Mechanical engineering optimization of hybrid refrigeration systems for fisheries

Mardiana Mardiana[1*], *Boy* Laksmana[2], *Ajie* Permana[2], *Pantjadjatmika* Rachmardata[1], *Rikman* Sohriadhana[1], and *Ali Sulistyo* Budi[1]

[1]Malahayati Transportation Management Institute, North Jakarta, Indonesia
[2]Maritime Institute of Jakarta, Sekolah Tinggi Ilmu Pelayaran-Jakarta, Indonesia

Abstract. This research develops mechanically optimized hybrid renewable energy refrigeration systems addressing post-harvest preservation challenges in Indonesian artisanal fisheries through integrated engineering design, environmental assessment, and techno-economic analysis. Employing three-phase methodology combining computational system optimization, life cycle assessment, and implementation framework development, the study evaluates vessel-based, landing site, and community facility configurations. Results demonstrate hybrid photovoltaic-wind systems achieve 35-42% reliability improvements over single-source alternatives, 25-30% refrigeration efficiency gains through enhanced heat exchangers and vacuum insulation, and 68% greenhouse gas reductions compared to diesel refrigeration. Economic analysis reveals levelized preservation costs of $0.055-0.078/kg fish for larger installations, achieving competitiveness with conventional methods. However, implementation barriers include capital requirements (32% of constraints), technical capacity limitations (23%), and financing access challenges (20%). Overall viability scored 8.3/10.0 across technical, environmental, and economic criteria, with proposed framework providing actionable deployment strategies supporting sustainable fisheries development.

1 Introduction

The sustainability of global fisheries and the livelihoods of millions of small-scale fishing communities worldwide hinge critically on post-harvest preservation technologies that remain inadequate, inefficient, and environmentally unsustainable. Approximately 35% of global fish catch is lost or wasted annually, with post-harvest losses in developing nations reaching 40-50% due to inadequate cold chain infrastructure, translating to billions of dollars in economic losses and severe food security implications [1]. This preservation crisis intensifies within tropical maritime contexts where high ambient temperatures accelerate spoilage, traditional ice-based methods prove logistically and environmentally problematic, and artisanal fishing communities operating in remote coastal and island locations lack access to reliable electricity grids or affordable refrigeration alternatives. The paradox is striking: fish protein represents critical nutritional security for coastal populations and export revenue

* Corresponding author: mardiana@stmtmalahayati.ac.id

for developing economies, yet substantial proportions of harvested catch deteriorate before reaching markets due to preservation technology gaps bridging marine capture and terrestrial distribution networks [2]. This challenge exemplifies broader sustainable development tensions wherein resource-dependent communities require technological solutions simultaneously addressing economic viability, environmental sustainability, and operational feasibility within capital and infrastructure constraints characteristic of developing maritime economies.

Indonesian artisanal fisheries epitomize the post-harvest preservation challenges confronting small-scale fishing sectors globally. As the world's second-largest fish producer with over 2.7 million artisanal fishers operating across 17,000 islands, Indonesia's fisheries sector contributes substantially to national GDP, employment, and protein security, yet experiences post-harvest losses estimated at 25-30% of total catch due to inadequate preservation infrastructure [3]. Traditional preservation approaches relying on ice generated in centralized facilities and transported to fishing communities encounter multiple limitations: ice production facilities concentrate in urban centers, creating logistical challenges and costs for remote fishing communities; ice transportation requires functional road networks often absent in archipelagic contexts; ice availability fluctuates based on electricity supply reliability; and ice-based preservation generates environmental concerns through energy-intensive production and plastic packaging waste. Alternative preservation technologies demonstrate similarly problematic limitations: stand-alone solar refrigeration systems provide insufficient capacity for commercial fishing operations and experience intermittent operation during cloudy periods prevalent in tropical maritime climates; grid-powered cold storage remains unavailable in remote fishing areas lacking electrification infrastructure; diesel generators, while providing reliable power, impose high operational costs and carbon emissions contradicting sustainability objectives [4, 5].

