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The influence of battery-powered engine on the reduction of carbon dioxide production from fishing boats

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Abstract

Several technologies are currently being applied in the maritime industry to reduce greenhouse gas (GHG) emissions. An example is the implementation of an electric propulsion system with a battery charged using a renewable energy source. Meanwhile, it is important to analyze the energy demand and the quantity of emissions reduced in a vessel after installing this system. Therefore, this study focused on analyzing the energy demand and emissions produced on fishing boats, specifically the "Sandeq" fishing boats in West Sulawesi. The primary objective was to quantify the carbon dioxide (CO_2) emissions reduced after the conventional engine of the vessel was replaced with an electric propulsion system. Moreover, the energy demand of the boat was estimated by analyzing the daily speed, length of voyage, and engine capacity. The results showed that six batteries were required to provide the power needed for daily operation. Furthermore, the electric propulsion system was able to reduce CO_2 emission by 7.94 tons annually per ship, leading to the reduction of fuel consumption and emission taxes to approximately 10 million Rupiah annually. These results were expected to encourage stakeholders to promote the transition from conventional diesel engines to electric-powered engines.

Keywords: CO_2 emission; fishing boats; battery propulsion; West Sulawesi; boat electrification.

I. Introduction

The shipping industry contributes approximately 2.3 % to global carbon emissions [1] and this shows that the maritime sector has a significant effect on the environment on a global level [2]. The sector would have been ranked the sixth-largest carbon dioxide emitter in the world if it were a nation, surpassing countries such as Brazil and Germany [3]. Moreover, the latest report by [4] showed that shipping accounted for 2.89 % of global anthropogenic emissions in 2018 because the total greenhouse gas (GHG) emissions including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) expressed in carbon dioxide equivalent (CO_{2e}), amounted to 1,076 million tons. Moreover, CO_2 emissions were recorded to be 1,056 million tons in the same year, making it the most significant GHG released by ships [4][5] in line with the report of a previous study [6].

As a maritime nation, Indonesia relies on water transportation to connect different regions and tap into the abundant marine resources scattered across its vast territory. However, there is a gradual shift away from fossil fuel-based power generation due to concerns related to environmental degradation, resource scarcity, and rising expenses [7]. This is possible because the country is benefitting from a plentiful and uninterrupted solar energy supply year-round due to its proximity to the equator. Moreover, consistent access to sunlight provides a

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clean and sustainable renewable energy source for electricity generation in the region [8]. This can be observed from its potential application as an energy source for the propulsion of small fishing boats. This is necessary because traditional fishermen make a substantial impact on both the national and local fishing sectors. As of February 2019, the Directorate of Sea Transportation within the Indonesian Ministry of Transportation reported that approximately 30,529 traditional fishing boats weighing less than seven gross tons (GT) were operating in Indonesia [9].

Electric propulsion systems are being used instead of conventional fossil fuel-powered engines to minimize the environmental impact of fishing. This is due to certain advantages of these systems such as lower GHG emissions, increased energy efficiency, and lower operating costs [10][11][12]. The concept of electric ships was initially implemented for ferries in the form of e-ferry which was identified as an innovative approach to reduce and eliminate CO_2 emissions [13][14].

Several studies have been conducted to comprehensively calculate and estimate the carbon footprint of ro-ro ships. For example, life cycle assessment (LCA) was applied to distinctive power system arrangements and the results showed that diesel-powered engines contributed to the highest carbon footprint while fully-battery ro-ro ships produced minimum carbon emissions [15][16]. Studies have also focused on the application of electric propulsion, battery, or hybrid systems to fishing vessels. LCA was applied to effectively analyze the environmental effect of electric-powered ships [17] while another study by [18] used the same approach to determine the implementation of alternative power for fishing trawlers in three phases. The results showed that Liquefied Natural Gas (LNG) and 20 Biodiesel (B20) were the most straightforward solutions while ammonia and hydrogen were the most expensive. Battery-powered was further considered an alternative solution because of its lower price compared to hydrogen and ammonia. Moreover, LCA was used for a control algorithm and CO_2 emission was recorded to be 7.6 %, showing that the battery hybrid system was eco-friendly in the energy production state [7]. An automotive model-based design was also applied to calculate the emissions of CO_2 equivalent and life cycle costs of lobster fishing vessels. The results showed that the hybrid energy storage system ensured lower life-cycle costs and reduced GHG emissions. Meanwhile, full electric propulsion could be implemented to achieve significant reduction [19].

