

TOWARDS SUSTAINABLE FISHING: ENERGY CONVERSION EFFICIENCY OF BALI'S FISHING BOATS

Menuju Perikanan Berkelanjutan: Efisiensi Konversi Energi Kapal Penangkap Ikan di Bali

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ABSTRACT

Energy efficiency in small-scale fishing boats has become a critical issue due to their high dependence on fossil fuels, rising operational costs, and environmental impacts. Fishing boats less than 5 GT generally operate with fluctuating engine loads, potentially reducing energy conversion performance. This study aims to analyze the energy conversion efficiency of fishing boats operating in Bali Province. The research method uses a descriptive-quantitative approach through field studies. Primary data were obtained from measurements of fuel consumption, engine power and speed, electrical load, and operating duration at each stage of the boat's activities, while secondary data came from technical documents and operational logbooks. Efficiency analysis was conducted by comparing the input energy from diesel fuel and the output energy in the form of mechanical and electrical energy. The results show that energy consumption is dominated by the propulsion system, especially during the cruising phase. The total energy conversion efficiency is still relatively low, ranging from 22%–30%, and decreases during the maneuvering and fishing phases due to partial engine loads. These findings suggest that improvements in operational efficiency and engine maintenance are needed to reduce fuel consumption, reduce operational costs, and support the aspirations of small-scale fishing.

Keywords: Energy Efficiency, Small-Scale Fishing Boats, Energy Conversion, Fuel Consumption, Sustainable Capture Fisheries

ABSTRAK

Efisiensi energi pada kapal penangkap ikan skala kecil menjadi isu penting akibat tingginya ketergantungan terhadap bahan bakar fosil, meningkatnya biaya operasional, serta dampak lingkungan yang ditimbulkan. Kapal penangkap ikan berukuran kurang dari 5 GT umumnya beroperasi dengan beban mesin yang fluktuatif sehingga berpotensi menurunkan kinerja konversi energi. Penelitian ini bertujuan menganalisis efisiensi konversi energi pada kapal penangkap ikan yang beroperasi di Provinsi Bali. Metode penelitian menggunakan pendekatan

deskriptif–kuantitatif melalui studi lapangan. Data primer diperoleh dari pengukuran konsumsi bahan bakar, daya dan putaran mesin, beban listrik, serta durasi operasi pada setiap tahapan kegiatan kapal, sedangkan data sekunder berasal dari dokumen teknis dan logbook operasional. Analisis efisiensi dilakukan dengan membandingkan energi masukan dari bahan bakar diesel dan energi keluaran berupa energi mekanik serta energi listrik. Hasil penelitian menunjukkan bahwa konsumsi energi didominasi oleh sistem propulsi, terutama pada fase pelayaran. Tingkat efisiensi konversi energi total masih relatif rendah, berkisar antara 22%–30%, dan menurun pada fase manuver serta penangkapan akibat beban mesin parsial. Temuan ini menunjukkan bahwa peningkatan efisiensi operasional dan perawatan mesin diperlukan untuk menekan konsumsi bahan bakar, mengurangi biaya operasional, dan mendukung keberlanjutan perikanan tangkap skala kecil.

Kata Kunci: Efisiensi Energi, Kapal Penangkap Ikan Skala Kecil, Konversi Energi, Konsumsi Bahan Bakar, Perikanan Tangkap Berkelanjutan

INTRODUCTION

The capture fisheries sector is highly dependent on energy, particularly fossil fuels, to support boat operations, from the voyage to the fishing grounds, through fishing activities, and through onboard handling of the catch (Suryanto & Wudianto, 2017). Energy consumption on fishing boats is generally dominated by propulsion systems, electrical systems, and supporting equipment such as fishing gear and refrigeration systems (Bueno Lopez *et al.*, 2024; Nhat *et al.*, 2023; Nugraha, 2020). This high energy demand directly impacts operational costs, making efficient energy use and conversion key factors in improving the competitiveness and sustainability of fisheries businesses (Khusniawati & Palippui, 2020; Rizal *et al.*, 2021; Utomo, 2020; Ziliwu, 2022).

On the other hand, energy conversion systems on fishing boats still face various challenges, including low engine efficiency under partial load conditions, energy loss during the conversion of chemical fuel energy into mechanical and electrical energy, and limited utilization of energy-saving technologies (Banjarnahor *et al.*, 2017; Is & Ariyadi, 2023; Munar *et al.*, 2024; Nikmatullah *et al.*, 2023; Nugraha *et al.*, 2025). The dynamic operating conditions of fishing boats, such as variations in speed, maneuvering during fishing, and long sailing times, further increase the potential for energy inefficiencies (Alimuddin & Herudin, 2016; Pulungan *et al.*, 2019). If not managed properly, these inefficiencies not only increase fuel consumption but also accelerate equipment wear and tear and increase exhaust emissions.

