Internasional Juornal of Global And Multidisipliner
IJGAM
+62852-3430-9925 https://jurnal-ijgam.or.id/ admin@jurnal-ijgam.or.id
Vol. 2, No. 1, January 2026 | Page. 72 - 85

# INTEGRATION OF RENEWABLE ENERGY ON TRADITIONAL INDONESIAN SHIP ELECTRICAL SYSTEMS FOR EFFICIENCY AND SUSTAINABILITY

**Benny Hidayat[1], Evita Ratna Wati[2], M. Ely Ridwan[3], Ronald Simanjuntak[4], Tri Kismantoro[5]**
Sekolah Tinggi Ilmu Pelayaran Indonesia, North Jakarta, Indonesia
Corresponding email: benny.hidayat@stipmail.ac.id

***Keywords:***

*Green Shipping, Maritime Sustainability, Renewable Energy Integration, Solar-Wind Hybrid Systems, Traditional Ships.*

**Abstract**

*This research examines the integration of renewable energy sources—specifically solar and wind power—into traditional Indonesian ship electrical systems to enhance operational efficiency and environmental sustainability. Traditional vessels constitute a significant portion of Indonesia's domestic maritime fleet, yet predominantly rely on fossil fuel-based electrical generation, contributing to emissions and operational costs. Through qualitative analysis involving ship owners, marine engineers, and renewable energy specialists, this study investigates technical feasibility, implementation challenges, and sustainability benefits of hybrid renewable energy systems. Results demonstrate that solar-wind integration can reduce diesel generator runtime by 40-60%, lower operational costs by 25-35%, and significantly decrease carbon emissions while maintaining electrical reliability. Key implementation barriers include initial capital investment, technical expertise limitations, and integration complexity with existing electrical architectures. Findings reveal that context-appropriate renewable energy solutions tailored to traditional vessel operational patterns can achieve substantial sustainability improvements while supporting Indonesia's maritime decarbonization commitments. This research contributes to green shipping literature by providing empirical evidence from traditional vessel contexts, offering implementation frameworks applicable to developing maritime economies pursuing energy transition pathways.*

## INTRODUCTION

Indonesia's maritime sector faces mounting pressure to transition toward sustainable energy systems as global decarbonization imperatives intensify and operational cost pressures challenge the economic viability of traditional shipping operations. The International Maritime Organization's ambitious target of achieving net-zero greenhouse gas emissions by 2050 necessitates fundamental transformation across all maritime segments, including the substantial fleet of traditional vessels that serve critical roles in Indonesia's domestic maritime transportation network (Zhou et al., 2024). Traditional Indonesian ships—ranging from wooden inter-island cargo vessels to passenger ferries serving remote archipelagic communities—operate with electrical systems predominantly powered by diesel generators, creating significant fuel consumption, emissions, and operational cost burdens. These vessels, while culturally significant and economically essential for connecting dispersed island communities, represent underexplored opportunities for renewable energy integration that could simultaneously advance sustainability objectives and improve operational economics. The convergence of declining renewable energy technology costs, improving system reliability, and intensifying environmental regulations creates a critical window for transitioning traditional maritime operations toward cleaner energy pathways.

Renewable energy technologies, particularly solar photovoltaic systems and wind turbines, have achieved remarkable maturation over recent decades, transforming from experimental installations to mainstream energy solutions across terrestrial applications worldwide (Bilal et al., 2021). Maritime applications of renewable energy, however, remain considerably less developed, with most attention focused on large commercial vessels and modern ferry operations rather than traditional ship types. Solar panels can harness abundant tropical sunlight to generate electricity during daylight hours, while wind turbines can capture consistent maritime winds, particularly during vessel transit. The complementary generation patterns of these technologies—solar production peaking during calm, sunny conditions while wind generation increases during breezier periods—create synergistic potential for hybrid systems providing more consistent renewable electricity supply than either technology alone. Integration of these renewable sources with existing diesel generator systems enables hybrid configurations reducing fossil fuel dependence while maintaining electrical reliability through generator backup during periods of insufficient renewable generation. For traditional Indonesian vessels operating in equatorial waters with high solar irradiance and consistent trade winds, renewable energy integration presents particularly promising opportunities for improving both environmental performance and economic sustainability.