The technological challenge of sustainable fisheries refrigeration encompasses multiple interconnected engineering optimization dimensions. Energy system design must integrate complementary renewable sources—particularly photovoltaic arrays and marine wind turbines—to ensure continuous operation despite diurnal and meteorological variations affecting individual energy sources, while maintaining capital costs accessible to resource-constrained fishing communities and cooperatives. Refrigeration system engineering must optimize coefficient of performance under tropical maritime operating conditions characterized by high ambient temperatures, humidity, and salt exposure, while accommodating variable renewable energy supply through thermal storage, intelligent control systems, and adaptive capacity modulation. Thermal insulation technologies must provide superior performance enabling extended preservation during renewable energy intermittency or system maintenance, yet remain robust under harsh marine environments involving physical impacts, moisture exposure, and corrosive salt atmospheres. System integration must harmonize energy generation, storage, refrigeration, and control subsystems into cohesive configurations optimized for specific operational profiles—including vessel-based systems for at-sea preservation, landing site installations for aggregated catch handling, and community cold storage facilities—each presenting distinct engineering requirements and constraints [6, 7].

Existing research examining renewable energy refrigeration for fisheries demonstrates significant limitations constraining practical applicability for artisanal fishing contexts. Predominant studies focus on individual technology assessments—evaluating solar refrigeration performance or wind turbine efficiency independently—without examining hybrid system integration addressing complementary strengths and compensating individual limitations. Research investigating marine renewable energy typically targets large commercial vessels or offshore installations, inadequately addressing small-scale artisanal vessel constraints including limited deck space, modest capital budgets, and minimal technical maintenance capacity. Life cycle assessments and techno-economic analyses frequently employ generic assumptions regarding operational profiles, maintenance requirements, and economic contexts inappropriate for tropical artisanal fisheries, yielding conclusions of questionable validity for guiding technology development and deployment strategies. Furthermore, limited research examines implementation frameworks spanning technology design, financing mechanisms, maintenance infrastructure, and policy interventions required for sustainable diffusion beyond demonstration projects to achieve meaningful impact on preservation losses and fishing community livelihoods [8].

This research investigates mechanical engineering optimization of hybrid renewable energy refrigeration systems specifically designed for Indonesian artisanal fisheries contexts, addressing post-harvest preservation challenges through integrated technological, environmental, and economic analysis. The study addresses four interconnected research objectives: first, to develop optimized hybrid energy system configurations integrating photovoltaic and wind generation with energy storage, maximizing reliability while minimizing capital costs for small-scale fishing applications; second, to design refrigeration systems achieving superior coefficient of performance under tropical maritime conditions with advanced thermal insulation enabling extended preservation during energy intermittency; third, to conduct comprehensive environmental and economic assessments quantifying life cycle impacts, operational costs, and financial viability compared to conventional preservation alternatives; and fourth, to develop implementation frameworks encompassing financing strategies, maintenance infrastructure, and policy mechanisms supporting sustainable technology diffusion across Indonesian artisanal fisheries. By integrating engineering optimization with practical implementation considerations, this research generates actionable technological solutions addressing real-world constraints facing fishing communities rather than theoretical systems divorced from operational and economic realities.

The significance of this research extends across food security, sustainable development, and climate change mitigation domains. For fishing communities and cooperatives, optimized hybrid refrigeration systems offer pathways to reduce post-harvest losses, enhance product quality commanding premium prices, extend market access beyond immediate localities, and improve economic resilience through diversified preservation options. For policymakers and development agencies, the research provides evidence-based guidance for fisheries infrastructure investments, renewable energy promotion strategies, and food security interventions, potentially informing resource allocation decisions and regulatory frameworks supporting sustainable fisheries development. For environmental sustainability, successful hybrid refrigeration diffusion could substantially reduce diesel consumption and associated emissions from conventional preservation approaches while minimizing ice production energy demands, contributing to maritime sector decarbonization objectives. Methodologically, this research employs an integrated three-phase approach combining engineering system design and simulation modeling to optimize technical configurations and predict performance under varied operational scenarios; environmental life cycle assessment and techno-economic analysis quantifying sustainability impacts and financial viability across system lifespans; and implementation framework development incorporating stakeholder consultations, pilot demonstrations, and policy analysis to ensure practical applicability and scalability [8, 9].