Beyond economic aspects, environmental issues are also a significant concern in fishing boat operations (Fajriah *et al.*, 2019; Pramoda *et al.*, 2021). The combustion of fossil fuels in ship engines contributes to greenhouse gas emissions and marine air pollution, potentially impacting the quality of the aquatic environment and the sustainability of fisheries resources (Braun *et al.*, 2025; Curran *et al.*, 2024; Korberg *et al.*, 2021; Mäkelä *et al.*, 2025; Zulfiqar & Chang, 2023). With increasing demands for environmentally friendly and sustainable fishing practices, concrete efforts are needed to reduce energy consumption and emissions by improving the efficiency of onboard energy conversion systems (Abdullah-Al-Mahbub *et al.*, 2023; Bolbot *et al.*, 2020; Mursidi & Sarjito, 2025; Shagar *et al.*, 2017; Vahabzad *et al.*, 2021; Yeh *et al.*, 2022).

Given these conditions, studying energy conversion efficiency in fishing boat operations is crucial. This research is expected to provide a comprehensive overview of the performance of the energy conversion systems used, identify sources of energy loss, and evaluate opportunities for implementing efficiency improvement strategies. The results of this study are expected to not only contribute to reducing operational costs and emissions but also form the

basis for developing more efficient and sustainable energy conversion policies and technologies to support the capture fisheries sector.

METHODS

Material

The research subjects included 107 fishing boats, all of which were under 5 Gross Tonnage (GT) and actively operating in the waters and fishing ports of Bali Province. These boats used diesel fuel as the primary energy source for their propulsion and electrical systems. Supporting materials included boat technical data, including specifications for the main and auxiliary engines, propulsion systems, and electrical system capacity, served as the basis for the energy conversion efficiency analysis.

Tools

The equipment used in this study consisted of measuring instruments and supporting data collection devices. The main instruments included a fuel consumption meter, a tachometer for measuring engine speed (RPM), and a device for measuring the boat's power and electrical load. Additionally, observation sheets and recording devices were used to document the duration of each stage of the boat's operation, such as the voyage to the fishing grounds, fishing activities, and the voyage back to port. Supporting data was obtained from the boat's technical documents and available operational logbooks.

Research Design

This research was designed using a descriptive-quantitative approach with a field study method. The research location is in Bali Province, with the research implementation period from January 2025 to November 2025, so that the data collected can represent variations in boat operational conditions during various fishing activity periods. Sample selection was carried out using a purposive sampling method by considering the uniformity of boat size, type of propulsion system, operating patterns, and the availability of technical and operational data. This research design focused on the study of energy conversion efficiency on small-scale fishing boats predominantly used by fishermen in the Bali region.

Research Stage

The research phase began with the identification and selection of fishing boats that met the research criteria. The next phase involved collecting field data through direct measurements and observations during boat operations. Primary data collected included main and auxiliary engine fuel consumption, engine output, engine rpm, boat electrical load, and the duration of each operational phase. Secondary data was then collected from boat technical documents and operational logbooks. After all data was collected, validation and grouping of the data were carried out based on the boat's operational phase to facilitate further analysis.

Analysis Procedure

The analysis procedure in this study was carried out using a quantitative approach by calculating the input and output energy of fishing boats during operational activities. This procedure aimed to evaluate the performance of boat engines in converting the chemical energy of diesel fuel into useful mechanical energy for propulsion and electrical energy for onboard auxiliary systems under different operating conditions.

Input energy was defined as the total chemical energy supplied by diesel fuel during boat operation. It was determined based on directly measured fuel consumption data combined with the calorific value of diesel fuel and the duration of operation. Quantifying input energy allowed the determination of the total energy available for conversion within the engine system

during each operational phase and served as the baseline for assessing the effectiveness of energy conversion in fishing boats.

Output energy was defined as the useful energy produced by the engine and effectively utilized for boat propulsion and onboard electrical demands. It was calculated based on the effective engine power and operating duration at each stage of boat activity, including sailing, maneuvering, and fishing. The calculation of output energy enabled an assessment of how much of the supplied fuel energy was converted into productive work during boat operations (Nugraha *et al.*, 2022, 2024).

Energy conversion efficiency was then calculated as the ratio between useful output energy and fuel input energy and used as a key indicator of engine performance. The efficiency analysis was conducted for each operational stage to identify variations in energy conversion performance resulting from changes in engine load and operating patterns. This approach provided insight into the influence of operational characteristics and boat conditions on energy utilization efficiency.

To further evaluate fuel utilization performance, specific fuel consumption was calculated as an additional indicator, representing the amount of fuel consumed per unit of power produced by the engine. This parameter provided insight into the intensity of fuel use under different operating conditions, where lower values indicate more efficient engine operation.

In addition to efficiency assessment, a complementary energy loss analysis was performed to identify the proportion of input energy that was not converted into useful output energy. Energy losses represent energy dissipated in the form of heat, mechanical friction, and other inefficiencies within the propulsion engine, transmission system, and onboard electrical system. Identifying these losses is essential for determining dominant sources of inefficiency and potential areas for technical improvement.

The results of the analysis were then evaluated descriptively and comparatively and presented in the form of tables support interpretation and conclusion regarding energy consumption patterns and energy conversion efficiency in fishing.