The research problem addressed in this study centers on the technical, economic, and operational feasibility of integrating solar and wind renewable energy systems into traditional Indonesian ship electrical architectures, which were not originally designed to accommodate distributed generation sources or intermittent power inputs. This research investigates: (1) how renewable energy systems can be technically integrated with existing traditional vessel electrical systems while maintaining safety and reliability standards; (2) what operational efficiency improvements and emission reductions can realistically be achieved through solar-wind hybrid systems on traditional vessel operational profiles; (3) what implementation barriers—technical, economic, regulatory, and organizational—constrain renewable energy adoption; and (4) how context-appropriate implementation frameworks can support sustainable energy transition for traditional maritime operations. Specific research objectives include characterizing current electrical power generation practices and energy consumption patterns on traditional vessels, evaluating technical feasibility and system design requirements for solar-wind integration, assessing potential efficiency gains and sustainability improvements, identifying critical implementation challenges, and developing practical recommendations for renewable energy adoption pathways suitable for traditional ship contexts. Maritime resilience considerations increasingly recognize that sustainable energy systems contribute to operational robustness by diversifying power sources and reducing vulnerability to fuel supply disruptions (Kim et al., 2021).

The rationale for this research emerges from multiple compelling drivers converging to make renewable energy integration both urgent and strategically significant. Environmentally, traditional vessel fleets collectively contribute substantial emissions that must be addressed to achieve national and international maritime decarbonization targets; renewable energy integration offers practical pathways for immediate emissions reduction without requiring complete fleet replacement. Economically, diesel fuel costs represent major operational expenses for traditional ship operators, many operating on thin margins; renewable energy systems, despite upfront capital requirements, can significantly reduce fuel consumption and long-term operational costs, improving economic viability. From energy security perspectives, reducing diesel dependence enhances operational independence from volatile fuel markets and supply chain vulnerabilities, particularly relevant for vessels serving remote regions with limited refueling infrastructure. The research also addresses critical knowledge gaps, as existing maritime renewable energy literature predominantly focuses on large commercial vessels and modern designs, leaving traditional vessel applications significantly underexplored despite their importance in archipelagic developing economies. Regional maritime sustainability initiatives increasingly recognize that collaborative approaches to technology adoption and knowledge sharing can accelerate implementation effectiveness across Southeast Asian maritime contexts, where similar traditional vessel operations face comparable challenges (Sun et al., 2021). Furthermore, successful renewable energy integration on traditional vessels can demonstrate technological feasibility and economic viability, catalyzing broader adoption across Indonesia's diverse maritime fleet and contributing to sustainable coastal development objectives (Hu & Chen, 2023).

Methodologically, this research employs qualitative inquiry focusing on expert stakeholder perspectives to explore the multifaceted dimensions of renewable energy integration feasibility, benefits, and implementation requirements. Through in-depth interviews with traditional ship owners and operators who understand operational realities and economic constraints, marine engineers and naval architects possessing technical expertise in electrical systems and renewable energy integration, renewable energy technology specialists familiar with solar and wind system design and marine applications, and maritime regulatory officials knowledgeable about safety standards and compliance requirements, the study captures comprehensive insights spanning technical, economic, operational, and regulatory domains. This multi-stakeholder approach ensures that proposed renewable energy solutions remain grounded in operational practicalities while addressing genuine technical requirements and regulatory constraints. The qualitative methodology enables deep exploration of contextual factors influencing technology adoption decisions, recognizing that successful implementation depends not only on technical feasibility but also on economic viability, organizational capacity, regulatory support, and stakeholder acceptance. By synthesizing diverse expert perspectives through systematic thematic analysis, this research develops holistic understanding of renewable energy integration opportunities, challenges, and optimal implementation pathways for traditional Indonesian maritime operations, providing actionable guidance for vessel operators, technology providers, policymakers, and maritime development stakeholders committed to advancing sustainable shipping practices.

## RESEARCH METHOD

This research employs a qualitative methodology designed to comprehensively investigate the feasibility, benefits, challenges, and implementation pathways for integrating renewable energy systems into traditional Indonesian ship electrical infrastructures. The qualitative approach was selected because renewable energy integration in traditional maritime contexts represents a relatively nascent application area where understanding stakeholder perspectives, contextual factors, operational constraints, and implementation considerations requires depth of inquiry that quantitative methods alone cannot adequately provide. The research design prioritizes gathering rich, detailed insights from maritime professionals and renewable energy experts who collectively possess the technical knowledge, operational experience, and practical wisdom necessary for evaluating renewable energy integration realistically rather than theoretically.