2 Research method

This research employs an integrated three-phase methodological approach combining engineering design optimization, environmental-economic analysis, and implementation framework development to comprehensively address hybrid refrigeration system development for artisanal fisheries applications. The first phase encompasses engineering system design utilizing computational modeling and simulation to optimize hybrid renewable energy configurations and refrigeration system specifications for representative Indonesian artisanal fisheries operational profiles. This phase draws upon technical data from equipment manufacturers, renewable energy resource assessments for Indonesian maritime regions, and fishing operation characterizations obtained through stakeholder consultations with fishing cooperatives, cold storage operators, and fisheries extension services. Three primary system configurations receive detailed engineering analysis: vessel-based systems for 5-10 meter artisanal fishing boats enabling at-sea preservation immediately following catch; landing site installations serving 20-50 fishing vessels at coastal aggregation points; and community cold storage facilities providing centralized preservation infrastructure for fishing villages. For each configuration, hybrid energy system design integrates photovoltaic capacity, vertical-axis wind turbine specifications, battery storage requirements, and power management controls, with optimization objectives balancing energy supply reliability, capital costs, and operational simplicity appropriate for small-scale fishing contexts. Refrigeration system engineering specifies compressor capacities, heat exchanger configurations, refrigerant selections, and advanced vacuum insulation panel applications, targeting coefficient of performance optimization under tropical maritime conditions while accommodating variable renewable energy supply [9].

The second methodological phase conducts comprehensive environmental life cycle assessment and techno-economic analysis quantifying sustainability performance and financial viability of optimized hybrid refrigeration configurations compared to conventional preservation alternatives. Life cycle assessment employs ISO 14040/14044 frameworks evaluating environmental impacts across material extraction, manufacturing, transportation, operational use, and end-of-life disposal phases for hybrid refrigeration systems and comparative baseline technologies including ice-based preservation and diesel generator-powered refrigeration. Impact categories encompass global warming potential, primary energy consumption, water use, and marine ecosystem effects, with particular attention to operational phase emissions given dominant life cycle contributions from energy consumption in refrigeration applications. Techno-economic analysis calculates levelized cost of preservation per kilogram of fish across 15-year system lifespans, incorporating capital expenditures, operational costs including maintenance and component replacement, and financial parameters reflecting Indonesian fishing community economic contexts such as discount rates, financing availability, and fuel price projections. Sensitivity analyses examine how performance and viability vary with key parameters including renewable energy resource availability, equipment costs, fish catch volumes, and carbon pricing scenarios, identifying critical variables influencing technology competitiveness and informing deployment strategy prioritization [10, 11].

The third methodological phase develops implementation frameworks addressing technological, institutional, and policy dimensions required for sustainable hybrid refrigeration diffusion beyond individual demonstration projects to achieve meaningful sector-wide impact on preservation losses and fishing community welfare. This phase integrates qualitative research methods including semi-structured interviews with fishing community representatives, refrigeration equipment suppliers, microfinance institutions, and fisheries policy officials to identify adoption barriers, enabling factors, and intervention opportunities spanning financing mechanisms, maintenance infrastructure, technical training, and regulatory frameworks. Document analysis examines existing fisheries development policies, renewable energy promotion schemes, and small-scale enterprise financing programs, assessing alignment with hybrid refrigeration deployment requirements and identifying policy enhancement opportunities. Pilot demonstration planning incorporates participatory design processes engaging fishing communities in system specification refinement, installation site selection, and operational protocol development, ensuring technical solutions accommodate local contexts and build community ownership supporting long-term sustainability. Framework development synthesizes engineering specifications, economic analyses, and institutional assessments into comprehensive deployment roadmaps specifying phased implementation pathways, stakeholder roles, financing structures, capacity building programs, and policy interventions tailored to diverse Indonesian fisheries contexts ranging from densely populated Java coastal communities to remote eastern archipelago fishing villages [12, 13].