RESULTS

The analysis shows that energy consumption patterns on fishing boats of less than 5 GT are significantly influenced by the boat's operational phase during a single fishing trip. During the voyage to the fishing grounds, boats operate for a relatively long average duration compared to other phases. Under these conditions, fuel consumption is highest, with engine loads tending to be stable and approaching optimal conditions. Consequently, this phase contributes the most to total energy consumption per trip, indicating that voyage activities are the dominant component of small-scale fishing boat energy use.

During the maneuvering and fishing activity phase, energy consumption is relatively lower than during the voyage phase. Operational duration during this phase is moderate, but engine loads tend to fluctuate due to changes in speed, boat maneuvers, and the use of auxiliary equipment during the fishing process. These partial and unstable load conditions cause greater variability in energy utilization efficiency, although their contribution to total energy consumption remains significant.

Furthermore, during the voyage back to port, energy consumption is at an intermediate level. Engine loads are relatively stable, but generally lower than during the voyage to the fishing grounds. This is influenced by the boat's loading conditions, more controlled speed patterns, and comparable distance traveled with less high power requirements than during the departure phase. Despite its smaller contribution, this phase still accounts for a significant portion of total energy consumption per trip.

Analysis of the ship's energy system load indicates that the main engine, as the primary propulsion system, is the most dominant component of the ship's total energy consumption. The main engine operates at medium to high load ranges and contributes the majority of energy requirements during boat operations. Meanwhile, the auxiliary engines contribute relatively little, primarily to support operational support systems such as pumps and additional mechanical equipment. The ship's electrical system, despite its relatively low power consumption, still contributes to total energy consumption, particularly during fishing activities and the use of navigation and lighting equipment.

Overall, these results indicate that energy consumption on fishing boats is dominated by propulsion requirements, particularly during the voyage phase. Variations in engine load and operating characteristics at each stage of activity are the main factors influencing the distribution of energy consumption. These findings underscore the importance of optimizing operating patterns and engine load management as key strategies for improving energy efficiency on small-scale fishing boats. Details regarding the OHS equipment used by QC can be seen in Table 1 and Table 2.

Table 1. Energy Consumption Pattern of Fishing Boats at Each Operational Stage

Operational Stage	Average Operating Duration (h/trip)	Fuel Consumption (L/h)	Relative Energy Consumption (%)	Engine Load Characteristic
Sailing to fishing ground	2.5 – 4.0	3.5 – 5.0	45 – 55	Stable load, near optimal
Maneuvering and fishing activities	2.0 – 3.5	2.0 – 3.5	25 – 30	Fluctuating, partial load
Sailing back to port	2.0 – 3.5	3.0 – 4.5	20 – 25	Stable, medium load

Table 2. Average Energy System Load of Fishing Boats

Energy System Component	Operating Load Range	Contribution to Total Energy Consumption (%)
Main engine (propulsion)	60 – 85% of capacity	85 – 90
Auxiliary engine	5 – 10% of capacity	5 – 8
Electrical system	2 – 5 kW	3 – 7

DISCUSSION

Operational Characteristics of Fishing Boats

Field observations indicate that fishing boats operating in Bali Province under 5 GT are dominated by small-scale boats with low to medium-power diesel engine-based propulsion systems (Figure 1). These engines are generally used as the main propulsion system and as a source of energy to meet the boat's electrical system needs. The operating pattern adopted by most boats is one-day fishing, where the boat departs from port in the morning, fishes in the surrounding waters, and returns to port the same day. This pattern reflects the limitations of boat capacity, engine power, and on-board catch storage facilities.

The operational activities of fishing boats can be divided into several main stages: the voyage to the fishing grounds, maneuvering and fishing activities, and the voyage back to port. During the voyage phase, the engine operates relatively stably with a more constant load to maintain boat speed. Conversely, during the maneuvering and fishing phase, engine load tends to fluctuate due to changes in boat speed, direction, and fishing gear operation. These load

fluctuations cause the engine to frequently operate at partial load conditions, which are technically less than optimal in terms of energy conversion efficiency.



Figure 1. Small-scale fishing vessel activities in Bali

The duration and intensity of each operational phase show significant variation between boats, influenced by several key factors. Weather conditions and wave height play a significant role in determining the distance and travel time to the fishing grounds. Furthermore, the distance of the fishing grounds from the port and the type of fishing gear used also influence the length of operation and energy consumption patterns. Boats with more distant fishing grounds or using gear that requires intensive maneuvering tend to have higher and more unstable energy consumption patterns.

In terms of electrical systems, most fishing boats use simple electrical installations that serve for lighting, operating fishing aids, and basic navigation equipment. The electrical load used is relatively small, but it fluctuates and is highly dependent on the boat's operational phase. During fishing, electricity demand generally increases, while on the voyage back to port, the electrical load tends to decrease. This fluctuation in electrical load indirectly affects engine workload, especially on boats without adequate energy management systems.

