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TECHNO-ECONOMIC EVALUATION AND LIFECYCLE DECARBONIZATION PATHWAYS OF GREEN LOGISTIC SHIPS IN INDONESIAN ARCHIPELAGIC MARITIME FREIGHT NETWORKS: A SCENARIO-BASED ASSESSMENT

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ABSTRACT

Decarbonizing maritime freight in Indonesia requires the joint assessment of ship propulsion, energy storage, wind assistance, and port electrification. This study develops a transparent scenario-based appraisal of a proposed 3,000-DWT-class hybrid green logistic ship for an illustrative Surabaya–Banjarmasin feeder service. The concept combines an LNG/diesel powertrain, 1,200-kWh battery energy storage, a Flettner rotor, and a 1-MW onshore power interface. The analytical framework follows IMO guidance for the Energy Efficiency Operational Indicator (EEOI), separate well-to-wake accounting, and discounted cash-flow analysis; national port statistics provide contextual evidence but cannot establish vessel-level fuel use or cash flows. A numerical consistency check of assumptions reported in the submitted manuscript—USD 1.85 million additional investment and USD 412,000 constant annual net savings over 15 years at 7.5%—produces a scenario NPV of USD 1.787 million, an internal rate of return of 21.0%, and discounted payback of approximately 5.69 years. These are conditional calculations, not observed commercial outcomes. The proposed 38.6% fuel saving and 82.3% life-cycle abatement cannot be validated without measured duty cycles, verified component performance, and fuel/electricity emission factors. The principal contribution is therefore an auditable assessment protocol and an explicit data-validation agenda for Indonesian short-sea freight electrification.

Keywords: Battery Energy Storage; EEOI; Green Logistic Ship; Life-Cycle Assessment; Maritime Decarbonization; Onshore Power Supply; Techno-Economic Appraisal.

1. Introduction

The Fourth IMO GHG Study reported that total shipping emitted 1,056 million tonnes of CO_2 in 2018, corresponding to approximately 2.89% of global anthropogenic CO_2 emissions in that year [1]. The 2023 IMO Strategy calls for international shipping to reach net-zero GHG emissions by or around 2050 and sets indicative reductions in annual GHG emissions of at least 20% by 2030 and 70% by 2040, relative to 2008 [2]. These strategic ambitions concern international shipping; their direct regulatory application to individual Indonesian domestic feeder ships must be determined from the applicable vessel categories and Indonesian law.

Indonesia's port system makes low-carbon inter-island logistics a significant engineering and planning question. Statistics Indonesia (BPS) publishes official indicators of ship calls, cargo loading/unloading and passenger movements through Indonesian seaports [3]. However, these aggregate observations are not voyage-level engine records, propulsion energy balances, or lifecycle inventories. For this reason, the submitted draft's figures of 78.7 million tonnes of inter-island freight and 549.9 million passengers are not repeated as verified statistics in this revision; the precise BPS tables and population definitions are needed before they can be used.

1.1 Related Literature and Research Gap

Prior studies provide methods rather than transferable performance guarantees. Zahari and McLellan [4] examine Indonesian transport-sector energy and resource trade-offs under low-carbon transition strategies. Perčić et al. [5] assess lifetime costs and emissions for electrified inland-waterway vessels. Kanchiralla et al. [6] compare battery technologies and charging designs for passenger ferries, showing why battery lifetime and electricity source are crucial in lifecycle appraisal. These studies concern different vessel and duty-cycle classes, so their numerical conclusions cannot automatically be assigned to a 3,000-DWT Indonesian cargo feeder.

Abu Bakar et al. [7] review the equipment, emissions and economic constraints of cold ironing, while Cui et al. [8] examine policy incentives for electric inland shipping. Akhavan [9] discusses the wider port-city implications of green shipping corridors. Together, the literature suggests a research gap: a transparent Indonesian feeder-cargo evaluation that separates verified external evidence from design assumptions, computes cash flows consistently, and distinguishes shipboard operational emissions from upstream fuel and grid impacts.

The objective of this article is therefore to formulate and audit a vessel-and-port evaluation framework based on the design presented by the authors. The work does not claim to have measured a retrofitted vessel, obtained price quotations, or validated lifecycle emission reductions at the cited Indonesian ports.

2. Materials and Methodology

2.1 Study Boundary and Data Provenance

The assessed object is a proposed 3,000-DWT-class general-cargo/feeder vessel operating between Surabaya (Tanjung Perak) and Banjarmasin (Trisakti). A nominal distance of 280 nautical miles is retained solely as a preliminary routing assumption from the submitted manuscript, not an independently verified nautical-chart distance. Any operational study must replace it with actual AIS route distance, scheduled calls, vessel draft limits, cargo manifests, turnaround times, weather records and fuel/electricity bills. BPS [3] serves only as national context, not as the source of these ship-specific model inputs.