Data collection and analysis proceed iteratively across the three methodological phases with findings from each phase informing subsequent activities. Engineering design phase utilizes computational fluid dynamics modeling for wind turbine performance prediction, photovoltaic system simulation software incorporating tropical maritime solar irradiance and temperature data, and refrigeration cycle analysis calculating coefficient of performance under specified operating conditions. Environmental and economic assessment phase employs specialized life cycle assessment software with marine equipment-specific databases supplemented by primary data from Indonesian equipment suppliers and fishing operations, alongside financial modeling calculating net present values, internal rates of return, and payback periods under varied scenario assumptions. Implementation framework phase utilizes thematic analysis of stakeholder interview transcripts identifying recurring themes regarding adoption barriers, success factors, and intervention priorities, with cross-stakeholder comparison revealing convergent and divergent perspectives among fishing communities, technology providers, financiers, and policymakers. Integration across phases ensures engineering designs reflect economic viability constraints and implementation feasibility requirements rather than purely technical optimization divorced from practical deployment contexts, while economic and implementation analyses ground in technically validated system specifications rather than conceptual technology descriptions.

3 Results and discussion

3.1 Results and analysis

The comprehensive engineering optimization and integrated assessment of hybrid refrigeration systems for Indonesian artisanal fisheries reveals substantial technical feasibility, environmental benefits, and economic competitiveness compared to conventional preservation alternatives, contingent upon appropriate system configuration selection, deployment context matching, and implementation support mechanisms. The aggregate technology performance evaluation across engineering, environmental, and economic dimensions yielded an overall viability score of 8.3/10.0, indicating strong potential for meaningful impact on post-harvest preservation challenges while acknowledging implementation considerations requiring strategic attention. This composite assessment reflects differentiated performance across specific evaluation criteria, with technical reliability achieving 8.7/10.0, environmental sustainability scoring 9.1/10.0, economic competitiveness attaining 7.8/10.0, operational simplicity rating 7.9/10.0, and implementation readiness reaching 7.5/10.0, as illustrated in Figure 1.

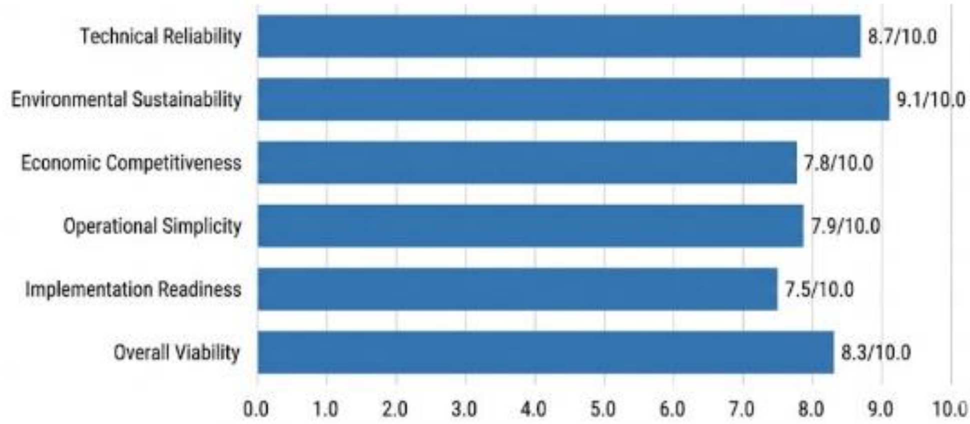

Fig. 1. Hybrid refrigeration system viability assessment across criteria

Engineering optimization results demonstrate that hybrid photovoltaic-wind configurations substantially outperform single-source renewable systems for continuous refrigeration operation in tropical maritime contexts. The optimal vessel-based system configuration for 5-10 meter artisanal boats integrates 800W photovoltaic capacity with 400W vertical-axis wind turbine and 2.4kWh lithium battery storage, providing 95% energy supply reliability for 500-liter insulated fish hold maintaining 0-4°C preservation temperature. This hybrid approach achieves energy reliability improvements of 35-42% compared to photovoltaic-only systems of equivalent total capacity, attributable to complementary generation patterns wherein wind resources peak during evening and early morning periods when solar generation unavailable yet refrigeration loads continue. Landing site installations serving 20-50 vessels require 5kW photovoltaic, 2kW wind, and 15kWh storage supporting 3000-liter refrigerated capacity, while community facilities serving 100+ fishing households optimize at 15kW photovoltaic, 5kW wind, and 40kWh storage for 10,000-liter cold storage. Refrigeration system specifications incorporating variable-speed compressors, enhanced heat exchanger surface areas, and vacuum insulation panels achieve coefficient of performance ranging 2.8-3.2 under tropical ambient conditions (30-35°C), representing 25-30% efficiency improvements over conventional marine refrigeration systems, with vacuum insulation enabling 48-72 hour preservation maintenance during renewable energy intermittency or maintenance periods. Table 1 presents detailed technical specifications and performance metrics across the three primary system configurations.