These operational conditions cause significant variations in engine load throughout the boat's operating cycle. Engines that frequently operate under suboptimal load conditions can potentially experience decreased energy conversion performance, increased specific fuel consumption, and increased exhaust emissions. Therefore, the operational characteristics of fishing boats are important factors to consider in energy conversion efficiency studies, as they directly affect energy system performance and the boat's overall operational efficiency.

Based on Table 1, it can be seen that the greatest energy consumption on fishing boats occurs during the voyage to the fishing grounds, accounting for more than half of the total energy consumption per trip. This condition is closely related to the high and continuous need for propulsion power to maintain boat speed while facing hydrodynamic resistance during the voyage. During this phase, the main engine operates relatively stably at a certain speed, so despite high fuel consumption, the energy conversion process occurs at conditions close to the optimal operating point.

Conversely, during the maneuvering and fishing activity phase, absolute fuel consumption is lower than during the voyage phase. However, the engine operating characteristics during this phase exhibit significant load fluctuations due to changes in speed, boat direction, and fishing gear operation. These fluctuations cause the engine to frequently operate at partial load and below optimal conditions, resulting in decreased energy conversion efficiency. Therefore, despite the smaller volume of fuel used, energy utilization during this phase is relatively less efficient.

Furthermore, Table 2 shows that the propulsion system is the primary energy-consuming component on fishing boats, contributing significantly more than the auxiliary engine and electrical systems. The dominance of energy consumption by the main engine confirms that propulsion performance is a key determinant of a boat's overall energy efficiency. Although the energy contribution from the auxiliary engines and electrical systems is relatively small, the operation of these auxiliary systems still places an additional load on the main engine, especially during partial operation, and can indirectly impact energy conversion efficiency.

These findings indicate that efforts to improve energy efficiency on small-scale fishing boats should focus on managing the load on the main engine and optimizing boat operating patterns. More efficient speed management, reducing load fluctuations during maneuvers, and controlling the use of auxiliary systems have the potential to increase energy conversion efficiency while reducing fuel consumption. Therefore, appropriate energy efficiency strategies not only reduce operational costs but also contribute to the sustainable operation of fishing boats.

Energy Conversion Efficiency on Fishing Boats

Energy conversion efficiency analysis results indicate that the performance of energy systems on fishing boats remains at a relatively low efficiency level and exhibits significant variation between boats. This variation reflects differences in engine technical conditions, operating patterns, and energy use management during fishing activities. In general, energy conversion efficiency is strongly influenced by the match between the boat's operating characteristics and the engine's optimal operating point.

The highest energy conversion efficiency is generally achieved during the cruise phase at constant speed, when the main engine operates at a load close to its optimal capacity. Under these conditions, the fuel combustion process is more stable, and the fuel's chemical energy can be converted into mechanical energy more effectively. Conversely, under operating conditions with low or fluctuating loads, such as during maneuvering and fishing activities, energy conversion efficiency decreases significantly. This is due to the engine operating outside its optimal operating range, resulting in an increase in specific fuel consumption that is not offset by a comparable power output.

The operational characteristics of small-scale fishing boats, which tend to experience rapid changes in speed and load, are a major factor contributing to low energy conversion efficiency. Main engines on ships are often used not only for propulsion but also as a power source for electrical systems and auxiliary equipment. This adds complexity to the engine load and increases the potential for energy inefficiency, especially on ships lacking adequate load regulation or energy management systems.

In addition to operational factors, variations in energy conversion efficiency are also influenced by the engine's technical condition, such as its age, component wear, and the quality and frequency of maintenance. Older engines with suboptimal maintenance tend to experience decreased combustion performance and increased energy losses in the form of heat and friction. Conversely, ships with well-maintained engines and relatively stable operation exhibit higher and more consistent energy conversion efficiency.

The match between engine power and the ship's operational needs is also a critical factor in determining energy conversion efficiency. Engines with overpowering power for the ship's size and operating pattern tend to operate more frequently at partial load, resulting in reduced efficiency. Conversely, engines with power appropriate to the ship's characteristics and operational needs allow the engine to operate closer to its optimal operating point. These findings indicate that increasing energy conversion efficiency on fishing boats depends not only on engine technology, but also on selecting the right engine specifications and managing efficient operating patterns.

Energy Loss Analysis in Fishing Boat Systems

Energy loss analysis results indicate that most of the energy generated from the fuel combustion process in the main engine is not fully converted into effective mechanical energy for boat propulsion. The largest energy losses occur as waste heat through exhaust gases and the engine cooling system, a common characteristic of conventional diesel engines. In fishing boats, this energy loss tends to be more significant due to engine operating conditions that often fall outside of optimal operating conditions.

In addition to heat loss, energy loss also occurs due to mechanical friction in engine components and transmission systems. Friction in shafts, bearings, and the power transmission system causes some mechanical energy to be dissipated before it can be effectively utilized to drive the propeller. On boats with less than optimal maintenance, this friction level tends to increase, increasing energy losses and reducing the overall efficiency of the propulsion system.