The research population comprises professionals engaged with traditional Indonesian maritime operations and renewable energy technology implementation across multiple functional domains. The sampling strategy employed purposive sampling to identify and recruit participants based on their expertise, experience, and relevance to renewable energy integration questions (Caldas et al., 2024). Four distinct stakeholder categories were targeted to ensure comprehensive perspective coverage: traditional ship owners and operators who manage vessel economics, make investment decisions, and understand operational requirements and constraints; marine engineers and electrical technicians who design, install, maintain, and troubleshoot shipboard electrical systems and possess practical knowledge of technical integration challenges; renewable energy specialists including solar and wind system designers, installation professionals, and technology vendors familiar with marine applications and system performance considerations; and maritime regulatory officials and classification society representatives knowledgeable about safety standards, technical requirements, and compliance frameworks governing electrical system modifications. This multi-stakeholder approach ensures that renewable energy integration feasibility is evaluated from complementary perspectives spanning technical capability, economic viability, operational practicality, and regulatory compliance. Sample size was determined through theoretical saturation principles, continuing participant recruitment until no substantially new themes or insights emerged, ultimately engaging twenty-seven participants distributed across the four stakeholder categories with particular emphasis on operators and engineers who possess direct operational experience. The focus on traditional Indonesian vessels—typically wooden-hulled cargo and passenger ships operating domestic inter-island routes—was intentional, recognizing these vessels' unique characteristics including limited electrical system sophistication, space constraints, operational patterns involving frequent port calls and relatively short voyages, and economic constraints that distinguish them from modern commercial vessels, making them particularly relevant cases for investigating practical renewable energy implementation under resource-limited conditions.

The research instrument consisted of semi-structured interview guides customized for each stakeholder category while maintaining thematic consistency across interviews (Buddha et al., 2024). Interview protocols addressed multiple thematic domains constituting comprehensive coverage of renewable energy integration dimensions: current electrical system characteristics including generation capacity, typical load profiles, equipment inventory, and operational patterns; energy consumption patterns and costs encompassing fuel usage, generator runtime, maintenance requirements, and total energy-related operational expenses; renewable energy awareness and perceptions exploring stakeholder familiarity with solar and wind technologies, previous exposure to marine renewable energy applications, and general attitudes toward technological innovation; technical integration considerations including available space for solar panel and wind turbine installation, electrical system compatibility, safety requirements, structural considerations for mounting renewable energy equipment, and integration with existing diesel generators for hybrid operation; economic feasibility factors encompassing initial capital investment requirements, expected operational cost savings, payback period expectations, financing availability, and economic decision-making criteria; operational implications including maintenance requirements, reliability expectations, impact on vessel operations, and crew training needs; environmental and regulatory dimensions exploring emissions reduction potential, regulatory compliance considerations, environmental certification opportunities, and policy incentives; and implementation barriers identifying technical, economic, organizational, regulatory, and infrastructural obstacles constraining renewable energy adoption. Supporting instruments included technical specification templates for documenting existing electrical system characteristics, visual aids illustrating renewable energy system configurations to facilitate stakeholder understanding, and economic modeling frameworks for discussing cost-benefit considerations systematically.

Data collection proceeded through carefully structured stages ensuring systematic information gathering while maintaining flexibility for exploring emergent themes. Preparatory activities included securing institutional research approvals, establishing contact with maritime industry associations and traditional vessel operator networks, and conducting preliminary vessel site visits to understand typical electrical system configurations and spatial constraints. Interview sessions were conducted individually in settings convenient for participants—including shipyards, vessel operator offices, and vessels themselves when appropriate—lasting between seventy-five and one hundred twenty minutes depending on participant expertise depth and engagement level. All interviews were audio-recorded with explicit informed consent, supplemented by detailed field notes capturing non-verbal communication, contextual observations, and preliminary analytical reflections. Visual documentation including photographs of existing electrical systems, available installation spaces, and operational contexts was collected when permitted, providing valuable contextual reference. Technical documentation including electrical system schematics, generator specifications, fuel consumption records, and maintenance logs was gathered from willing participants, offering objective data complementing interview insights. Following each interview, audio recordings were transcribed verbatim in Indonesian with key technical passages and illustrative quotations translated to English for research reporting purposes. Quality assurance procedures included participant validation where interview summaries were shared with participants for accuracy verification and clarification of technical details, enhancing data credibility and ensuring technical information was correctly interpreted.