Solar photovoltaic (PV) were observed to have been integrated into fisheries technology in three areas of Indonesia with a focus on two configurations, including grounded and floated, and the results confirmed that the floating PVs were more beneficial [20]. Meanwhile, another study showed that solar PVs have not been used optimally as a fishing cold storage [21]. Several studies have showed the installation of solar panels on fishing boats such as the A 4 x 250-watt solar panel mounted on the wheelhouse which was found from a trial test to have saved three hours compared to a conventional engine [22]. A previous study also analyzed the implementation of solar PV on eight-meter inland river fishing boats and reported that the boats ran up to four hours [23].

This literature review shows some inadequacies in the studies related to the calculation of energy demand and emission reduction for electric fishing boats. Therefore, the main focus of this study is to comprehensively calculate the energy demand and emission reduction for the electrification of fishing boats. This led to the formulation of the following primary questions:

1. What is the power requirement of conventional and electric propulsion systems on "Sandeq" fishing boats in West Sulawesi?
2. What is the quantity of carbon dioxide emissions generated by the conventional propulsion systems used in "Sandeq" fishing boats in West Sulawesi?
3. What is the quantity of carbon dioxide emissions reduced and the operational costs of using electric propulsion systems in "Sandeq" fishing boats in West Sulawesi assuming no carbon dioxide emissions were recorded?

A specific category of fishing boats known as "Sandeq" which is classified to be under the 3 gross tonnage (GT) threshold and commonly found in Mamuju, West Sulawesi is used as the case study. These boats, characterized as sailboats, are very important to the inter-island transportation and fish-catching activities of Mandar fishermen. Therefore, the focus of this study was to determine the possibility of reducing carbon dioxide emissions in these boats by transitioning from conventional propulsion systems to electric motors. The assessment was conducted by estimating the power demand and battery needed for the fleet. Moreover, CO_2 emission generated by diesel-powered fishing boats was calculated followed by the possible reduction in operational cost after the installation of electric propulsion. This article is structured in such a way that the first aspect explains the introduction and literature review followed by the methodology to calculate the energy demand and emission reduction, the analysis of emission reduction in terms of quantity and cost, while the final aspect is the conclusion.

II. Materials and Methods

A. Research design

This study was conducted using a quantitative research design and this was achieved by examining and analyzing the relationships between numerical variables through different statistical and graphical techniques. Moreover, several quality control approaches were adopted to ensure data accuracy [24][25]. The evaluative study is normally used in business and management to assess the effectiveness of strategies, policies, programs, initiatives, or processes within an organization [25]. It was applied in this case to determine the potential of reducing emissions by shifting to electric

Figure 1. Study area: Mamuju Regency in West Sulawesi

propulsion systems. Furthermore, the research strategy applied was a "case study" within a "cross-sectional study framework". The preference for the case study strategy was because it focuses on an in-depth investigation of a specific subject or phenomenon in a real-life context [25]. The subject or 'case' in this study was the potential reduction of carbon dioxide emissions from "Sandeq" fishing boats through the transition to electric propulsion systems. Meanwhile, the cross-sectional approach is normally used to capture or take snapshots of a specific phenomenon at a fixed moment. It was applied in this study to calculate the annual emission reductions using electric propulsion systems compared to conventional engines.

B. Study area

The study was conducted in Mamuju, West Sulawesi presented in Figure 1. Mamuju is one of the areas in Indonesia with high sun exposure, making it possible to develop solar-powered electric boat technology with photovoltaics. Mamuju is also one of the fishing villages with a high population and this means solar-powered boat technology can be developed to benefit fishermen due to the possibility of reducing the operating costs. Moreover, Tambi fishing village is located on the coast of Mamuju Regency with most of the villagers working as fishermen and wooden boat artisans.