Energy losses are also influenced by a mismatch between engine power output and actual requirements during boat operations. During maneuvering and fishing phases, engines often operate at partial loads with high fluctuations. This condition results in less efficient fuel combustion and increases specific fuel consumption. As a result, even though the power output is relatively small, energy loss in the form of heat and emissions remains high, reducing energy conversion efficiency.

The use of the main engine as the primary energy source for both propulsion and the electrical system also contributes to energy loss. The additional load from the electrical system and auxiliary equipment, even if relatively small, can affect engine load stability, especially on small-scale boats. Without an adequate energy management system, these load fluctuations increase the potential for energy loss and accelerate engine performance degradation.

This analysis shows that energy loss on fishing boats is caused not only by limited engine technology but also by inefficient operating patterns and energy management. Therefore, efforts to reduce energy loss need to focus on improving engine maintenance quality, managing more stable operating loads, and optimizing the use of support systems. By reducing energy loss, the energy conversion efficiency of small-scale fishing boats can be significantly improved, ultimately resulting in reduced fuel consumption and increased operational sustainability.

Technical Implications and Recommendations for Efficiency Improvement

The results of a study on energy conversion efficiency in fishing boats indicate that low efficiency is not solely due to limitations in engine technology but is also influenced by onboard operating patterns and energy management. The technical implications of these findings indicate that there is still significant room for optimization in energy efficiency in small-scale boats through relatively simple and applicable technical approaches for fishermen.

One key technical implication is the need to manage the main engine load to approach its optimal operating point. Engines that frequently operate at partial and fluctuating loads have been shown to experience a significant decrease in energy conversion efficiency. Therefore, managing a more stable boat speed during voyages and reducing unnecessary engine rpm changes during maneuvers can be initial strategies for improving energy efficiency. This approach is relatively easy to implement without requiring significant technological investment.

From a technical perspective, engine maintenance is a key factor in maintaining energy conversion performance. Routine maintenance such as fuel system cleaning, injector adjustments, and cooling and lubrication system inspections can reduce energy losses due to incomplete combustion and mechanical friction. Boats with well-maintained engines exhibit higher energy conversion efficiency and lower fuel consumption, thus directly reducing operational costs.

Furthermore, the use of electrical systems and auxiliary equipment needs to be managed more efficiently. Although the contribution of electrical energy to total energy consumption is relatively small, simultaneous and uncontrolled operation of equipment can increase the load on the main engine, especially during partial operation. Timing the use of electrical equipment and selecting equipment with low power consumption has the potential to improve overall energy efficiency.

In the medium term, technical recommendations can also be directed at adjusting engine specifications to the actual operational needs of the boat. Engines with excessive power for boats tend to operate below their optimal capacity, reducing energy conversion efficiency. Therefore, selecting engine power appropriate to the boat size and fishing operation pattern is a crucial aspect in improving energy efficiency while extending engine life.

Table 3 shows that the highest energy conversion efficiency is achieved during the voyage to the fishing grounds, when the main engine operates at a load range close to its optimal capacity. Under these conditions, the combustion process is more stable and energy losses are relatively small. Conversely, the lowest efficiency occurs during the maneuvering and fishing activity phases, characterized by engine load fluctuations and partial load operation.

The average overall energy conversion efficiency of fishing boats remains relatively low, indicating that a significant portion of the fuel energy is not being optimally utilized. This finding corroborates previous analyses that suggest that energy efficiency improvements need to focus on stabilizing engine loads, improving maintenance quality, and managing the use of support systems. With the implementation of appropriate technical recommendations, the energy conversion efficiency of small-scale fishing boats has the potential to be significantly improved, thereby supporting reduced fuel consumption, reduced operational costs, and increased sustainability in the capture fisheries sector.

Table 3. Energy Conversion Efficiency of Fishing Boats

Operational Stage	Engine Load Range (% of capacity)	Energy Conversion Efficiency (%)	Operational Characteristics
Sailing to fishing ground	70 – 85	28 – 35	Stable load, near optimal
Maneuvering and fishing activities	30 – 60	18 – 25	Fluctuating, partial load
Sailing back to port	60 – 80	25 – 32	Relatively stable load

Implications of Energy Conversion Efficiency for Operational Costs and the Environment

Low energy conversion efficiency in fishing boats has a direct impact on increased fuel consumption and the high operational costs borne by fishermen. On small-scale boats, fuel is the largest cost component in the daily operational cost structure. When engines operate under suboptimal load conditions and experience high energy losses, specific fuel consumption increases without a corresponding increase in fishing productivity. This condition leads to decreased fishing efficiency and narrows fishermen's profit margins.

The operating patterns of boats which tend to be daily (one-day fishing), make fishermen highly sensitive to fuel price fluctuations and changes in energy efficiency. Low energy conversion efficiency means fishermen must incur higher costs for each fishing trip, while catches do not always increase proportionally. Conversely, improving energy efficiency through engine load management, better engine maintenance, and efficient operating patterns has the potential to reduce fuel consumption per trip. These savings can increase fishermen's net income and strengthen the economic sustainability of small-scale fishing businesses.