2.2 Resistance and Propulsion Modeling

The original text invokes Holtrop–Mennen. Its published resistance/power prediction approach [10] requires a defined hull geometry, displacement, wetted surface and speed. To avoid double-counting resistance components, the present evaluation writes the resistance balance at a conceptual level as:

$$R_T = R_{viscous} + R_{wave} + R_{appendage} + R_{air} + R_{other}$$

$$P_B = (R_T \times V) / (\eta_D \times \eta_M \times \eta_G)$$

Here R_T is total resistance, V is speed, η_D is overall propulsive efficiency, η_M mechanical transmission efficiency and η_G gearbox efficiency, subject to the precise definitions selected for the installed system. In a future numerical model, resistance terms must be generated with non-overlapping definitions, and sea margin, added resistance in waves and auxiliary electrical loads must be separately included. Because the draft contains no hull lines, resistance coefficient inputs, shaft measurements or engine maps, no hydrodynamic validation is claimed.

2.3 Proposed Powertrain and Shore-Power Interface

The authors' concept consists of a nominal 2,400-kW LNG/diesel main engine, a 1,200-kWh LFP battery system, one 18 m × 3 m rotor sail, and a 1.0-MW onshore power connection. These are proposed engineering specifications, not confirmed equipment selected from a manufacturer. Battery energy available for operation depends on permissible depth of discharge, degradation, conversion efficiency and thermal-management demand. Rotor assistance requires wind-route and aerodynamic assessment. The shore interface must be designed against applicable shore-connection requirements, including IEC/IEEE 80005-1 for high-voltage systems where relevant [13]. Shutting down auxiliary engines at berth may remove local engine exhaust, but it does not make supplied electricity carbon-free [7].

2.4 EEOI and Lifecycle Emission Boundaries

The IMO voluntary EEOI guidelines [11] measure fuel-related CO_2 per transport work using recorded fuel consumption, appropriate carbon factors, cargo carried and distance traveled. For multiple cargo voyages, the corresponding conceptual expression is:

$$EEOI = \Sigma_i\Sigma_j (FC_{ij} \times CF_j) / \Sigma_i (m_i \times D_i)$$

FC_{ij} denotes fuel mass by voyage i and fuel j, CF_j its tank-to-wake CO_2 factor, m_i cargo mass and D_i voyage distance. Consistent units and the treatment of ballast legs must be documented. Shore electricity is not entered as a negative emission credit inside this fuel-based numerator. Its electricity-related emissions must be counted separately in the chosen expanded system boundary. For lifecycle assessment, the IMO guidelines [12] require well-to-tank, tank-to-wake and well-to-wake perspectives and consideration of CO_2, methane and nitrous oxide. LNG methane slip, upstream fuel pathways, electricity carbon intensity and battery manufacture must therefore be characterized before reporting percentage lifecycle savings.

2.5 Discounted Cash-Flow Protocol

A 15-year equal-annual-savings illustration is computed from the original author-supplied figures: additional capital cost C_0 = USD 1,850,000, constant annual net benefit B = USD 412,000, discount rate r = 7.5%, no residual value and no annual escalation. These are conditional inputs, not market-validated Indonesian quotations or operating records. The scenario metrics are:

$$NPV = -C_0 + \Sigma_{t=1}^{n} [B / (1 + r)^t]; \quad IRR: NPV(IRR) = 0$$

Discounted payback is defined as the date at which cumulative discounted net benefits first offset C_0, with linear interpolation between annual periods. Sensitivity analysis should subsequently vary fuel, LNG bunkering, electricity tariffs, system replacement costs, utilization, financing, and discount rates before an investment decision.

3. Results And Discussion

3.1 Design-Input Audit

Table 1. records the numerical design scenario in the submitted manuscript. Values are retained to preserve the authors' proposal, but are clearly classified as preliminary assumptions and are not represented as measured vessel specifications.

Table 1. Author-proposed concept inputs (preliminary, unvalidated design assumptions).

Parameter	Conventional Case	Green Ship Concept	Verification Needed
Length overall	88.5 m	88.5 m	Class drawings
Beam / draft	14.2 m / 4.80 m	14.2 m / 4.85 m	Hydrostatic plan
Nominal DWT	3,000 t	2,920 t	Load-line and stability book
Service speed	12.0 knots	11.5 knots	Route and sea-trial data
Main powertrain	HSD/MGO (not specified)	2,400 kW LNG/diesel	OEM performance map
Battery storage	Not fitted	1,200 kWh LFP	Usable kWh and lifetime
Wind support	Not fitted	One 18 m × 3 m rotor	Wind/route simulation
Shore power	Not fitted	1.0 MW interface	Electrical single-line design

Cargo capacity is not identical between the two concepts (3,000 versus 2,920 DWT). A fair EEOI and business comparison must use actual cargo carried rather than assume identical transport work. The quoted 195.0 versus 119.7 g/kWh "equivalent diesel SFOC" values are not retained as verified engine efficiencies because fuel substitution, battery input and rotor-sail assistance cannot be treated as a single engine-specific measurement without a complete energy balance.

