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AUTONOMOUS ELECTRIC SHIPS (AES) FOR ARCHIPELAGIC MARITIME LOGISTICS: FEASIBILITY, COLREGs COMPLIANCE, AND DECARBONIZATION SCREENING IN INDONESIA

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ABSTRACT

Autonomous electric ships (AES) combine battery-electric propulsion with advanced navigation and shore-side supervision. This paper develops a source-traceable conceptual screening framework for their potential deployment on Indonesian inter-island routes. The analysis is based on the published scope of Statistics Indonesia (BPS) Sea Transportation Statistics for 2021–2024, International Maritime Organization (IMO) instruments on greenhouse gases, maritime autonomous surface ships (MASS), and collision prevention, together with peer-reviewed studies of autonomous navigation and ship electrification. A proposed four-layer architecture links battery and propulsion safety, multimodal perception and COLREGs decision support, resilient communications, and human-supervised shore services. The assessment specifies indicators needed for corridor selection and equations for future energy, well-to-wake emissions, and cost comparisons. It does not report measured AES emissions, economic payback, collision-avoidance performance, or route-specific battery sizing, because the corresponding engineering logs and test datasets were not supplied. The contribution is a transparent design and validation agenda rather than a completed technology demonstration.

Keywords: Autonomous Electric Ships; Battery-Electric Propulsion; COLREGs; Evidence-Based Feasibility; Indonesian Archipelagic Logistics; Maritime Autonomous Surface Ships.

1. Introduction

Indonesia's dispersed islands and marine transport network make reliable inter-island connections essential for passengers, goods, and regional economic activity. BPS provides annual national Sea Transportation Statistics that report vessel visits, goods loading and unloading, and passenger movements. The 2021 and 2022 editions cover 33 provinces, whereas the 2023 and 2024 editions cover 36 provinces; the changing statistical coverage must be respected in longitudinal comparisons [1]–[4].

The IMO 2023 Strategy on Reduction of GHG Emissions from Ships (Resolution MEPC.377(80)) establishes an international ambition of net-zero greenhouse gas emissions by or around 2050, with indicative checkpoints in 2030 and 2040 [5]. Battery-electric propulsion may reduce direct exhaust at the vessel, but net greenhouse gas impact depends on upstream electricity, vessel duty cycle, battery production, charging losses, and the counterfactual vessel. An electric vessel is not automatically zero-emission on a well-to-wake basis [12].

The autonomy component introduces a separate safety and governance problem. The IMO regulatory scoping exercise identifies issues requiring future regulation of MASS, including the roles of the master and crew, operational responsibility, and the interaction between human supervision and automated decision-making [6]. The International Regulations for Preventing Collisions at Sea (COLREGs) remain central to route planning, lookout, safe speed, risk assessment, and encounter management [7]. Reviewed research also cautions that apparently successful simulation results cannot substitute for multi-vessel trials, adverse-weather evaluation, and assured communications [8]–[11].

These issues reveal a gap between the technological potential of autonomous electric vessels and the evidence required to assess their practical deployment in Indonesian archipelagic logistics. Existing literature addresses autonomous navigation and electric propulsion largely as separate technical domains, while corridor-level assessment requires their integration with documented transport activity, energy requirements, navigational safety, communication resilience, and environmental and economic evaluation. A screening approach is therefore needed to determine what evidence should be available before an Indonesian route is considered for AES testing.

This study develops an evidence-informed conceptual screening framework for Autonomous Electric Ships (AES) in Indonesian inter-island logistics. The framework integrates four dimensions: (1) battery-electric propulsion and safety, (2) perception and COLREGs-based navigation support, (3) resilient communication, and (4) human-supervised shore operations. It further defines indicators and analytical requirements for subsequent assessment of energy demand, well-to-wake emissions, and operating costs. The study does not claim prototype deployment, route-specific battery sizing, collision-avoidance performance, emission reduction, or economic payback. Its contribution is a transparent basis for corridor screening and subsequent technical validation.