In addition to its economic impact, energy conversion efficiency also has important environmental implications. The combustion of fossil fuels in marine engines is a major source of exhaust emissions, including carbon dioxide (CO₂), nitrogen oxides (NO_x), and particulates, which contribute to marine air pollution and climate change. Low energy conversion efficiency results in higher exhaust emissions per unit of energy or per unit of catch, increasing pressure on coastal marine environments.

Increasing energy conversion efficiency allows for reduced fuel consumption without reducing boat operational intensity. This significantly reduces exhaust emissions and the potential for marine air pollution. This positive impact is particularly relevant for Bali's waters, which have high ecological and tourism value, requiring sustainable marine environmental quality maintenance. Efforts to improve energy efficiency in fishing boats align with the principles of sustainable fisheries and support environmentally friendly marine resource management policies.

Overall, energy conversion efficiency not only plays a role in reducing fishermen's operational costs but is also a crucial instrument in mitigating the environmental impacts of fishing activities. Therefore, improving energy efficiency in small-scale fishing boats should be viewed as an integrated strategy that integrates economic and environmental aspects. This approach is expected to encourage the sustainability of capture fisheries businesses while supporting long-term marine ecosystem protection efforts.

Policy Implications for Regional Governments and Fishermen

The results of the study on energy conversion efficiency in fishing boats provide important policy implications for regional governments in formulating sustainable capture fisheries management strategies. Regional governments should consider energy efficiency as an indicator of the operational performance of small-scale fishing boats, given its close relationship to operational costs, fisher welfare, and environmental impact. Policies that encourage increased energy efficiency have the potential to provide direct economic benefits for fishers while supporting emission reduction targets in the marine and fisheries sector.

One policy implication that can be implemented is strengthening technical assistance programs for fishermen, particularly regarding efficient engine operation and routine maintenance. Regional governments can facilitate technical training on engine load management, efficient boat speed regulation, and the wise use of auxiliary equipment. A structured and sustainable training program is expected to raise fishermen's awareness of the importance of energy efficiency and encourage changes in operational behavior in the field.

In addition, regional governments can consider incentive policies for fishermen who implement energy-efficient operational practices. These incentives could include assistance with engine maintenance, spare parts subsidies, or easier access to supporting technology that improves energy efficiency. An incentive approach is considered more effective than a purely regulatory approach, especially for small-scale fishers who have limited capital and access to technology.

From a fishing fleet planning perspective, the results of this study also provide a basis for local governments to formulate policies to standardize engine specifications for fishing boats. Adjusting engine power to actual boat operational needs should be considered to avoid the use of excessively powerful engines, which could potentially reduce energy efficiency. This policy can be integrated into the boat licensing process or engine procurement assistance programs for fishermen.

For fishers, the findings of this study emphasize the importance of energy management as part of a strategy to increase fishing efficiency. Fishermen need to be encouraged to adopt more stable operating patterns, perform routine engine maintenance, and efficiently manage the use of support systems. By increasing energy conversion efficiency, fishers have the

potential to reduce fuel consumption, reduce operational costs, and increase net income without having to increase fishing intensity.

Overall, the implications of policies aimed at improving energy conversion efficiency on fishing boats require synergy between local governments and fishers. Local governments act as facilitators and regulators, while fishers are the primary actors in implementing efficient operational practices. This synergy is expected to encourage the realization of more energy-efficient, environmentally sustainable, and economically competitive capture fisheries, especially in the Bali Province.

CONCLUSION

This study shows that the energy conversion efficiency of fishing boats of less than 5 GT operating in Bali Province is still relatively low and varies between boats, which is mainly influenced by operational characteristics, energy usage patterns at each operational stage, and the technical condition of the engines used. The greatest energy consumption occurs during the voyage phase to and from the fishing grounds, while during the maneuvering and fishing phases, although fuel consumption is relatively lower, energy conversion efficiency tends to decrease due to engine operation at partial and fluctuating loads. The analysis results also indicate that the propulsion system is the main energy-absorbing component of fishing boats with low efficiency mainly caused by engine operation that is not at its optimal working point, lack of engine maintenance, and a mismatch between engine power and boat operational needs, which ultimately has a direct impact on increasing fishermen's operational costs and potentially increasing exhaust emissions. Therefore, increasing the efficiency of energy conversion on small-scale fishing boats needs to be a concern in the management of capture fisheries, both through the implementation of more efficient operational management by fishermen, such as regulating boat speed, stabilizing engine loads, and routine engine maintenance, as well as through policy support from local governments in the form of technical assistance, training on efficient engine operation, and the provision of incentives or technical support. In addition, further research is needed to examine the potential for implementing energy-saving technologies, including more efficient propulsion systems and the integration of alternative energy on small-scale fishing boats, and to deepen understanding of the relationship between energy efficiency and catch productivity to support the formulation of sustainable and evidence-based fisheries policies.

