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Research Article

Development of a Simple, Low-Cost Electric Propulsion System for Electrifying Long-tail Canal Boats: A Case Study in Bangmod Canel, Bangkok

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Abstract:
This study aims to convert a long-tail boat's propulsion system from an internal combustion engine to an electric motor for enhanced sustainability and reduced environmental impact. The 5-meter boat underwent design modifications, incorporating an electric hub motor connected to the propeller via a power transmission system. Tests conducted in Bangmod Canal, Bangkok, compared the electric and engine-powered boats in terms of energy consumption and noise levels. Results indicated that the electric boat, despite a slightly lower speed, exhibited advantages in energy efficiency and noise reduction. Economic analysis projected a return on investment within 2 years and 8 months, with a notable Internal Rate of Return (IRR) of 26.20%. The electric conversion proved economically superior, offering cost savings, improved quality of life for residents, and mitigation of pollution along the canal.

Keywords: *Long-tail boat, Electric propulsion, Hub motor, Energy saving, Noise reduction, Ecotourism*

1. Introduction

Currently, people's commuting habits worldwide predominantly rely on vehicles for transportation to conserve time and energy. These means of transportation, known as vehicles, encompass options for land, water, and air travel. These include automobiles, motorcycles, boats, and airplanes, all powered by internal combustion engines, which utilize fuel that undergoes combustion. Focusing specifically on the ASEAN region, data indicates an escalation in crude oil consumption from 250 million tons of oil equivalent in 2005 to 350 million tons in 2020. The highest proportion of this consumption is attributed to transportation [1], driven by elevated fuel consumption rates, resulting in subsequent air pollution. This pollution includes carbon monoxide gas, hydrocarbon compounds, and particulate matter, contributing to the greenhouse effect and subsequent global warming. Consequently, the global community recognizes the significance of energy sources and has increasingly turned towards alternative energy solutions. The shift towards utilizing electricity to power vehicles is a response to this issue. This trend is observable in the plans of the European Union (EU), which aims to reduce carbon dioxide emissions from automobile usage, significantly boosting the electric vehicle market. Gartner's report during the COP26 conference indicates that electric vehicle shipments reached 6,022,147 units in 2022, marking a 34.6% increase from 2021 [2].

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As the use of electric cars is becoming more main stream, there have been some interests in EV conversion of marine vehicles as reported in published literature. Caprara et al. [3] investigated the conversion of internal combustion engines in small leisure boats to electric motors, with a focus on battery sizing and usage planning. By calculating the suitable battery capacity for each usage cycle and assessing the long-term cost implications, it was found that transitioning to electric motors could result in substantial long-term savings compared to internal combustion engines, despite higher initial investment costs.

Nurachman and Imfianto [4] conducted a study on the design and calculation of a mechanical system for a solar-powered electric boat. The research aimed to optimize the boat's mechanical systems for potential recreational use in Indonesian waters. Through literature study, expert discussions, and surveys, data were collected and used for calculations and simulations. The propulsion system, steering system, and bilge pump system were analyzed to enhance the boat's efficiency and performance. Results showed that the boat's minimum power requirement for the motor was determined, and energy consumption for a targeted sailing range was calculated. The study concluded that the mechanical system design could significantly impact the boat's efficiency and suitability for replacing traditional water recreational vehicles in Indonesia, aligning with the country's renewable energy goals.

Minak [5] provided a comprehensive review of the current state of solar energy-powered boats, focusing on maritime drones, sporting boats, and short-range touristic vessels. The review discusses the applications of solar energy in the maritime sector, emphasizing the advantages of solar-powered boats, such as reduced environmental impact and sustainability. The document covers various aspects of solar-powered boats, including their design, energy sources, and economic viability. It also highlights the use of solar energy in different types of boats, such as autonomous naval vehicles and touristic boats, and provides insights into their design and performance. The review concludes that solar energy holds significant promise for the maritime industry, offering a sustainable and environmentally friendly alternative to traditional energy sources, with potential applications in various types of boats.