2. Literature Review

2.1 Autonomous Navigation and Colregs Assurance

The IMO identifies four degrees of autonomy for Maritime Autonomous Surface Ships (MASS), ranging from automated functions with human decision support to fully autonomous operation [6]. These categories are intended to support regulatory assessment and should not be interpreted as operational approval or safety certification. Within autonomous navigation, collision avoidance involves a sequence of functions, including environmental perception, target tracking and prediction, COLREGs interpretation, manoeuvre selection, and continuous monitoring [8]–[11]. Accordingly, autonomous navigation cannot be assessed solely from the ability to generate a collision-free path; the decision process must also account for navigational rules and ongoing situational changes. For AES deployment, these findings support the need to evaluate autonomy as an integrated safety function in which automated decision-making remains consistent with COLREGs requirements and appropriate human supervision.

2.2 Battery-Electric Propulsion and Shore Connections

Electrification feasibility is route-specific. It depends on actual propulsion power, hotel loads, reserve energy, shore grid capacity, turnaround time, battery degradation, and charging infrastructure. A peer-reviewed techno-economic study of short-sea electrification documents how vessel route and energy conditions shape feasibility [12]. IEEE/IEC 80005-1:2019 is a real high-voltage shore-connection standard; it should not be described as a universal technical certification for high-power battery recharging without additional applicable requirements [13].

2.3 Verified Synthesis of Relevant Literature

Table 1. Traceable research and regulatory foundations for AES screening.

Source	Documented Focus	Use in This Study
IMO (2021) [6]	Regulatory scoping for MASS; degrees of autonomy	Separate technology proposal from regulatory approval
Zhang et al. (2021) [8]	Survey of MASS collision-avoidance navigation	Define perception and safety-assurance tasks
Akdağ et al. (2022) [9]	Review of collaborative collision avoidance	Require coordination and communications analysis
Chang et al. (2024) [11]	COLREG/MASS review of trends and gaps	Define auditable COLREGs coverage
Mackenbach et al. (2026) [12]	Techno-economic feasibility of short-sea electrification	Identify information needed for cost and energy models

These references support the plausibility and research motivation of autonomous and battery-electric shipping. They do not establish a 99.4% collision-avoidance rate, a specific Indonesian vessel battery requirement, a 76% carbon reduction, or a 4.8-year payback for the article's proposed routes.

3. Research Methodology

3.1 Source Verification and Limits of the Data

The study draws on three source groups: (i) official BPS Sea Transportation Statistics for 2021–2024 [1]–[4], (ii) official IMO instruments and regulatory documents [5]–[7], and (iii) peer-reviewed and standards-body publications with identifiable DOI or publisher records [8]–[13]. Quantitative figures were retained only when they could be traced to a specific primary table, dataset, engineering record, or reproducible calculation. Untraceable figures from earlier drafts were excluded.

The available sources provide national-level transport information but do not contain the vessel-specific and route-level parameters required to validate an AES design, such as ship resistance characteristics, detailed berth schedules, battery-health records, or route-specific metocean conditions. Therefore, the analysis uses the available evidence for conceptual screening and framework development, rather than for validating route-level energy demand, charging requirements, or operational readiness.

3.2 Proposed Four-Layer AES Architecture

The engineering design is conceptual and must be specified for an actual vessel class before certification or deployment. Layer 1 concerns the electric propulsion chain and battery management. Layer 2 supports navigation with radar, optical sensors, AIS, and COLREGs-aware decision logic, while retaining safe-speed and lookout obligations. Layer 3 provides authenticated, redundant maritime communications and degraded-mode handling. Layer 4 comprises shore-side supervision, emergency response, and port charging interfaces.