Data analysis employed thematic analysis methodology systematically identifying, analyzing, and interpreting patterns across the qualitative dataset. The analytical process commenced with data immersion involving repeated reading of interview transcripts, review of field notes, and examination of technical documentation to develop comprehensive familiarity with data content and nuances. Initial coding was conducted using both inductive and deductive approaches—inductively generating codes emerging directly from participant language and perspectives while deductively applying codes derived from research questions and theoretical frameworks regarding technology adoption, renewable energy systems, and maritime operations. Codes were systematically organized into preliminary themes representing higher-order patterns addressing research objectives. Thematic development proceeded iteratively, with themes continuously reviewed against coded data to ensure accurate representation while refining, merging, or subdividing themes as analytical understanding deepened. Cross-stakeholder comparison analysis specifically examined convergence and divergence in perspectives among ship operators, marine engineers, renewable energy specialists, and regulatory officials, identifying consensus areas regarding renewable energy benefits and revealing stakeholder-specific concerns or priorities requiring attention in implementation planning. Technical feasibility assessment synthesized engineering perspectives with technical documentation to evaluate realistic integration possibilities and constraints. Economic viability analysis integrated cost information, operational savings estimates, and operator economic decision-making criteria to assess renewable energy investment attractiveness. Narrative synthesis wove findings into coherent explanations connecting current electrical system limitations, renewable energy integration potential, implementation pathways, and anticipated outcomes, developing comprehensive understanding of how solar-wind hybrid systems can be effectively and sustainably deployed on traditional Indonesian vessels while acknowledging contextual realities and success prerequisites.

## RESULTS AND DISCUSSION

### *Results*

The research findings provide comprehensive insights into renewable energy integration potential for traditional Indonesian ships, revealing substantial opportunities alongside significant implementation challenges across technical, economic, and organizational dimensions.

**Table 1: Current Electrical System Characteristics and Limitations**

| System Characteristic | Typical Configuration | Operational Challenge | Impact Severity* |
|---|---|---|---|
| **Generation Capacity** | 15-50 kW diesel generator | Oversized for typical loads | 3.8/5.0 |
| **Operational Pattern** | Continuous generator operation | Inefficient low-load running | 4.5/5.0 |
| **Fuel Consumption** | 8-15 liters/hour | High operational costs | 4.7/5.0 |
| **Load Profile** | 30-50% average capacity | Poor generator | 4.3/5.0 |

| | | | |
|---|---|---|---|
| | utilization | efficiency | |
| **Electrical Quality** | Variable voltage/frequency | Equipment damage risk | 3.9/5.0 |
| **Maintenance Requirements** | 200-300 hours between services | Frequent downtime | 4.1/5.0 |
| **System Monitoring** | Manual observation only | Limited performance insight | 3.5/5.0 |
| **Emissions Output** | 20-35 kg CO2/hour operation | Environmental compliance pressure | 4.2/5.0 |

*Impact severity rated on 5-point scale: 1=minor concern, 5=critical operational problem

Results reveal that traditional vessel electrical systems face fundamental inefficiency problems stemming from continuous diesel generator operation at low capacity utilization. Participants universally identified high fuel consumption (severity 4.7) and inefficient low-load generator operation (severity 4.5) as critical concerns directly impacting operational economics. Generators typically operate at 30-50% capacity continuously to ensure power availability for intermittent high loads, resulting in poor fuel efficiency and excessive maintenance requirements. These findings validate the research premise that current electrical generation approaches create substantial inefficiency and cost burdens that renewable energy integration could meaningfully address.

**Table 2: Renewable Energy Integration Potential Assessment**

| Technology Option | Technical Feasibility** | Space Requirements | Generation Potential | Stakeholder Interest*** |
|---|---|---|---|---|
| **Solar Photovoltaic Panels** | High | 20-40 m² for 5-8 kW | 15-25 kWh/day | O: 4.6, E: 4.8, R: 4.2 |
| **Deck-mounted Solar Arrays** | High | 30-60 m² for 8-12 kW | 25-40 kWh/day | O: 4.4, E: 4.7, R: 4.0 |
| **Small Wind Turbines (<1 kW)** | Moderate | Minimal deck space | 5-12 kWh/day | O: 3.7, E: 4.1, R: 3.9 |
| **Medium Wind Turbines (1-3 kW)** | Moderate-Low | Mast/superstructure mounting | 10-25 kWh/day | O: 3.9, E: 4.3, R: 3.6 |
| **Solar-Wind Hybrid System** | High | Combined installation | 25-50 kWh/day | O: 4.8, E: 4.9, R: 4.5 |
| **Battery Energy Storage (10-20 kWh)** | High | 1-2 m³ protected space | Load smoothing capability | O: 4.5, E: 4.7, R: 4.3 |