Palconit and Abundo [6] authored a research paper on the implementation of an electric ferry ecosystem for sustainable inter-island transport in the Philippines. The study aimed to verify the suitability of the electric motor, observe the performance of the outboard motor in a real situation, and evaluate the sustainability of the system. The research involved field-testing a 4.5m monohull electric boat in Samal Island, comparing its performance when powered solely by batteries and when supplemented by photovoltaic (PV) modules. The results indicated that the PV module supplemented energy by approximately 13.4% to 38.7% at different speeds, extending the navigational range. The study concluded that the electric boat with the aid of PV modules effectively addresses the energy management system's sustainability in inter-island transport in the Philippines. This research contributes to understanding the potential benefits of green energy sources in maritime transportation and the challenges of transitioning to renewable energy.

Cheng et al. [7] presented a comprehensive study on the development of zero-emission electric vessels. The paper discusses the advantages of electric vessels over traditional fuel-powered ones, focusing on design, energy storage, and regenerative energy. The authors emphasize the potential for electric vessels to replace short-range diesel-powered vessels in the near future. The study also highlights the environmental benefits, cost savings, and performance improvements associated with electric vessels. The results indicate that electric vessels have a high energy-saving potential, estimated at 13% better than electric vehicles on roads. The conclusion emphasizes the need for further research in control, motor, and energy storage for electric vessels, as well as the potential for renewable energy sources to be integrated into these vessels.

Kaleg et al. [8] conducted a research on the key factors in engine conversion from internal combustion to electric motors. There are three main considerations for this study: distance traveled, desired speed, and cost. Knowing the distance can help determine the battery capacity needed. The target speed depends on motor efficiency. It is essential to consider total resistance forces and associated costs, which are influenced by various factors stemming from equipment selection fundamentals. In summary, once the desired distance is known, determine the speed and then calculate the battery capacity.

Villa et al. [9] described a transportation route by boat to study the electrical energy consumption per trip and establishes two charging stations. The first station utilizes alternating current (AC) charging, while the second station employs direct current (DC) fast charging. Energy consumption for each journey at a fixed speed is calculated to optimize charging efficiency and compare it with a simulation program. The aim is to demonstrate the program's closeness to real-world testing. The study concludes that the simulation closely approximates actual testing with comparable energy usage.

Eydgahi and Long [10] provided a comprehensive design approach for converting internal combustion engine cars into electric cars, considering electric cars as an alternative fuel vehicle type that uses electric motors and motor controllers instead of internal combustion engines. The energy comes from a battery pack rather than carbon-based fuel, resulting in savings and environmental benefits, with the condition that the cost of electric cars is lower than the cost of using petroleum fuels in a single year.

Chiche et al. [11] explored the use of hybrid systems, utilizing fuel cells working in conjunction with motors in rescue boats and compare it with internal combustion engines in terms of weight, cost, and carbon dioxide emissions. Missions were defined to conduct tests and found that over the long term or during multiple missions, hybrid systems emit less carbon dioxide than internal combustion engines and are more cost-effective when used for more than 1000 missions. In terms of weight, hybrid systems depend on hydrogen fuel storage, which is generally heavier than internal combustion engine systems.

In Thailand, we can observe that electrically powered vehicles are playing an increasingly significant role in our daily lives. This is evident from the emergence of new automobile industry companies investing and trading more in the country, including FOMM, TESLA, GWM, and BYD. Moreover, the government is actively promoting and encouraging the public to recognize the benefits of electric vehicles. This can be seen through the announcements of reduced tax rates and policies by both local and national governments, aimed at reducing air pollution and empowering low- to middle-income groups to accumulate more wealth and participate in national development. The shift towards using electrically powered vehicles, whether they are cars, motorcycles, or boats, not only aids in decreasing air pollution but also leads to greater savings in travel expenses. Although the initial investment costs may be relatively high, a longer-term perspective reveals that they offer a significantly more worthwhile value proposition.