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REFERENCES

- Abdullah-Al-Mahbub, M., Towfiqul Islam, A. R. M., Alam, E., & Asha, M. R. (2023). Sustainable solar energy potential on marine passenger ships of Bay of Bengal: A way of reducing carbon dioxide emissions and disaster risk reduction. *Energy Exploration and Exploitation*, 41(5). <https://doi.org/10.1177/01445987231173097>
- Alimuddin, A., & Herudin, H. (2016). Analisa efisiensi konsumsi energi listrik pada kapal motor penumpang nusa mulia. *Setrum: Sistem Kendali-Tenaga-Elektronika-Telekomunikasi-Komputer*, 3(1). <https://doi.org/10.36055/setrum.v3i1.499>
- Banjarnahor, D. A., Hanifan, M., & Budi, E. M. (2017). Design of hybrid solar and wind energy harvester for fishing boat. *IOP Conference Series: Earth and Environmental Science*, 75(1), 012007. <https://doi.org/10.1088/1755-1315/75/1/012007>

- Bolbot, V., Trivyza, N. L., Theotokatos, G., Boulougouris, E., Rentizelas, A., & Vassalos, D. (2020). Cruise ships power plant optimisation and comparative analysis. *Energy*, 196. <https://doi.org/10.1016/j.energy.2020.117061>
- Braun, A., Gierenz, N., Braun, S., Kubach, H., Bernhardt, S., Prehn, S., Müller, M., Engelmeier, L., Fehlemann, L., Steffen, M., Baufeld, T., Neuhaus, G., Müller, K., & Mohr, H. (2025). Aspects of ammonia as green fuel for propulsion systems of inland water vessels. *Energy Technology*, 13(2), 2301648. <https://doi.org/10.1002/ente.202301648>
- Bueno Lopez, M., Rengifo Ordoñez, M. T., Chacón Campo, D., Tocancipá-Falla, J., & Osorio Arias, A. (2024). Energy Transition for rural development: A preliminar case study in Colombia for improving artisanal fishing. *Scientia et Technica*, 29(02), 89–96. <https://doi.org/10.22517/23447214.24944>
- Curran, S., Onorati, A., Payri, R., Agarwal, A. K., Arcoumanis, C., Bae, C., Boulouchos, K., Dal Forno Chuahy, F., Gavaises, M., Hampson, G. J., Hasse, C., Kaul, B., Kong, S. C., Kumar, D., Novella, R., Pesyridis, A., Reitz, R., Vaglieco, B. M., & Wermuth, N. (2024). The future of ship engines: Renewable fuels and enabling technologies for decarbonization. *International Journal of Engine Research*, 25(1). <https://doi.org/10.1177/14680874231187954>
- Fajriah, F., Mustafa, A., Rais, M., Isamu, K. T., & Arami, H. (2019). Improved level of environmentally friendly boat liftnet fishing gear through Underwater Dip Light Technology (UFL +). *IOP Conference Series: Earth and Environmental Science*, 348(1). <https://doi.org/10.1088/1755-1315/348/1/012021>
- Is, N. P., & Ariyadi, T. (2023). The use of alternative energy as a driver fishing boat. *Buletin Ilmiah Sarjana Teknik Elektro*, 5(4), 438–447. <https://doi.org/10.12928/biste.v5i4.9127>
- Khusniawati, F., & Palippui, H. (2020). Analisis perawatan injector akibat penyumbatan bahan bakar pada main engine kapal. *Zona Laut : Jurnal Inovasi Sains Dan Teknologi Kelautan*. <https://doi.org/10.20956/zt.v1i2.10832>
- Korberg, A. D., Brynolf, S., Grahn, M., & Skov, I. R. (2021). Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. *Renewable and Sustainable Energy Reviews*, 142, 110861. <https://doi.org/10.1016/j.rser.2021.110861>
- Mäkelä, M., Niemi, S., Nuortila, C., & Nyystilä, L. (2025). Applicability of hydrogen fuel for a cruise ship. *Clean Technologies*, 7(1), 1–10. <https://doi.org/10.3390/cleantechnol7010006>
- Munar, M. F., Espiritu Diokno, S., Cruzate-Tayo, R. J., & Andrew Ravelas Tria, L. (2024). Electrification of boats for small-scale rural fishing. *2024 IEEE Transportation Electrification Conference and Expo, Asia-Pacific, ITEC Asia-Pacific 2024*, 589–593. <https://doi.org/10.1109/ITECAsia-Pacific63159.2024.10738648>
- Mursidi, M., & Sarjito, A. (2025). Implementation strategy of ship engine maintenance management system to improve operational efficiency. *Jurnal Aplikasi Pelayaran dan Kepelabuhanan*, 15(2), 201–214. <https://doi.org/10.30649/japk.v15i2.137>
- Nhat, N. D., Tien, D. T., Van Dan, T., Quynh Tram, N. D., Lich, N. Q., Phuc, H. D., & Phuoc, N. N. (2023). The effectiveness of light emitting diode (LED) lamps in the offshore purse seine fishery in Vietnam. *Aquaculture and Fisheries*, 8(5), 551–557. <https://doi.org/10.1016/j.aaf.2022.01.005>
- Nikmatullah, M. I., Baharuddin, B., Zulkifli, Z., Alwi, M. R., & Sitepu, A. H. (2023). Modification of traditional fishing boat outriggers into a simple electric power plant. *Indonesian Journal of Maritime Technology*, 1(2), 65–70. <https://doi.org/10.35718/ismatech.v1i2.1050>
- Nugraha, I. M. A. (2020). Penggunaan pembangkit listrik tenaga surya sebagai sumber energi pada kapal nelayan: Suatu kajian literatur. *Jurnal Sumberdaya Akuatik Indopasifik*, 4(2), 101–110. <https://doi.org/10.46252/jsai-fpik-unipa.2020.vol.4.no.2.76>