3.2 Technology Readiness and Evidence Requirements

Table 2. distinguishes the expected physical mechanism of each intervention from the records required to establish its effect. The precise fuel savings and pollutant-reduction percentages in the submission remain hypotheses until supported by manufacturer testing or measured voyages; individual percentages cannot simply be summed because measures interact.

Table 2. Engineering mechanisms and measurement requirements for the proposed retrofit.

Intervention	Mechanism / potential impact	Minimum validation evidence
LNG/diesel engine	Different combustion emissions and energy conversion; methane slip relevant	Engine map, LNG rate, CO_2/CH_4/N_2O factors
1.2-MWh LFP BESS	Peak shaving and possible reduced generator run time	Measured charging/discharging and degradation
18 m × 3 m rotor sail	Wind-derived auxiliary propulsive thrust	Wind rose, rotor power demand, route trial
1.0-MW onshore power	Substitutes shore electricity for auxiliaries at berth	Berthing energy, grid factor, HVSC compatibility

3.3 Recalculation of Financial Results

The source manuscript specifies USD 1.85 million incremental CAPEX, USD 412,000 annual savings, a 7.5% discount rate and a 15-year analysis period. Recomputing a uniform annual cash-flow annuity gives the results in Table 3. This is an arithmetic audit of the supplied scenario, not an independent feasibility finding.

Table 3. Verified arithmetic for the author-supplied flat-cash-flow scenario.

Indicator	Correct scenario value	Interpretation
Incremental initial CAPEX	USD 1,850,000	Input assumed; not independently priced
Annual net benefit	USD 412,000/year	Input assumed constant
Analysis period / r	15 years / 7.5%	Input assumed
Simple payback	4.49 years	CAPEX / annual benefit
Discounted payback	5.69 years	Interpolated after discounting
Net present value	USD 1.787 million	Annuity calculation; no terminal value
Internal rate of return	21.0%	Equal annual cash inflows

The original text reported USD 1.94 million NPV, a 4.9-year discounted payback and 19.4% IRR; these do not follow from the simultaneously stated flat-cash-flow assumptions. If the authors used uneven annual benefits, battery replacements, taxes, financing or residual values, the year-by-year model must be disclosed and the results recalculated accordingly. The calculation above does not establish that USD 412,000 will actually be saved per year.

3.4 Carbon Intensity and Well-to-Wake Claims

The submitted operational EEOI figures (18.45 and 11.32 g-CO_2 per tonne-nautical mile) imply a mathematical reduction of approximately 38.6% when compared directly. This numerical relationship is consistent arithmetically but neither input is traceable to logged fuel use, cargo work or a documented modeled energy balance. These values therefore remain author-proposed scenario endpoints, not empirical observations. Further, an EEOI fuel-CO_2 result cannot by itself demonstrate a 44.8% or 82.3% well-to-wake GHG improvement: those claims require lifecycle fuel factors, LNG methane slip assumptions, shore-power electricity mix, vessel utilization and upstream equipment/material inventories in a common functional unit [11,12].

Published findings support the relevance of the technologies but not the transfer of specific savings to this vessel. For example, the ferry-specific lifecycle appraisal of Kanchiralla et al. [6] highlights battery chemistry, charging strategy and fleet operation as material model drivers. Likewise, Abu Bakar et al. [7] show that shore-power outcomes depend on infrastructure, grid supply and vessel interfaces. A defensible future assessment would present tank-to-wake CO_2, full well-to-wake CO_2-equivalent and local port air emissions as distinct outputs rather than blend them into one percentage.

3.5 Operational and Policy Implications

Before investment decisions, the proposed Surabaya–Banjarmasin corridor requires a verified set of sailing and berthing cycles, draft and payload records, energy-quality and grid-emission data, and economic quotations. Policy incentives and port-specific shore-power business models may influence uptake, as suggested by Cui et al. [8] and Akhavan [9]. National BPS statistics [3] can guide where traffic is concentrated but cannot demonstrate that a specific port currently provides a 1-MW compatible shore-power berth. The operational design should also verify grid capacity, safety interlocks, frequency compatibility and terminal responsibilities under the applicable IEC/IEEE interface framework [13].

4. Conclusion

This article retains the technical concept of a hybrid-electric Green Logistic Ship proposed for Indonesian inter-island freight and converts its evaluation into a traceable scenario-based framework. Official IMO and BPS publications and verified peer-reviewed studies establish the environmental and methodological context; they do not independently confirm the draft's vessel-specific fuel savings, LNG emissions, port loads or lifecycle abatement percentages. Hydrodynamic, EEOI and well-to-wake results remain unverified pending the required vessel, fuel, route and electricity data.

Under the explicitly stated illustration of USD 1.85 million incremental investment and USD 412,000 constant yearly net savings for 15 years at 7.5%, the internally consistent outputs are an NPV of USD 1.787 million, IRR of 21.0%, and discounted payback of approximately 5.69 years. These outputs are conditional and must not be characterized as realized financial performance. The next research step is a documented vessel-and-port pilot that logs fuel/electricity consumption, cargo-transport work, operational reliability, battery degradation and shore-power emissions to test the proposed architecture.

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