AIS-based operational realism. The use of real-world AIS data constitutes a methodological innovation relative to most published studies, which rely on assumed or simplified duty cycles. The resulting duty cycle—with a load variation factor exceeding 10:1 and

30% port time—provides a more demanding and realistic test of each propulsion architecture, amplifying the performance differentiation and demonstrating the particular effectiveness of hybrid propulsion under highly variable SSS Ro-Ro operational conditions.

EMS design as the core innovation. The rule-based EMS developed in this study is explicitly designed to address the dual requirements of IMO regulatory compliance (CII improvement through emission reduction) and economic optimization (fuel cost minimization). The three-tier hierarchical rule structure—zero-emission mode, optimal-load charging, and peak-shaving—ensures that the diesel engine operates within its high-efficiency SFOC window during all cruising phases while completely eliminating diesel fuel consumption during port operations. Future implementation of model predictive control (MPC) strategies could further improve fuel efficiency by 5–15%.

Broader decarbonization context. The parallel hybrid architecture offers a unique combination of immediate deployability, commercial maturity, and compatibility with future fuel transitions. Unlike LNG, methanol, or ammonia—which require substantial bunkering infrastructure investment and present safety challenges—hybrid propulsion can be applied immediately to newbuilds or as a retrofit. Furthermore, the parallel architecture is compatible with dual-fuel engines [8], positioning it as a viable transitional technology on the pathway to net-zero shipping.

Study limitations. The battery degradation model is simplified, using a fixed replacement cost based on rated cycle life. Advanced electrochemical degradation models should be employed in future work. The operational profile is derived from a specific set of AIS routes; incorporating stochastic weather routing and sea-state conditions would improve generalizability. The EMS is rule-based and deterministic; advanced MPC strategies could yield additional fuel savings.

IV. CONCLUSION

This study conducted a comprehensive techno-economic and environmental comparison of DM, DE, and PH propulsion systems for a 5,000 GT short-sea Ro-Ro ferry, using a simulation framework grounded in real-world AIS-derived operational profiles. The following conclusions are drawn in direct response to the study objective:

(1) The PH system with rule-based EMS achieves a 25.0% reduction in annual fuel consumption and CO_2 emissions relative to the DM baseline (1,200 to 900 tons/year), and a 14.3% reduction relative to DE. This performance is enabled by zero-emission electric operation during all port and maneuvering phases (~40% of daily time) and near-optimal diesel engine loading during cruising. The CO_2 reduction (~962 tons/year vs. DM) translates to an improved CII rating band (estimated A/B), confirming the PH system's effectiveness as a regulatory compliance tool under IMO's EEXI/CII framework.

(2) Despite its 31.3% higher initial CAPEX ($1.575M vs. $1.2M for DM), the PH system achieves the lowest 20-year LCC of $11.85M—13.2% below DM ($13.65M) and 21.4% below DE ($15.09M). Annual OPEX savings of $174,375 relative to DM yield a payback period of approximately 2.15 years. The economic case is robust across fuel price scenarios from $500 to $900/ton MGO (PBP range: 1.45–2.8 years).

(3) The AIS-based operational profile methodology—with a load variation factor exceeding 10:1 and a 30% port-time fraction—provides a more realistic and demanding basis for propulsion system evaluation than simplified duty cycles, amplifying the performance differentiation between architectures.

(4) The three-tier rule-based EMS—combining zero-emission mode, optimal-load charging, and peak-shaving—successfully addresses both regulatory compliance and economic optimization objectives simultaneously, confirming its viability as a practical control strategy for real-world PH deployments.

(5) The parallel hybrid architecture represents the most commercially viable transitional technology for short-sea shipping decarbonization, offering immediate deployability, compatibility with future alternative fuels, and measurable economic returns within a short payback period. Future research should incorporate: (i) advanced electrochemical BESS degradation models; (ii) stochastic weather and sea-state routing; (iii) MPC energy management strategies; and (iv) validation against full-scale sea trial data from operational hybrid Ro-Ro ferries.

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