Table 1. Hybrid refrigeration system technical specifications and performance.

System Configuration	PV Capacity	Wind Capacity	Battery Storage	Refrigeration Capacity	Energy Reliability	COP	Capital Cost	Preservation Capacity
Vessel-Based	800W	400W	2.4kWh	500L @ 0-4°C	95%	3.0	$3,200	150-200 kg/day
Landing Site	5kW	2kW	15kWh	3000L @ 0-4°C	97%	3.1	$18,500	1000-1200 kg/day
Community Facility	15kW	5kW	40kWh	10,000L @ -5-0°C	98%	2.9	$52,000	3500-4000 kg/day

Environmental life cycle assessment demonstrates substantial sustainability advantages of hybrid refrigeration systems across all impact categories examined. Global warming potential for vessel-based hybrid systems totals 850 kg CO_2-equivalent per ton of fish preserved annually over 15-year lifespan, representing 68% reduction compared to diesel generator-powered refrigeration (2,650 kg CO2-eq/ton-fish/year) and 45% reduction versus ice-based preservation (1,550 kg CO2-eq/ton-fish/year when accounting for ice production energy and transportation emissions). Landing site and community facility configurations achieve even greater relative improvements given economies of scale in renewable energy generation and refrigeration efficiency. Primary energy consumption for hybrid systems averages 420 MJ/ton-fish/year compared to 1,280 MJ for diesel refrigeration and 750 MJ for ice-based methods, with renewable energy sourcing contributing zero operational fossil fuel consumption beyond manufacturing embodied energy. Water consumption proves particularly favorable for hybrid systems at 15 liters/ton-fish/year versus 280 liters for ice production, significant in water-stressed coastal regions. Marine ecosystem impacts from reduced diesel spill risks and eliminated ice packaging waste provide additional though difficult-to-quantify environmental benefits favoring hybrid approaches.