Based on the aforementioned information, it has given rise to the idea of promoting the use of electrically powered vehicles. If we consider the commuting habits of the Thai population, we find that both land and water transportation are prevalent. In Bangkok, in particular, there are numerous canals spread out across the city, densely populated with residents. Many people rely on boats for regular transportation, leading to the consideration of transforming the traditional long-tail boats used in everyday life. These long-tail boats are typically equipped with loud internal combustion engines that emit a significant amount of exhaust gas. The idea is to convert them into electrically powered boats, using electric motors for propulsion. Upon closer examination, it's apparent that some electric motor-powered boats have already started to be used, especially in the convenient Khlong Damnoen Saduak. This trend suggests the possibility of further developments in creating more electric boats.

However, given the nature of the long-tail boats which are primarily used by local population in South East Asia, there have been quite a few relevant work from literature survey. Tran Tuan et al. [12] authored an academic journal publication titled "E-Engine for a Long-Tail Boat, an Application in ASEAN (Association of Southeast Asian Nations)-Design and Comparison with Internal Combustion Engine." The study aimed to design and compare an electric engine for long-tail boats in ASEAN with traditional internal combustion engines with a case study in Thailand. Through finite element analyses and lump-parameter thermal simulations, the authors designed and tested the electric engine prototype. The results indicated that the electric engine outperformed the Honda GX270 internal combustion engine in terms of torque, power, size, and weight. The electric engine also offered advantages such as regenerative braking and the ability to start the propeller in water. The study concluded that the electric engine is a viable alternative to the internal combustion engine for long-tail boats in ASEAN, offering improved performance and environmental benefits. The authors also highlighted the potential of the electric engine to address the unique challenges faced by long-tail boats, such as the need for high torque at low rotational speeds and the ability to control the hydrodynamic torque. The findings suggest that the electric engine presents a promising solution for the electrification of water transportation in the ASEAN region.

Hung et al. [13] presented a comprehensive study on the development of an energetic system model for a solar-powered long-tail electric boat. The research delves into the boat's operational capabilities, revealing its capacity to function independently from an external power source. Results indicate that the boat can make 1-2 trips per day in summer and 1 trip every 4 days in winter, underscoring its potential for sustainable transportation. The solar panel and charger model, coupled with the component sizing outcomes, demonstrate the boat's requirement of a 4 kWh battery and 5 solar panels, totaling 978 kg in weight. The proposed system model is designed to optimize the boat's battery capacity based on its energy consumption. The paper concludes by emphasizing the solar electric boat's potential for low-carbon transportation in coastal and riverside tourist areas, highlighting its environmental benefits and the positive impact on local businesses and service quality.

Panprayun and Pitaksintorn [14] presented a study on the development and evaluation of a solar-powered catamaran for sustainable tourism in the Southeast of the Gulf of Thailand. The study area is Ko Mak Island, and the research encompasses ship design, PV system design, and shipbuilding. The solar-powered catamaran underwent performance evaluations in open water along the designated route. Results indicated that the catamaran could discharge power up to 10.8 kWh at a depth of discharge equal to 0.6 and travel for 5.4 hours, covering distances of 41.96 km with a motor power of 2,000 W. The conclusion drawn from the research is that the solar-powered catamaran serves as a tool for promoting low carbon destinations and sustainable tourism. The study also highlighted the need for alternative batteries and charging stations to ensure the sustainability of the solar-powered catamaran and its potential impact on tourism and the environment.