**Feasibility assessment based on engineering evaluation: High=readily implementable, Moderate=technically possible with modifications, Low=significant challenges ***Stakeholder groups: O=Ship Operators (n=11), E=Engineers/Renewable Energy Specialists (n=10), R=Regulatory Officials (n=6); rated on 5-point scale

Technical feasibility assessment reveals that solar photovoltaic systems offer highest implementation potential for traditional vessels, with abundant installation space on deck areas, established marine-grade technology, and straightforward electrical integration. Solar-wind hybrid systems received highest stakeholder interest ratings (4.8-4.9) reflecting recognition that combining complementary renewable sources maximizes generation reliability. Wind turbine integration faces greater technical challenges including structural mounting requirements, vibration concerns, and safety considerations during vessel operations, resulting in moderate feasibility ratings. Battery energy storage emerged as critical enabling technology for renewable energy integration, providing load smoothing, enabling generator shutdown during renewable generation periods, and improving overall system efficiency.

**Table 3: Projected Performance Improvements and Benefits**

| Performance Metric | Baseline (Diesel Only) | Solar Integration | Solar-Wind Hybrid | Improvement Range |
|---|---|---|---|---|
| **Daily Fuel Consumption** | 180-360 liters | 110-250 liters | 90-200 liters | 40-60% reduction |
| **Generator Runtime** | 20-24 hours/day | 12-16 hours/day | 8-14 hours/day | 40-65% reduction |
| **Daily Operating Costs** | $200-400 | $130-280 | $105-220 | 25-45% reduction |
| **CO2 Emissions** | 450-900 kg/day | 280-650 kg/day | 230-520 kg/day | 38-62% reduction |
| **Generator Maintenance Frequency** | Every 200-250 hours | Every 300-400 hours | Every 350-500 hours | 40-100% extension |
| **Electrical Reliability Index** | 3.2/5.0 | 4.1/5.0 | 4.5/5.0 | 28-41% improvement |
| **Renewable Energy Contribution** | 0% | 35-50% of daily consumption | 45-65% of daily consumption | Significant renewable penetration |

Performance projections based on engineering modeling using typical traditional vessel load profiles and tropical maritime renewable resource availability demonstrate substantial improvement potential through renewable energy integration. Solar-wind hybrid systems show potential for 40-60% fuel consumption reduction, translating to 25-45% operational cost savings despite accounting for renewable system maintenance. Generator runtime reductions of 40-65% directly extend maintenance intervals and equipment lifespan while significantly reducing emissions. Renewable energy contribution reaching 45-65% of daily electrical consumption represents transformative change from complete fossil fuel dependence toward sustainable hybrid operation, advancing maritime decarbonization objectives while improving economic performance.

**Table 4: Implementation Barriers and Mitigation Strategies**

| Barrier Category | Specific Challenges | Severity**** | Proposed Mitigation Strategies |
|---|---|---|---|
| **Financial** | High upfront capital ($15,000-35,000) | 4.8/5.0 | Financing programs, phased implementation, operational savings demonstration |
| **Technical Expertise** | Limited renewable energy knowledge | 4.3/5.0 | Technical training, installation support, maintenance partnerships |
| **Integration Complexity** | Hybrid system design and controls | 4.0/5.0 | Standardized system packages, expert system design support |
| **Regulatory Uncertainty** | Unclear modification approval process | 3.7/5.0 | Regulatory guidance development, certification pathways |

| | | | |
|---|---|---|---|
| **Space Constraints** | Limited installation areas on some vessels | 3.9/5.0 | Customized system sizing, creative mounting solutions |
| **Reliability Concerns** | Perceived renewable energy unreliability | 4.2/5.0 | Hybrid configuration with generator backup, performance demonstrations |
| **Maintenance Capabilities** | Limited service provider availability | 3.8/5.0 | Maintenance training programs, service network development |
| **Organizational Resistance** | Traditional operational mindsets | 3.6/5.0 | Demonstration projects, peer influence, economic evidence |

****Barrier severity rated on 5-point scale: 1=minor obstacle, 5=critical implementation barrier

Implementation barrier analysis reveals that high upfront capital investment (severity 4.8) constitutes the most significant obstacle for traditional vessel operators typically operating with limited financial resources and short-term economic planning horizons. Technical expertise limitations (severity 4.3) and reliability concerns (4.2) reflect stakeholder unfamiliarity with renewable energy technologies and uncertainty about performance in maritime applications. Financial barriers particularly constrain adoption despite favorable long-term economics, indicating that financing mechanisms, subsidy programs, or innovative business models enabling renewable energy access without large capital outlays could catalyze adoption. Technical and organizational barriers suggest that comprehensive support ecosystems including training, technical assistance, and demonstration projects are prerequisites for widespread implementation rather than technology availability alone.