- Nugraha, I. M. A., Desnanjaya, I. G. M. N., & Pramana, P. I. (2024). Generator load optimization management on tourist ships in Labuan Bajo. *Jurnal RESISTOR (Rekayasa Sistem Komputer)*, 7(3), 144–152. <https://doi.org/https://doi.org/10.31598/jurnalresistor.v7i3.1766>
- Nugraha, I. M. A., Desnanjaya, I. G. M. N., & Pramana, P. I. (2025). Optimization of safety and reliability of electrical systems of tourist ships in Labuan Bajo through fmea. *Kapal: Jurnal Ilmu Pengetahuan Dan Teknologi Kelautan*, 22, 85–93. <https://doi.org/https://doi.org/10.14710/kapal.v22i2.69260>
- Nugraha, I. M. A., Luthfiani, F., Sotayaramadhani, G., & Idrus, M. A. (2022). Analisis konsumsi energi listrik dan bahan bakar kmp. xyz dalam mendukung operasi pelayaran di Nusa Tenggara Timur. *Jurnal Sumberdaya Akuatik Indopasifik*, 6(4). <https://doi.org/10.46252/jsai-fpik-unipa.2022.vol.6.no.4.220>
- Pramoda, R., Muliawan, I., Apriliani, T., Witomo, C. M., & Yulisti, M. (2021). Competency of fishing boat crew from Indonesia in the framework of standards of training, certification, and watchkeeping for fishing vessel personnel 1995 (STCW-F 1995). *IOP Conference Series: Earth and Environmental Science*, 860(1). <https://doi.org/10.1088/1755-1315/860/1/012088>
- Pulungan, A. B., Asnil, A., Hidayat, R., Sardi, J., & Islami, S. (2019). Pemanfaatan motor listrik bertenaga energi matahari sebagai penarik jaring pada kapal nelayan. *Jurnal Pendidikan Teknologi Kejuruan*, 2(3). <https://doi.org/10.24036/jptk.v2i3.5723>
- Rizal, D. R., Purwangka, F., Imron, M., & Wisudo, S. H. (2021). Kebutuhan bahan bakar minyak pada kapal perikanan di pelabuhan perikanan nusantara palabuhanratu. *ALBACORE Jurnal Penelitian Perikanan Laut*, 5(1). <https://doi.org/10.29244/core.5.1.029-042>
- Shagar, V., Jayasinghe, S. G., & Enshaei, H. (2017). Effect of load changes on hybrid shipboard power systems and energy storage as a potential solution: A review. *Inventions*, 2(3), 1–22. <https://doi.org/10.3390/inventions2030021>
- Suryanto, S., & Wudianto, W. (2017). Model estimasi konsumsi bahan bakar kapal ikan huhate dan rawai tuna. *Jurnal Penelitian Perikanan Indonesia*, 23(2). <https://doi.org/10.15578/jppi.23.2.2017.99-110>
- Utomo, B. (2020). Hubungan antara konsumsi bahan bakar dengan berbagai perubahan kecepatan pada motor diesel penggerak kapal. *Jurnal Rekayasa Mesin*, 15(2). <https://doi.org/10.32497/jrm.v15i2.1957>
- Vahabzad, N., Mohammadi-Ivatloo, B., & Anvari-Moghaddam, A. (2021). Optimal energy scheduling of a solar-based hybrid ship considering cold-ironing facilities. *IET Renewable Power Generation*, 15(3). <https://doi.org/10.1049/rpg2.12015>
- Yeh, C. K., Lin, C., Shen, H. C., Cheruiyot, N. K., Nguyen, D. H., & Chang, C. C. (2022). Real-time energy consumption and air pollution emission during the transpacific crossing of a container ship. *Scientific Reports*, 12(1). <https://doi.org/10.1038/s41598-022-19605-7>
- Ziliwu, B. W. (2022). Studi konsumsi bahan bakar solar pada mesin induk km. fortuna. *Machine: Jurnal Teknik Mesin*, 8(2). <https://doi.org/10.33019/jm.v8i2.3015>
- Zulfiqar, K., & Chang, Y.-C. (2023). Climate change and maritime law: A review of IMO governance mechanism. *J. of Atmosphere and Oceanography Environment*, 11(1), 9511. <https://doi.org/10.18686/jaoe.v11i1.9511>