Based on the provided information and preliminary surveys, there is a reason to initiate the development and design of electric long-tail boats. This initiative aims to contribute in a small way to the country's development, starting from nearby communities. It's intended to disseminate knowledge within these communities while supporting community-based cultural tourism. Furthermore, this effort seeks to help local residents save expenses and potentially establish a business in boat modification in the future. Our group focused our efforts in the vicinity of Bang Mod Canal community, South of Bangkok due to its proximity to the university, convenient accessibility, and connection to major rivers. Additionally, the area boasts numerous tourist attractions that draw visitors. As a result, this research aims to modify the conventional long-tail boats that the local community regularly uses. The study area extends from the coffee shop area to Bangmod Tanpeaw Wittayakan School. The boats used are 10 cubits in size, accommodate 3 passengers each with a weight of 76 kilograms per person. They can travel at a maximum speed of 20 kilometers per hour. Through on-site observations and interactions with local residents, we were able to determine that the maximum distance traveled per day is 14 kilometers. This research entails designing a power transmission system, specifically focusing on the power source or the electric motor itself, while retaining the original boat tail system. This approach ensures that the electric long-tail boat functions similarly to conventional ones, providing maximum efficiency and usability for users.

2. Components

In the testing process, the researchers have changed the propulsion system of the original engine, utilizing the existing boat tail along with its base fixtures. During the selection of replacement components, the objective is to choose equipment that can efficiently substitute the original engine while maintaining compatibility.

2.1 Long-Tail Boats

The boats used by the local residents in the Bang Mod canal area are mostly small-sized boats due to their household and occasional hire use. The predominant boat type used is the "E-Pae" boat, which measures 10 cubits in length, 5.1 meters long, 0.75 meters wide, and 0.45 meters tall. The materials used for constructing these boats are sourced from the budgets of individual households. Wooden boats, although cheaper, are heavier. In contrast, fiberglass boats are lighter but come at a higher cost. The boat's capacity, regardless of type, accommodates three individuals: one driver and two passengers, as depicted in Fig. 1(a).

2.2 Engine

The commonly used engine for small-sized boats is the Honda GX-200 engine, a 4-stroke gasoline engine. The engine has a 6.5 HP output, single-cylinder, inclined OHV (Overhead Valve) design, with a displacement of 196 cc. The fuel tank capacity is 3.1 liters, and the engine oil capacity is 0.60 liters. The engine features a forced-air cooling system and air intake. The net weight of the engine is 16.1 kg. The engine shaft size is 19 mm, as shown in Fig. 1(b). The specification of the engine is reported in Table 1 [15].

Table 1: HONDA GX-200 Engine Specifications [15].

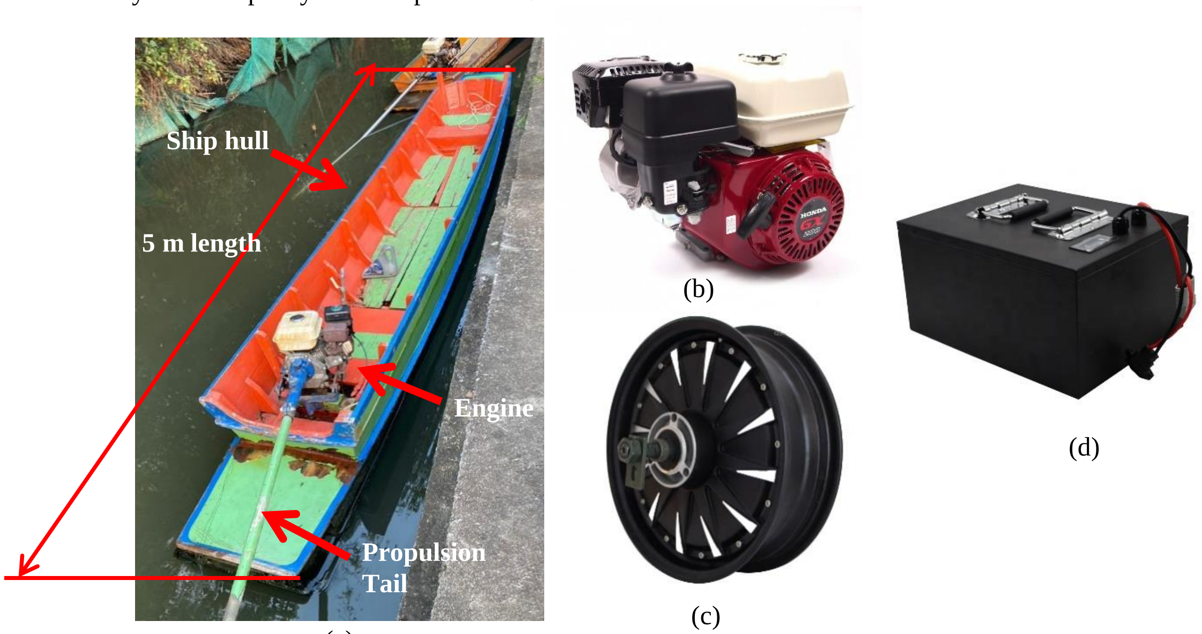
Engine type	Air cooled 4 stroke OHV petrol engine, 25° inclined cylinder, horizontal shaft, cast iron sleeve
Bore x stroke	68 x 54 mm
Displacement	195 cm3
Compression ratio	8.5 : 1
Net power	4.3 kW at 3600 RPM
Continuous rated power	3.7 kW at 3600 RPM
Maximum net torque	12.4 N.m at 2500 RPM
Ignition system	Transistorized
Starting system	Recoil Starter
Fuel tank capacity	3.1 liters
Fuel consumption at continuous rated power	1.7 liter/hour at 3600 RPM
Engine oil capacity	0.6 liters
Dimensions (LxWxH)	376 x 313 x 335 mm
Dry weight	16.1kg