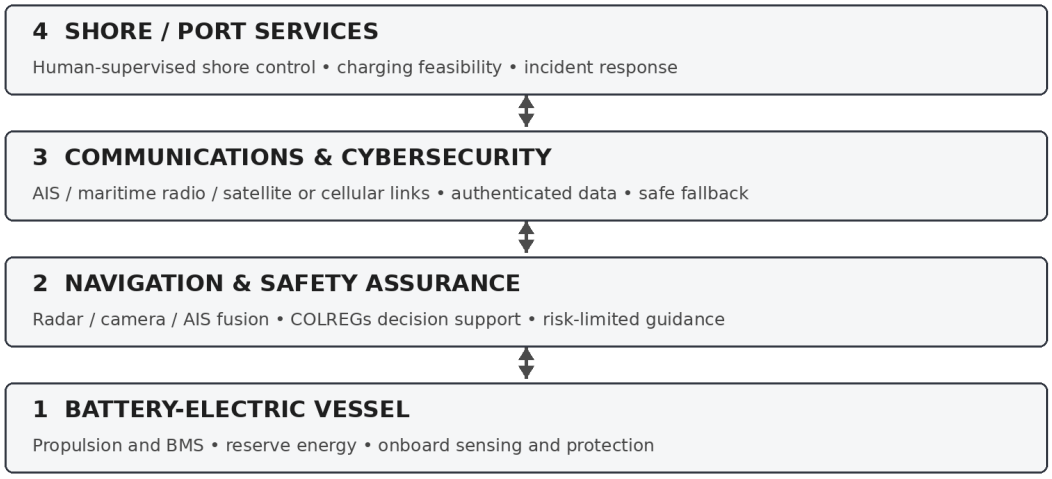


Figure 1. Proposed AES architecture (conceptual design; not a deployed or validated system).

3.3 Feasibility Indicators and Prospective Calculations

A route-level assessment should begin with recorded distance and travel-time distributions, vessel displacement and speed, propulsion energy by sea state, auxiliary loads, battery usable capacity, statutory reserves, port dwell time, charging power, and local grid carbon intensity. Transparent energy and emissions calculations can then be performed using the following screening relationships (variables require measured inputs):

$$E_{voyage} = \int (P_{prop}(t) + P_{aux}(t))\, dt / \eta_{electric}$$

$$E_{usable} = E_{nominal} \times DoD_{allowable} \times SOH$$

$$CI_{WtW,elec} = (E_{grid} \times EF_{grid} + E_{upstream,other}) / transport_{work}$$

Here P_{prop} and P_{aux} are time-dependent propulsion and auxiliary loads, $\eta_{electric}$ is the relevant conversion efficiency, $DoD_{allowable}$ is allowable depth of discharge, SOH is battery state of health, EF_{grid} is a documented electricity emission factor, and $transport_{work}$ must use a consistent ton-nautical-mile or passenger-nautical-mile denominator. Economic appraisal also requires vessel CAPEX, operating labor arrangements, battery replacement, finance, maintenance, insurance, grid charges, and charging infrastructure CAPEX. These equations are methodological definitions, not computations performed in this manuscript.

4. Results And Discussion

4.1 Verified BPS Series and Data-Comparability Boundary

The official BPS releases establish that consistent categories of ship calls, cargo flow, and passenger movements are documented annually. However, the original manuscript attributed several exact 2021–2024 totals to BPS without including source table numbers, archived data extracts, or the calculation workbook. Accordingly, they are not reproduced here as verified results. Table 2 documents the traceable source series and coverage only.

Table 2. Official BPS Sea Transportation Statistics verified at publication level.

Reference Year	BPS Release Date	Provincial Coverage	Documented Indicators
2021	28 Nov 2022	33 provinces	Ship visits; cargo; passengers
2022	27 Nov 2023	33 provinces	Ship visits; cargo; passengers
2023	25 Nov 2024	36 provinces	Ship visits; cargo; passengers
2024	1 Dec 2025	36 provinces	Ship visits; cargo; passengers

Sources: BPS official publication records [1]–[4]. These entries verify the existence, dates, and coverage of the releases, not individual numerical totals from the original draft.

4.2 Safety and Operational Requirements

Table 3. Minimum design evidence required before an Indonesian AES trial.