C. Energy demand calculation

The primary parameters needed in the conversion of the engine in the "Sandeq" boat into an electric motor ship are presented in Table 1 and displayed in Figure 2.

D. Boat arrangement

The annual energy demand for fishing boats is normally calculated using the following equations based on several variables such as the average engine power, the length of the voyage, and the time required for each trip. Meanwhile, power is proportional to the cubic meter of the speed and this led to the formulation of main engine average power ($P_{ME,ave}$) as stated in equation (1) [15][16][26].

$$P_{ME,ave} = (P_{ME} \cdot 0.8) \cdot \left(\frac{V_{ave}}{V_{de}}\right)^3 \quad (1)$$

Figure 2. "Sandeq" boat in Tambi village

The value of the main engine power for fishing boats (P_{ME}) was obtained using the Maxsurf Resistance software and this was achieved by inputting the boat model and the ship design (V_{de}) of 6 knots. The holtrop approach was applied to determine the resistance [27] while the average speed of one voyage (V_{ave}) was obtained by dividing the length (l) by the time (t). An hour was used for one trip and the daily length for the fishing boat with a size under 3 gross tonnage (GT) was stated as one trip. Therefore, the energy consumption of the fishing boat (EC) in kWh/nm was calculated using equation (2).

$$EC = \frac{P_{ME,ave}}{V_{ave}} \quad (2)$$

Meanwhile, the daily energy consumption (EC_{daily}) in kWh was obtained through equation (3).

$$EC_{daily} = EC \cdot l \quad (3)$$

The estimation of the number of days the boat goes fishing in one year (OD) was used to formulate the annual energy consumption (EC_{total}) in equation (4).

$$EC_{total} = n \cdot EC_{daily} \cdot OD \quad (4)$$

where the number of fishing boats supplied by solar energy is designated as n.

The battery capacity was critical for the evaluation of the energy demand required by 100 % electric-powered fishing boats. This led to the determination of the required battery capacity for a battery-powered fishing boat (BC_{BEF}) in kWh using equation (5):

$$BC_{BEF} = EC_{daily} \cdot 1.5 \quad (5)$$

Figure 3 shows the general arrangement of the "Sandeq" 3 GT boat from laminated wood. The cargo space is in the front, the battery is in the stern area, and the electric motor is directly connected to the propeller shaft. From the concept design, it is estimated that six batteries are the maximum threshold to be installed.

E. Emission analysis and operational cost comparison

The quantification of the emissions generated by diesel-engine fishing boats is important to the assessment of the GHG reduction capabilities of specific technologies. Therefore, the quantity of emission produced by "Sandeq"-type fishing using fuel was calculated in this study. This was based on the sail of the boat from the docking area to the fishing ground location and return which required an average of 12 hours per voyage at a maximum speed of 6 knots and power of 6.5 HP. Moreover, the average engine power ($P_{ME,\ ave}$) obtained through energy demand calculation was considered an additional parameter due to the actual operation of a fishing boat and designated as the minimum threshold for the emission.

The fuel consumption (FC) was obtained based on the following Fisheries and Aquaculture Division of the Food and Agriculture Organization (FAO) formula [28]:

$$FC = 0.75 \cdot P_{ME} \cdot S \cdot t \quad (6)$$

where P_{ME} is the total power from the main engines (HP), t is the time required for one voyage (hour), and S is the specific fuel consumed (kg/HPhr) which is assumed to be 0.17 for fishing boats [28].