2.3 Motor

The main propulsion device of the electric long-tail boat is a hub motor provided by QS MOTOR Company Limited, with a wheel diameter of 12 inches and a wheel rim size of 3.5x12 inches. It has a power output of 3000 watts and an electric voltage of 72 volts. The maximum rotational speed is 900 revolutions per minute (RPM), with a maximum torque of 145 N.m. It has a water resistance rating of IP67 and operates within a temperature range of 70-120 degrees Celsius. The rotating part is located on the outer circumference of the motor, also known as the rotor. It includes brake disc mounts with 3 brake disc installation holes, as shown in Fig. 1(c).

2.4 Battery

The battery has an electrical voltage of 72 volts and a capacity of 40 ampere-hours (Ah). It is a lithium-ion battery type and comes with 2 wires for connecting to the controller, used for charging the battery. Fig. 1(d) illustrates the 72-volt battery with a capacity of 40 ampere-hours.



(a)

Fig. 1. (a) A long-tail boat with a length of *5* meters, (b) HONDA GX-200 engine, (c) QS HUB MOTOR, rim size 12 inches, and (d) 72-volt, 40 amp-hour battery.

3. Design

In the power transmission system design, the use of hub motors has resulted in the need for a new power transmission system design. This is due to the change in power transmission method from direct connection to a belt-driven system through a pulley, based on the calculated transmission ratio. As a result of this change in power transmission, there is a requirement for equipment to hold onto the hub motor shaft. Therefore, an additional motor mount structure has been designed as a supplementary component of the power transmission system, as depicted in Fig. 2(a).

3.1 Design of Motor Mounting Frame

This component is assembled from sub-components, divided into two main parts: 1. Frame section 2. Device Mounting Plate section. The Frame section is made of aluminum profile set as the backbone with 4 support posts connected to other parts using brackets. It serves as the structural support for various devices within the motor mount frame section. The Device Mounting Plate section is made of 5mm thick sheet metal and is responsible for attaching to the frame section, which is made of aluminum profiles. This part is used to secure various components of the power transmission system, such as the motor, motor controller, bearing set, pulley, and winch. The overall concept is illustrated in Fig. 2(b).

Designed to position the motor on the upper section, allowing power transmission through a large pulley located on top to a smaller pulley below, using a belt. The lower small pulley then transmits power to the attached pulley and further to the joint or PTO SHAFT, passing through the bearing hole in the bottom metal plate to reach the long tail pulley. The motor mount frame or SUPPORT is secured to the base, which connects to the control lever, as well as accommodating additional components such as the controller and protective enclosure box. The overall concept after equipment mounting is depicted in Figs. 2(c) and 2(d).