Domain	Evidence that must be Collected	Critical Acceptance Question
Colregs	Encounter simulations, sea trials, rule-by-rule decision logs	Does the vessel respond safely across representative traffic and weather?
Electrical Energy	Measured speed–power curves, battery reserve and thermal data	Can the route be completed safely under adverse conditions?
Communications	Availability, latency distribution, loss-of-link and takeover tests	Can the vessel reach a safe condition during link failure?
Shore Facilities	Actual grid capacity, connection design and turnaround logs	Can charging and port operations work without unsafe peak loading?
Economics and GHG	Auditable WtW inventory, lifecycle costs and sensitivity tests	Is the benefit robust to actual grid, labor and financing assumptions?

4.3 Candidate Corridor Screening—Without Invented Rankings

Four corridors—Batam–Tanjung Uban, Sanur–Nusa Penida, Ketapang–Gilimanuk, and Merak–Bakauheni—are retained as candidate corridors for further investigation. The available national and aggregate port statistics do not provide sufficient route-level evidence to rank these links for AES deployment or determine battery capacity and shore-charging readiness. Therefore, no readiness score or preferred corridor is assigned at this stage.

The required verification differs across corridors according to their operational characteristics. Batam–Tanjung Uban requires AIS traffic profiles, port-electricity information, and vessel duty cycles. Sanur–Nusa Penida requires sea-state conditions, fast-craft load profiles, and berth schedules. Ketapang–Gilimanuk requires Ro-Ro load cases, crossing frequency, and shore-side interfaces, while Merak–Bakauheni requires assessment of mixed traffic, longer-duty schedules, charging infrastructure, and safety requirements. These requirements define the evidence needed before comparative feasibility can be established.

Table 4. Conceptual corridor assessment (no readiness score assigned).

Illustrative Corridor	Needed Technical Verification	Current Determination
Batam–Tanjung Uban	AIS traffic profiles; port electricity; vessel duty cycles	Not assessed
Sanur–Nusa Penida	Sea-state exposure; fast-craft load curves; berth schedule	Not assessed

Illustrative Corridor	Needed Technical Verification	Current Determination
Ketapang–Gilimanuk	Ro-Ro load cases; crossing frequency; shore interfaces	Not assessed
Merak–Bakauheni	Mixed traffic; longer-duty scheduling; charging and safety	Not assessed

4.4 Decarbonization, Cost, and Evidence Gaps

Battery-electric propulsion eliminates onboard combustion exhaust during battery operation, but its well-to-wake emissions depend on electricity generation and upstream processes [5], [12]. Similarly, assumptions regarding reduced crewing costs cannot be generalized because staffing arrangements and regulatory responsibilities vary with the autonomy level [6]. The previously reported 76.0% GHG reduction, 70.8% OPEX saving, and 4.8-year payback are excluded as empirical findings because their energy baseline, grid-emission factor, cost assumptions, and sensitivity inputs cannot be reconstructed from the available evidence.

A defensible assessment therefore requires transparent input data, including the energy baseline, electricity and fuel assumptions, operational scenarios, and costing parameters. Future studies should provide the underlying calculation workbook and test alternative grid-carbon and operating conditions [5], [12]. At the regulatory level, AES deployment also requires route-specific hazard assessment and a controlled testing environment. General claims of “COLREGs compliance” are insufficient without traceable system requirements, test scenarios, failure conditions, and corresponding mitigation measures [6]–[11].

5. Conclusion

Autonomous battery-electric shipping is a plausible research and development pathway for selected Indonesian short-sea corridors, but the materials examined do not establish proven technical or commercial feasibility. This paper provides a four-layer conceptual design, an explicit distinction between BPS national statistics and vessel-level engineering evidence, and a list of auditable safety, charging, energy, greenhouse-gas, and cost indicators.

Policy Recommendations

The immediate priorities are to verify national statistics from the exact BPS tables, obtain route-specific operational and electrical data, conduct COLREGs-focused simulator and sea trials with human oversight, and develop a transparent lifecycle and financial comparison with sensitivity analysis. Commercialization or regulatory readiness should only be claimed after these steps are documented.

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