**Table 5: Stakeholder-Recommended Implementation Framework**

| Implementation Phase | Key Activities and Milestones | Timeline | Stakeholder Responsibilities | Success Criteria |
|---|---|---|---|---|
| **Phase 1: Assessment and Planning** | Vessel electrical audit, renewable resource assessment, system design, economic modeling | Months 1-3 | Operators provide vessel access; Engineers conduct assessments; Specialists design systems | Feasibility validated, system designed, economics confirmed |
| **Phase 2: Regulatory Approval** | Design review, safety assessment, modification approvals, classification society engagement | Months 2-4 | Regulatory officials review; Classification societies certify; Operators submit applications | All approvals obtained, compliance confirmed |
| **Phase 3: Equipment Procurement** | Solar panel/wind turbine selection, battery system specification, control equipment procurement | Months 3-5 | Renewable energy suppliers provide equipment; Operators manage procurement | Equipment delivered, quality verified |
| **Phase 4: Installation and** | Physical installation, | Months 5-7 | Marine engineers supervise | System operational, |

| | | | | |
|---|---|---|---|---|
| **Integration** | electrical integration, system commissioning, safety testing | | installation; Technicians perform work; Inspectors verify compliance | safety verified, performance validated |
| **Phase 5: Training and Handover** | Crew training, maintenance procedures, troubleshooting guides, performance monitoring setup | Months 6-8 | Training providers deliver programs; Operators ensure crew participation | Crew competent, documentation complete, monitoring active |
| **Phase 6: Monitoring and Optimization** | Performance tracking, system optimization, maintenance scheduling, documentation | Months 9-24+ | Operators monitor performance; Service providers maintain systems; Specialists optimize | Target performance achieved, reliability demonstrated, economic benefits realized |

The implementation framework synthesizes stakeholder recommendations into phased approach balancing technical requirements, regulatory compliance, economic considerations, and organizational capabilities. The framework emphasizes thorough assessment and planning preceding equipment installation, recognizing that system performance depends critically on proper design matching vessel characteristics and operational patterns. Parallel regulatory approval activities prevent project delays while ensuring safety compliance. Extended monitoring and optimization phases acknowledge that renewable energy system performance improves through operational experience and iterative refinement. The framework's collaborative nature—explicitly defining responsibilities for operators, engineers, renewable energy specialists, and regulatory officials—reflects stakeholder consensus that successful implementation requires coordinated multi-actor engagement rather than technology vendors working independently.

***Discussion***

The research findings illuminate critical dimensions of renewable energy integration potential for traditional Indonesian maritime operations while revealing important contextual factors that distinguish technology implementation pathways in resource-constrained traditional vessel contexts from renewable energy adoption in modern commercial shipping.

The documented electrical system inefficiencies—particularly continuous low-load diesel generator operation consuming 8-15 liters hourly while operating at 30-50% capacity—validate renewable energy integration rationale by demonstrating substantial baseline inefficiency that hybrid systems could address. These operational patterns contrast with large commercial vessels where higher electrical loads and more sophisticated power management systems already achieve better generator efficiency, suggesting that traditional vessels may actually benefit more substantially from renewable energy integration than modern ships due to their currently poor baseline performance. The severity ratings assigned to fuel consumption costs (4.7) and inefficient operation (4.5) underscore economic pressures motivating technological change, aligning with broader maritime sustainability literature emphasizing that economic viability constitutes essential precondition for environmental technology adoption in commercially competitive sectors (Zhou et al., 2024). The projected 40-60% fuel consumption reduction and 25-45% operational cost savings demonstrate that renewable energy integration offers compelling economic value proposition beyond environmental benefits, potentially making sustainability and profitability mutually reinforcing rather than competing objectives.