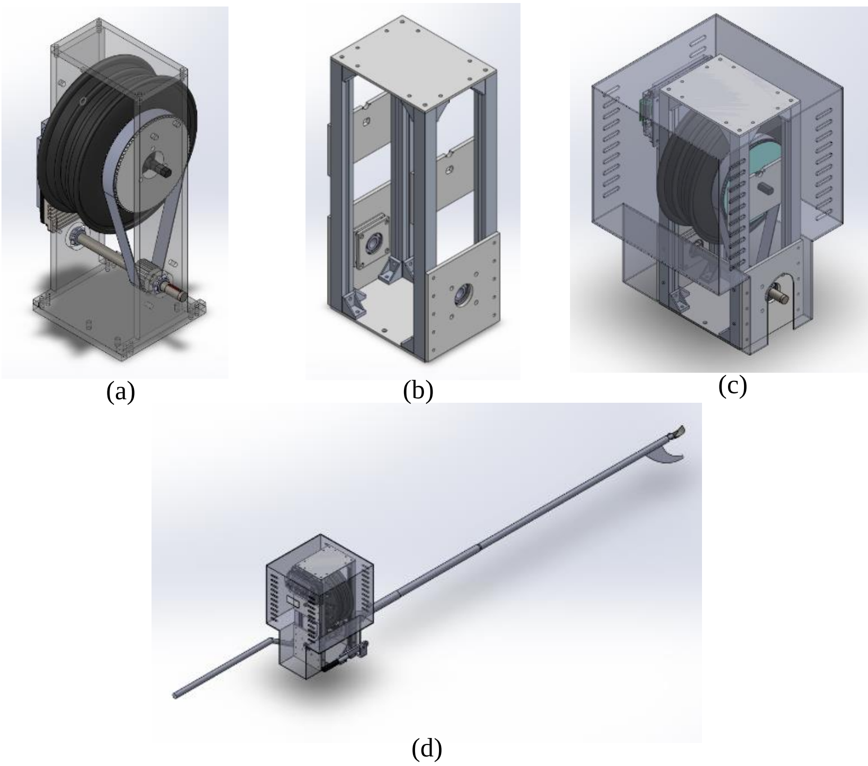


Fig. 2. (a) Preliminary Designed Power Transmission System, (b) Motor Mount Frame Section, (c) Power Transmission System with Equipment Mounting, (d) Power Transmission System Connected to the Original Boat Tail [16].

3.2 Design of Equipment Arrangement on Board

When designing the arrangement of internal equipment on the boat, safety considerations regarding electrical components and overall vessel balance are crucial. The newly designed power transmission system will replace the original engine's position. As it involves electrical systems, additional devices such as key switches, display screens, motor controllers, and batteries are included. In the case of the motor controller, it will be attached to the equipment mounting plate, which will then connect to the frame support posts, forming an integrated part of the power transmission system. As part of electrical safety reinforcement, a waterproof casing is provided for the power transmission system. For components like key switches and display screens, they are stored in a box located by the driver's side, equipped with a hole to pass wires and prevent water infiltration. The battery, due to its substantial weight, will be positioned in the center of the boat in front of the driver to maintain balance and act as a central balance point for the vessel. Wires will be routed from the motor controller to the battery, using waterproof sleeves, and fastened along the boat's side by passing through the driver's right side and connecting to the battery. The configuration will resemble Figs 3(a) and 3(b).

(a) (b)

Fig. 3. (a) CAD equipment placement on board and (b) Equipment placement on the actual boat.

4. Testing

4.1 Testing and Data Collection of Internal Combustion Engine-Powered Boat Propulsion for Motor Sizing Consideration

The purpose is to gather data on speed, water temperature, time, distance, and the angle of the boat when lifted at an angle relative to the water surface. This data is then used to calculate the overall resistance acting on the boat and subsequently determine the required motor power. The testing will be conducted using a boat powered by a commonly used internal combustion engine, the HONDA GX-200. This engine is a 4-stroke, single-cylinder engine with a displacement of 196 cc and a maximum horsepower of 5.8 HP at 3600 RPM. Data collection will employ the DEWESOFT equipment, which serves as the satellite signal receiver and transmitter.