The determination of the fuel consumption was followed by the evaluation of CO_2 emissions (E) using Equation (7) with the emission factor (EF) of diesel fuel for marine stated to be 3.17 CO_2 per ton/ton [29]. The annual CO_2 emission was estimated based on the assumption that the boats sail for 28 days/month and nine months/year. This was associated with the forecast of severe weather during June – August that often instigated fishermen to postpone fishing schedules.

$$E = EF \cdot FC \quad (7)$$

The operational cost of diesel fuel and emission costs need to be compared with the price of electricity. However, the investment costs associated

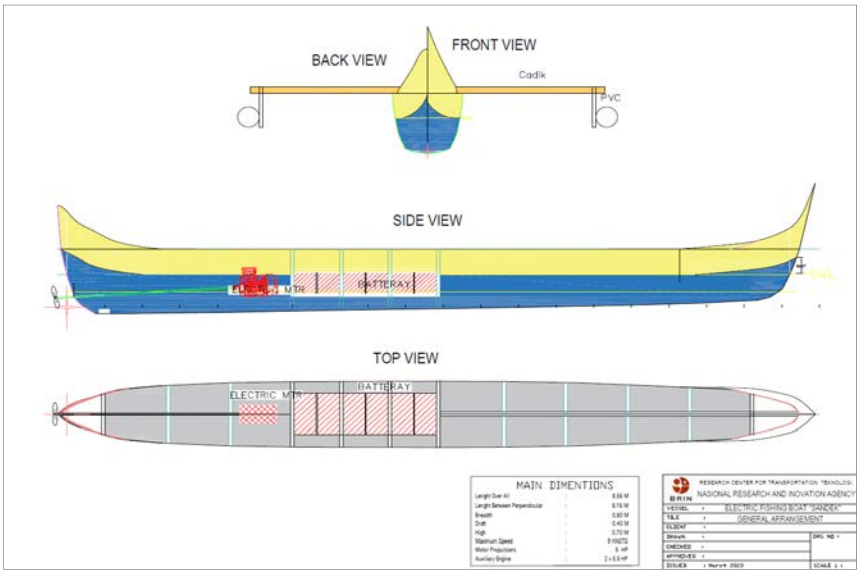

Figure 3. General arrangement of electric "Sandeq" boat

Table 1.
Engine and fishing boat specifications

Electric Motor Propulsion Specifications	Unit
Ship dimensions (m)	8.56 x 0.80 x 0.70
Engine power (kW / HP)	4.84 / 6.5 (on the fishing ground)
Design speed (knots)	6
Average speed (knots)	4
Duration of voyage (hours)	12
Length of the voyage (nm)	31.28
Annual distance traveled (nm)	7680

Table 2.
Energy demand per fishing boat

Energy Demand	< 3 GT
Average engine power (kW / HP.)	1.15 / 1.54
Energy consumption (kWh/nm)	0.286
Daily energy consumption (kWh)	8.972
Battery capacity (kWh)	13.45
Number of battery per boat (12 V 220Ah)	5 + 1
Average engine power (kW / HP.)	1.15 / 1.54

with conversion and the price of the newly installed battery are not to be considered. This omission is justified by the clear observation that the investment price significantly exceeds that of diesel-powered fishing boats. Therefore, the annual fuel consumption cost was calculated by multiplying the annual fuel consumption per kg with the fuel cost of Rp 20,200/kg. At the same time, the annual CO_2 emissions were computed by multiplying the annual CO_2 emissions with the emission tax rate of Rp 1,160,700/ton of CO_2 based on the carbon tax recommended by the International Maritime Organization (IMO) [30]. The electricity price in Indonesia at the time of conducting this study was Rp 1700/kWh and this was used to calculate the annual electricity price.

III. Results and Discussions

A. Energy consumption and battery capacity calculation for fishing boats

Table 1 shows that fishing boats are categorized as "one-day" with a voyage distance of 32 nm, including the transit from and to the fishing ground, and this is considered very suitable for a battery plug-in system. Moreover, the batteries are to be charged at the charging station designed as part of the PV array and subsequently installed efficiently on the boats by the fishermen. The results presented in Table 2 showed that the daily energy consumption for one ship during one voyage was 8.97 kWh. This could be satisfied using six batteries consisting of five as the primary power source and one as redundancy.