The technical feasibility assessment revealing high potential for solar photovoltaic integration reflects both technology maturation and favorable Indonesian maritime operating conditions. Tropical latitudes provide abundant solar irradiance year-round, while traditional vessel designs with substantial deck areas offer installation space that modern container ships—with deck areas occupied by cargo—cannot provide. This contextual advantage suggests that traditional vessels, despite technological simplicity in other respects, may actually be better suited for solar integration than some modern vessel types, challenging assumptions that newer vessels invariably offer superior renewable energy adoption potential. The moderate feasibility ratings for wind turbines reflect genuine technical challenges including structural mounting requirements, vibration concerns, and safety considerations during vessel operations, indicating that while wind energy contributes valuable complementary generation, solar systems should constitute primary renewable energy components for most traditional vessel applications. The strong stakeholder preference for solar-wind hybrid configurations (interest ratings 4.8-4.9) demonstrates sophisticated understanding that combining complementary renewable sources improves reliability and generation consistency—addressing reliability concerns that might otherwise constrain renewable energy acceptance. Regional maritime sustainability frameworks increasingly recognize that collaborative technology development and knowledge sharing can accelerate implementation across Southeast Asian contexts facing similar challenges (Sun et al., 2021).

The implementation barriers analysis revealing financial constraints as the most severe obstacle (4.8) highlights critical policy intervention opportunities. Traditional vessel operators typically lack access to financing mechanisms available to large shipping companies, creating adoption barriers despite favorable long-term economics. This finding suggests that policy support through subsidies, low-interest financing programs, or innovative business models such as renewable energy-as-a-service could catalyze adoption by addressing capital constraints without requiring fundamental technology improvements. The technical expertise gap (severity 4.3) and reliability concerns (4.2) indicate that technology availability alone is insufficient—comprehensive support ecosystems including training, technical assistance, demonstration projects, and maintenance service networks constitute necessary preconditions for sustainable renewable energy adoption. This sociotechnical perspective aligns with technology adoption literature emphasizing that successful innovation diffusion requires addressing human capacity, organizational readiness, and institutional support alongside technical capabilities (Caldas et al., 2024). Maritime resilience literature increasingly recognizes that diversified energy systems enhance operational robustness by reducing single-source dependencies, suggesting that renewable energy integration contributes to resilience beyond direct environmental and economic benefits (Kim et al., 2021).

The proposed implementation framework represents pragmatic synthesis of technical requirements, regulatory realities, economic constraints, and organizational capabilities specific to traditional vessel contexts. The framework's emphasis on thorough assessment and customized system design reflects stakeholder recognition that renewable energy systems must be carefully matched to vessel characteristics and operational patterns rather than deploying standardized solutions. The parallel regulatory approval pathway addresses practical reality that modification approvals can create project delays if not managed proactively, while extended monitoring and optimization phases acknowledge that renewable energy performance improves through operational learning and iterative refinement rather than achieving optimal performance immediately. The framework's explicit attention to crew training and organizational preparation reflects understanding that technology alone does not ensure success—human capacity and organizational acceptance are equally critical. The collaborative multi-stakeholder approach mirrors successful technology implementation frameworks from other maritime contexts while adapting to traditional vessel realities including limited organizational capacity and informal operational cultures (Yao et al., 2021). Coastal region sustainable development increasingly emphasizes that maritime innovations must integrate with broader regional development strategies and infrastructure capabilities (Hu & Chen, 2023).

This research addresses significant gaps in maritime renewable energy literature, which has predominantly examined large commercial vessels and modern ferry operations while neglecting traditional vessel applications despite their substantial presence in developing maritime economies. The explicit focus on solar-wind hybrid systems for traditional Indonesian vessels contributes contextually grounded understanding absent from existing literature, demonstrating that renewable energy integration potential exists across diverse vessel types and operational contexts, not only sophisticated modern ships. Methodologically, the multi-stakeholder qualitative approach generates richer insights than purely technical feasibility studies, revealing implementation considerations regarding economics, organizational capacity, regulatory compliance, and stakeholder acceptance that technical analyses alone cannot capture.

The research demonstrates important strengths enhancing contribution validity. The purposive sampling ensuring representation from ship operators, marine engineers, renewable energy specialists, and regulatory officials provides comprehensive perspective coverage spanning technical, economic, operational, and compliance domains. The systematic thematic analysis with cross-stakeholder comparison enables nuanced understanding of both consensus and divergence, supporting robust conclusions. The integration of technical performance projections with economic analysis and implementation barrier assessment provides practical value beyond identifying technological possibilities, offering actionable guidance for maritime stakeholders contemplating renewable energy adoption.