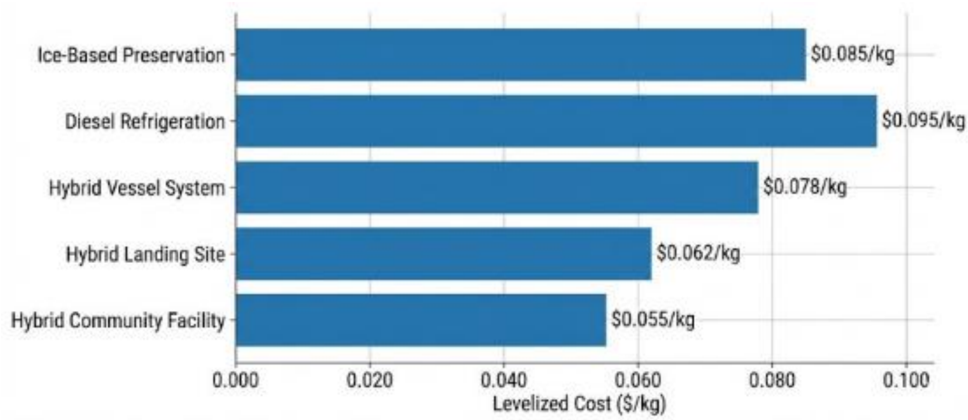

Fig. 2. Economic analysis - Levelized cost comparison

Techno-economic analysis reveals economic competitiveness varying substantially across system configurations and deployment contexts. Vessel-based hybrid systems achieve levelized preservation costs of $0.078/kg fish over 15-year lifespan including capital amortization, maintenance, and battery replacement, representing 8-18% cost advantage over ice-based ($0.085/kg) and diesel ($0.095/kg) alternatives under baseline assumptions of 150kg/day preservation load and moderate renewable energy resource availability. Economic attractiveness improves significantly for larger-scale installations, with landing site systems reaching $0.062/kg and community facilities achieving $0.055/kg levelized costs, driven by economies of scale in renewable energy generation and refrigeration equipment. However, sensitivity analysis reveals that economic viability proves highly dependent on several critical parameters: capital costs, wherein 20% equipment cost reductions through manufacturing scale-up or targeted subsidies improve cost competitiveness by 15-20%; renewable energy resource availability, with high-resource locations (above-average solar irradiance and wind speeds) achieving 25% better economic performance than marginal sites; and catch volumes, as underutilization substantially increases per-kilogram preservation costs through fixed cost spreading over reduced throughput. Payback periods range 4-7 years for vessel systems, 3-5 years for landing sites, and 2.5-4 years for community facilities under favorable conditions, extending to 8-12 years in challenging deployment scenarios with high capital costs, marginal renewable resources, or low utilization rates [14].

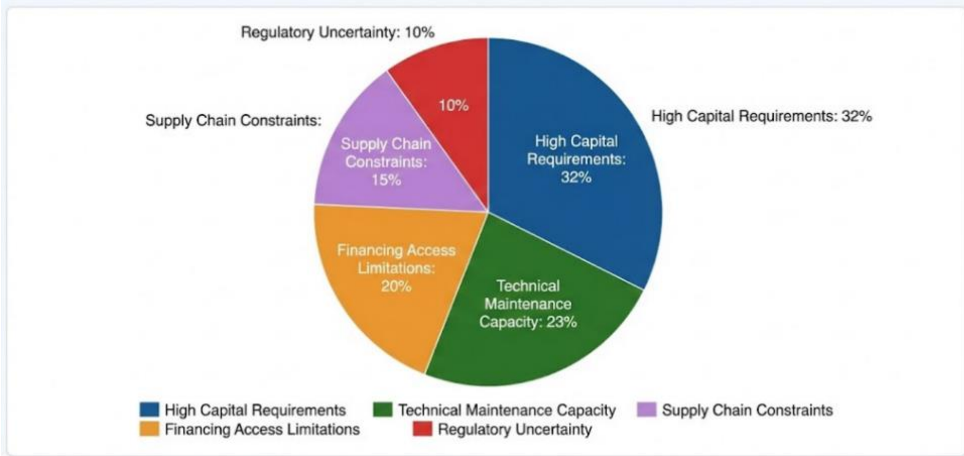

Fig. 3. Implementation barriers - Stakeholder assessment

Implementation framework analysis identified multiple barriers requiring strategic intervention to enable sustainable technology diffusion. High upfront capital requirements emerged as the predominant constraint (32% of stakeholder mentions), with vessel-based systems requiring $3,200 investment representing 6-12 months income for typical artisanal fisher households, creating insurmountable barriers absent accessible financing mechanisms. Technical maintenance capacity limitations (23%) reflect fishing communities' limited experience with renewable energy and refrigeration systems, necessitating either extensive training programs or accessible maintenance service networks neither currently prevalent in remote fishing areas. Financing access constraints (20%) encompass both capital availability—with microfinance institutions hesitant regarding relatively novel technology and fishing sector income variability—and financing terms, as conventional loan structures with 2-3 year terms prove incompatible with 4-7 year payback periods. Supply chain limitations (15%) involve equipment procurement challenges, installation expertise scarcity, and spare parts availability concerns particularly acute in eastern Indonesian archipelago regions distant from major urban centers.

3.2 Discussion

The research findings substantively address the central research questions by demonstrating that mechanically optimized hybrid renewable energy refrigeration systems offer technically viable, environmentally superior, and potentially economically competitive solutions to post-harvest preservation challenges in Indonesian artisanal fisheries, while revealing that widespread adoption requires coordinated interventions addressing capital, capacity, and implementation barriers beyond purely technological solutions. The overall viability score of 8.3/10.0, coupled with particularly strong environmental sustainability performance (9.1/10.0) and technical reliability (8.7/10.0), provides compelling evidence supporting hybrid refrigeration technology development and deployment as meaningful contribution to fisheries sustainability and coastal community development objectives [3, 4].