B. Conceptual framework of electric motor propulsion

The electric "Sandeq" boat was designed to be driven by an electric motor powered through a photovoltaic array system installed in the shore area. The conceptual framework of electricity to be used for fishing boats is presented in Figure 4. The part of the design located on land includes the solar panels to be used in producing electrical energy from solar irradiation, a solar current regulator that controls the flow of DC to AC, and an inverter to transform DC voltage into AC voltage. Meanwhile, the part on the ship includes an adapter to convert AC to DC, a battery to produce DC electric current, and an electric motor that turns electric current into the motion or mechanics needed by the propeller.

C. Emissions analysis

The fuel consumption and CO_2 emission of the fishing boat are presented in Table 3. The results showed that one fishing boat has the capacity to produce 7.47 - 31.52 kg of CO_2 emission per trip and

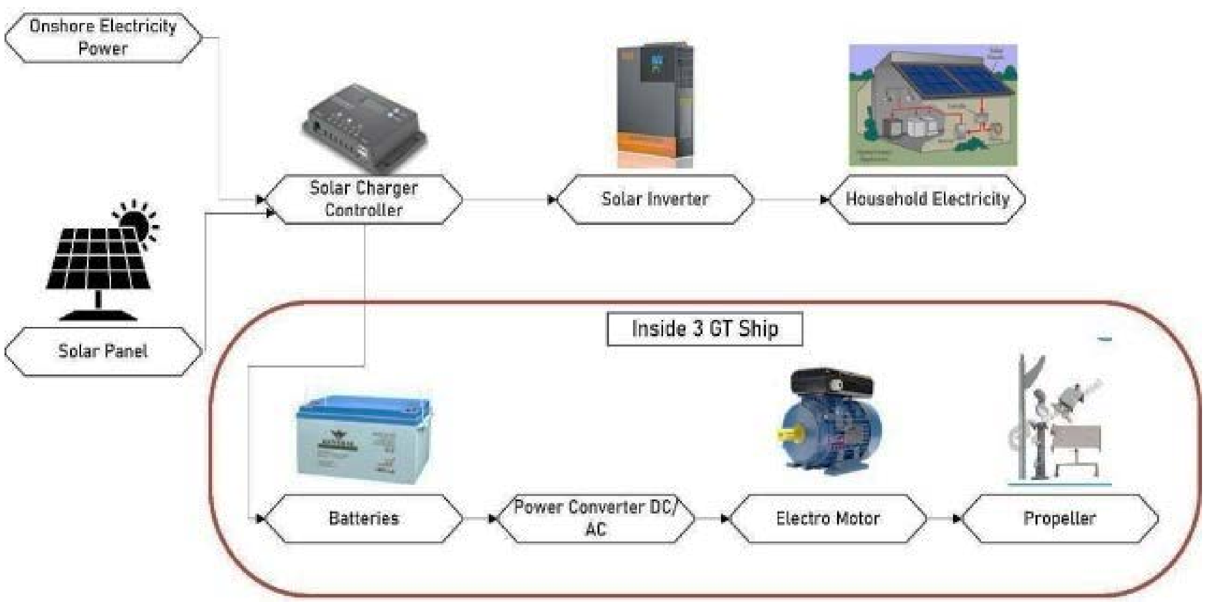

Figure 4. The framework of the electric power generated by the propulsion system

Table 3.
CO_2 emission by fishing boats

	Fuel Consumption (kg)	CO_2 Emission per Trip (kg CO_2)	CO_2 Emission per Year (kg CO_2)
Maximum capacity	9.95	31.52	7944.46
Engine operational	2.35	7.47	1792.23

Table 4.
Comparison of operational conditions between diesel-powered and battery-powered fishing boats

Cost Scenario	Diesel Fishing Boats (Rp)	Battery-Powered Fishing Boats (Rp)
Annual diesel fuel cost	11,994,000	-
Annual electricity price	-	3,931,887
Annual CO_2 emission cost	2,080,667	-

1.79 - 7.94 tons annually. Meanwhile, there are 2,252 units of "Sandeq" fishing boats under 3 GT in West Sulawesi and this shows that the total CO_2 emission produced from the fleet is 4.24 – 17.89 kilotons annually.