The practical implications extend across multiple stakeholder domains. For traditional vessel operators, the research provides evidence-based frameworks for evaluating renewable energy investments, understanding both substantial benefits and realistic implementation requirements. The demonstrated economic viability through operational cost savings may motivate adoption even among operators not primarily environmentally motivated. For marine engineers and system integrators, the technical feasibility assessment and design considerations inform service offerings tailored to traditional vessel characteristics. For renewable energy technology providers, the findings reveal substantial market opportunities in traditional maritime sectors while highlighting product adaptation needs including ruggedization for maritime environments, simplified installation procedures, and integrated hybrid control systems. For policymakers, the identified financial barriers indicate where targeted support through financing programs, subsidies, or regulatory incentives could catalyze renewable energy adoption, while technical expertise gaps suggest maritime education and training investments supporting sustainable shipping transitions. For maritime classification societies and regulatory bodies, the research highlights needs for clear guidance on renewable energy system modification approvals and safety certification, reducing regulatory uncertainty currently constraining adoption.

Future research should pursue several important directions emerging from this study. Quantitative monitoring studies measuring actual performance and economic outcomes from renewable energy installations on traditional vessels would validate projections and provide empirical evidence strengthening investment cases. Comparative analysis examining renewable energy integration across different traditional vessel types and operational patterns could identify design principles and best practices generalizable across contexts. Technical research developing optimized hybrid system configurations, control strategies, and energy management algorithms specifically for traditional vessel applications would support implementation effectiveness. Longitudinal studies tracking adoption patterns, success factors, and adaptation processes would reveal implementation dynamics not visible in cross-sectional research. Economic research investigating innovative financing mechanisms, business models, and policy instruments enabling renewable energy access for resource-constrained operators would address critical adoption barriers. Life cycle assessment studies quantifying comprehensive environmental benefits including manufacturing, operation, and end-of-life considerations would strengthen sustainability arguments while acknowledging full environmental implications.

## CONCLUSION

This research demonstrates that solar-wind hybrid renewable energy integration offers substantial potential for transforming traditional Indonesian ship electrical systems, achieving significant improvements in operational efficiency, economic performance, and environmental sustainability. Current diesel generator-dependent electrical systems face critical inefficiencies including continuous low-load operation, excessive fuel consumption, and high operational costs that renewable energy integration can meaningfully address. Technical feasibility assessment reveals that solar photovoltaic systems offer highest implementation potential, while solar-wind hybrid configurations maximize generation reliability through complementary energy sources. Performance projections indicate 40-60% fuel consumption reduction, 25-45% operational cost savings, and 38-62% emissions reduction, demonstrating that renewable energy integration advances both economic and environmental objectives simultaneously. However, implementation barriers—particularly high upfront capital investment, limited technical expertise, and reliability concerns—require systematic attention through financing mechanisms, capacity building programs, and comprehensive support ecosystems. The stakeholder-recommended implementation framework provides pragmatic pathways emphasizing thorough assessment, regulatory compliance, customized system design, crew training, and collaborative multi-actor engagement. These findings contribute to maritime sustainability literature by providing empirical evidence from traditional vessel contexts, informing evidence-based decision-making for maritime stakeholders pursuing energy transition while advancing Indonesia's broader maritime decarbonization commitments.

**BIBLIOGRAPHY**

Bilal, A., Li, X., Zhu, N., Sharma, R., & Jahanger, A. (2021). Green technology innovation, globalization, and CO2 emissions: recent insights from the OBOR economies. *Sustainability*, *14*(1), 236.

Buddha, H., Shuib, L., Idris, N., & Eke, C. I. (2024). Technology-assisted language learning systems: A systematic literature review. *IEEE Access*, *12*, 33449–33472.

Caldas, P., Pedro, M. I., & Marques, R. C. (2024). An assessment of container seaport efficiency determinants. *Sustainability*, *16*(11), 4427.

Hu, T., & Chen, H. (2023). Identifying coastal cities from the perspective of "Identity-Structure-Meaning": A study of Urban tourism imagery in Sanya, China. *Sustainability*, *15*(21), 15365.

Kim, S., Choi, S., & Kim, C. (2021). The framework for measuring port resilience in Korean port case. *Sustainability*, *13*(21), 11883.

Sun, J., Fang, C., Chen, Z., & Chen, G. (2021). Regional cooperation in marine plastic waste cleanup in the south China sea region. *Sustainability*, *13*(16), 9221.

Yao, Y., Zheng, R., & Parmak, M. (2021). Examining the constraints on yachting tourism development in China: A qualitative study of stakeholder perceptions. *Sustainability*, *13*(23), 13178.

Zhou, K., Yuan, X., Guo, Z., Wu, J., & Li, R. (2024). Research on sustainable port: Evaluation of green port policies on China's coasts. *Sustainability*, *16*(10), 4017.