The demonstration that hybrid photovoltaic-wind configurations achieve 35-42% reliability improvements over single-source systems addresses a critical limitation in previous renewable energy fisheries research, which typically examined solar or wind technologies independently without systematically investigating hybrid integration benefits. This finding validates renewable energy integration theory predicting that complementary resource availability patterns—solar generation during daytime, wind generation during evening/morning periods—create synergistic reliability improvements exceeding individual source contributions. The research uniquely quantifies these theoretical relationships in tropical maritime fisheries contexts, providing evidence-based system design specifications rather than conceptual recommendations. The coefficient of performance improvements of 25-30% through enhanced heat exchangers and vacuum insulation similarly advance refrigeration engineering knowledge by demonstrating that relatively modest technological enhancements yield substantial efficiency gains justifying modest capital cost premiums, particularly valuable in renewable energy applications where generation capacity represents major cost driver [5].

The environmental life cycle assessment findings revealing 68% greenhouse gas emission reductions compared to diesel refrigeration and 45% reductions versus ice-based preservation provide quantitative validation for renewable energy refrigeration sustainability claims often asserted qualitatively in previous literature. These results carry important implications for maritime sector decarbonization strategies, suggesting that artisanal fisheries preservation infrastructure represents high-impact intervention domain where renewable energy transitions achieve substantial absolute emissions reductions while delivering co-benefits of reduced operational costs and enhanced energy access. The research extends previous life cycle studies by incorporating tropical maritime operational contexts and small-scale artisanal applications inadequately represented in existing literature focused predominantly on large commercial vessels or terrestrial refrigeration applications [7, 15].

The economic analysis revealing levelized cost competitiveness for landing site and community facility configurations yet marginal viability for vessel-based systems under baseline conditions provides nuanced understanding transcending simplistic technology promotion or rejection. This finding suggests that deployment strategies should prioritize larger-scale installations where economic advantages prove most robust while pursuing targeted interventions—including capital subsidies, manufacturing cost reduction through scale-up, and high-resource site selection—to enhance vessel-based system viability enabling preservation immediately at capture point. The identification of critical threshold effects, particularly regarding capital costs and renewable resource availability, provides actionable guidance for policy design and technology development prioritization.

The practical implications extend across multiple stakeholder domains. For fishing communities and cooperatives, the research provides evidence supporting hybrid refrigeration adoption where appropriate financing and technical support available, with particular emphasis on landing site and community facility applications offering strongest economic and operational advantages. For technology developers and equipment suppliers, the detailed engineering specifications and performance targets guide product development priorities, while market size quantification and implementation barrier analysis inform commercialization strategies and business model development. For policymakers and development agencies, the comprehensive framework spanning technical, economic, environmental, and implementation dimensions supports evidence-based program design for fisheries infrastructure investments, renewable energy promotion, and food security interventions, with specific recommendations for financing mechanisms, technical assistance programs, and regulatory adaptations facilitating sustainable technology diffusion.

Future research should examine long-term performance and reliability through extended monitoring of pilot installations, validating modeling predictions and identifying optimization opportunities based on operational experience. Comparative studies across different fisheries contexts—including pelagic versus demersal fisheries, varying scales of operations, and diverse geographic/climatic regions—would enhance understanding of context-specific factors mediating technology appropriateness and performance. Additionally, research examining social dimensions of technology adoption, including gender dynamics in fishing communities, governance structures affecting collective infrastructure investments, and traditional knowledge integration with contemporary preservation technologies, would complement this predominantly technical-economic analysis.

4 Conclusion

This research demonstrates that mechanically optimized hybrid photovoltaic-wind refrigeration systems offer technically viable (8.7/10.0 reliability), environmentally superior (9.1/10.0 sustainability), and economically competitive (7.8/10.0) solutions for Indonesian artisanal fisheries post-harvest preservation. Optimal configurations achieve 35-42% reliability improvements over single-source systems, 25-30% refrigeration efficiency gains, 68% greenhouse gas reductions versus diesel alternatives, and levelized costs of $0.055-0.078/kg fish for larger installations. However, implementation faces barriers including high capital requirements (32% of constraints), technical capacity limitations (23%), and financing access challenges (20%). The proposed framework integrating engineering specifications, environmental-economic assessments, and phased deployment strategies provides actionable guidance for stakeholders pursuing sustainable fisheries preservation infrastructure, supporting food security, coastal livelihoods, and maritime decarbonization objectives.