The conversion of the conventional engine to a battery-powered system reduced CO_2 emissions from the maritime transportation sector. This was because the battery propulsion system generated practically zero emissions during the operational conditions [7]. The results cannot be directly compared to similar studies [31] due to the differences in location, fishing boat type and size, and engine power. However, the relationship between emissions produced by fishing boats is exponential. A boat with a more prominent size and engine capacity has the capacity to produce more CO_2 emissions. For example, a fishing vessel with 182 GT, 480 kW engine power, and a daily voyage of 132 nm was studied by [31] and the results showed that the produced 77.3 tons of CO_2 annually while the smaller size analyzed in this study to be below 3 GT produced 1.83 tons.

D. Comparison of operational costs

Table 4 compares the annual price of using conventional diesel-powered and battery-powered electric fishing boats based on the average operational power. The total operational cost for the diesel system was estimated to be 12 million Rupiah and this was considerably higher than the 4 million Rupiah recorded for battery-powered systems which also saved emission costs by another 2 million Rupiah. However, the annual investment, fixed maintenance, and conversion cost of the battery were estimated to be 95, 85, and 40 million Rupiah, respectively. This showed that the operational cost of implementing the battery-powered fishing boat is more expensive than the conventional one.

The limitation of this study is that the emission was calculated without considering those produced in manufacturing batteries despite the usage of several engines powered by generators during the process. This shows the need to conduct a comprehensive study to determine the quantity of emissions produced in the process.

IV. Conclusion

In conclusion, the electrification of ships is one of the solutions to reduce CO_2 emissions in the maritime sector and this can be achieved through the implementation of smaller scale greener propulsion systems suitable for fishing boats. This led to the introduction of an electric propulsion system to replace the conventional diesel engine in these boats using batteries coupled with an electric motor as the prime mover. This study determined the number of batteries needed in the design due to its influence on the stability, payload, and technical requirements. Moreover, the average power of fishing boats per voyage was estimated through the distance and average speed. "Sandeq" fishing boat with a size below 3 GT was estimated to have an energy consumption (EC_{daily}) of 1.15 kW per one voyage and this showed that six batteries were enough to power the engine. The installation of the battery-powered system led to the elimination of 1.88 – 7.94 tons of CO_2 and a reduction in the annual operational cost by 72 %. However, the investment cost for the battery and conversion process was found to be tremendously expensive compared to the usage of conventional engines. Future study is expected to explore the different potentials of using electric propulsion to reduce carbon emissions in transportation with a specific focus on the optimization of green energy integration. Moreover, the improvement of energy transfer efficiency from renewable sources to electric vehicles needs to be considered. There is also the need to conduct a thorough assessment of the public health impact and explore broader economic and social implications of transitioning to electric propulsion. Further studies also need to provide holistic insights into the complex interactions between technology adoption, societal behavior, and environmental outcomes through interdisciplinary collaboration across environmental science, engineering, economics, sociology, and public policy. Finally, it is important to study the application of life cycle assessments and techno-economic analyses to assess the overall sustainability of electric propulsion systems. The results are expected to serve as a reference for academics and government stakeholders intending to conduct a feasibility study or formulate policies to reduce the emissions generated through maritime transportation.

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Declarations

Author contribution

N.S. Octaviani: Conceptualization, Supervision, Formal Writing; D.H.Waskito: Formal Writing, Data Analysis, Conceptualization; Iskendar: Supervision, Conceptualiza tion, Original Manuscript; A. Muis: Supervision, Conceptualisation; N.M.R. Fuadi: Formal Writing, Conceptualisation, Formal Analysis; Muhajirin: Data collecting, Formal Analysis; H. Palebangan: Formal Analysis, Review & Editing; K. Ismoyo: Formal Analysis, Review & Editing; D. Kartikasari: Funding Acquisition; N.I. Gutami: Original Manuscript, Editing, Funding Acquisition; K. Ajidarmo: Formal Analysis, Review & Editing.

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence this study.

Additional information

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