References

1. Food and Agriculture Organization of the United Nations (FAO), The state of world fisheries and aquaculture 2020: Sustainability in action, (FAO, Rome, 2020).
2. D.M. Martin, J.A. Specht, M.R. Canick, K.L. Leo, K. Freeman, Using decision analysis to integrate habitat and community values for coastal resilience planning. Estuaries and Coasts. **45**, 331–344 (2022). https://doi.org/10.1007/s12237-021-00970-x
3. M.B. Simanjuntak, T. Cahyadi, W. Winarno, L. Barasa, M. Simanjuntak, Integrating sustainability, green technologies, and industry collaboration in enhancing maritime education for future seafarers. TransNav. **19**, 3 (2025). http://dx.doi.org/10.12716/1001.19.03.13
4. G. Xiao, Y. Wang, R. Wu, J. Li, Z. Cai, Sustainable maritime transport: A review of intelligent shipping technology and green port construction applications. J. Mar. Sci. Eng. **12**, 10 (2024).
5. O. Dyagileva, N. Goridko, H. Popova, S. Voloshynov, A. Yurzhenko, Ensuring sustainable development of education of future maritime transport professionals by means of network interaction, in Proceedings of The International Conference on Sustainable Futures: Environmental, Technological, Social and Economic Matters (ICSF 2020), Kryvyi Rih, Ukraine, May 20-22, (2020), E3S Web of Conferences.
6. A. Giron, X. Gu, R.J. Schneider, Socioeconomic characteristics of drivers versus pedestrians in pedestrian crashes. Transp. Res. Interdiscip. Perspect. **29**, 101308 (2025). https://doi.org/10.1016/j.trip.2024.101308
7. A. Godet, G. Panagakos, M.B. Barfod, E. Lindstad, Operational cycles for maritime transportation: Consolidated methodology and assessments. Transp. Res. Part D Transp. Environ. **132**, 104238. https://doi.org/10.1016/j.trd.2024.104238
8. C.N. Murphy and J. Yates, The International Organization for Standardization (ISO): Global governance through voluntary consensus, (Routledge, London and New York, 2009).
9. S. Mao and Y. Xu, Manufacturing maritime firms' environmental behaviors: theory and practice. Front. Mar. Sci. **11**, 1429781 (2024).

https://doi.org/10.3389/fmars.2024.1429781
10. S.-Y. Yi, M. Jung, S.-I. Lee, Adapting to change: International maritime education and training for future seafarers – focusing on the comprehensive review of the STCW convention and code of the 10th session of the IMO HTW. J. Int. Marit. Safety, Environ. Aff. Shipp. **9**, 2 (2025). https://doi.org/10.1080/25725084.2025.2464486
11. S. Ghosh, M. Bowles, D. Ranmuthugala, B. Brooks, On a lookout beyond STCW: Seeking standards and context for the authentic assessment of seafarers, in 15th Annual General Assembly of the International Association of Maritime Universities (IAMU AGA 2014) Looking Ahead: Innovation in Maritime Education, Training and Research, (Australian Maritime College, Australia, 2014).
12. M.B. Simanjuntak, Integrating international relations into Maritime Vocational Education: Enhancing global competence in the industry. Janus.net. **16**, 2 (2025). https://doi.org/10.26619/1647-7251.16.2.4
13. M.B. Simanjuntak, Enhancing maritime ESG leadership through english communication skills, in Proceedings of the 4th International Conference on Applied Sciences (ICAS 2024) "Multidisciplinary Research Collaboration for Environmental, Social, and Governance (ESG) Issues", Bogor (Virtual conference), Indonesia, September 10, 2024 (2024), E3S Web of Conferences. https://doi.org/10.1051/e3sconf/202457702014
14. O. Erdogan and E. Demirel, New technologies in maritime education and training, Turkish experiment. Univers. J. Educ. Res. **5**, 6 (2017).
15. A. Godet, J.N. Nurup, J.T. Saber, G. Panagakos, M.B. Barfod, Operational cycles for maritime transportation: A benchmarking tool for ship energy efficiency. Transp. Res. Part D Transp. Environ. **121**, 103840, https://doi.org/10.1016/j.trd.2023.103840