4.1.1 Test Distance

Based on the field observations of the long-tail boat usage behavior among the villagers along Bang Mod Canal, it was found that there are three preferred destinations. These are the mosque, the Buddhist temple, and Bangmod Tanpeaw Wittayakan School. Particularly, Bangmod Tanpeaw Wittayakan School is a common destination for parents who drop off and pick up their children. This increases the distance traveled, as they have to make round trips during the morning and evening hours. Consequently, the total distance covered in a day is approximately 13.55 kilometers, or roughly 14 kilometers. During the boat running test, the starting point is set at the riverside coffee shop, then the boat is driven to Bangmod Tanpeaw Wittayakan School, and finally back to the coffee shop, completing one circuit.

4.1.2 Installation of Testing Equipment

Determining the Center of Gravity is of paramount importance in establishing positions for installing the DEWESOFT data acquisition equipment during testing. Placing the DEWESOFT data acquisition equipment at the

Center of Gravity is essential to achieve the most accurate and precise measurements. The calculation of the Center of Gravity distance involves calculating the moment based on the weights of the driver, passengers, equipment, engine, and the distance from the reference point or DATUM to each position. Refer to Table 2 for further details.

Table 2: The calculated weight, distance and moment data.

Component	Weight (kg)	Distance from Reference Point (m)	Moment (N.m)
Tail Shaft	3	-1.26	-37.08
Engine and Others	26.8	0.8	210.33
Passenger 1	76	1.9	1416.56
Passenger 2	76	2.4	1789.34
Passenger 3	76	3.2	2385.79
Boat	149.6	2.5	3668.94
	Total Moment (N.m)		9433.88
	Total Weight (N)		3996.59

Based on the calculations, it was found that the center of gravity of the boat is located at a distance of 2.36 meters from the reference point at the boat's stern. Therefore, the DEWESOFT equipment was installed at that position.

4.1.3 Determining the Resistance Acting on the Boat

The resistance acting on the boat will encompass all natural forces. This occurs when the boat is in motion at a certain speed, leading to the generation of air resistance on the upper part of the boat above the water and water resistance on the submerged part below the water. When the boat is moving forward, the stern of the boat submerges into the water while the bow of the boat rises, creating an angle with the water surface known as the trim angle (α). This trim angle influences the thrust force, which is essential for boat propulsion, as it interacts with various resistance forces acting on the boat. These forces include the hydrostatic force caused by water resistance (Hydrostatic Force), the force arising from fluid motion (Hydrodynamic Force), and the force experienced on the surface or hull of the boat (Skin Friction Force) [17, 18]. The combination of these forces acting on the boat is depicted in the free body diagram shown in Fig. 4(a).

From the free body diagram, equations of equilibrium can be established along each axis. The equilibrium equation along the vertical axis is given by Equation 1, while the equilibrium equation along the horizontal axis is given by Equation 2. According to Newton's second law, when an object experiences acceleration, the equation can be expressed as Equation 3 [17, 18].

$$W + F_s \sin\alpha = F_h \cos(\psi + \alpha) + F_p \sin(\alpha + \phi) + T\sin\alpha \quad (1)$$

$$T\cos\alpha = F_h \sin(\psi + \alpha) + F_p \sin(\phi + \alpha) + F_s \cos\alpha \quad (2)$$

$$ma = T\cos\alpha - F_h \sin(\psi + \alpha) - F_p \sin(\phi + \alpha) - F_s \cos\alpha \quad (3)$$

For the hydrostatic force acting on the boat, denoted as or Hydrostatic Force, F_h, its value can be determined using Equation 4. The trim angle, α, can be obtained from data collected through the DEWESOFT equipment during testing [17, 18].

$$F_h = \frac{1}{2} \rho_w g b_w {l_w}^2 \sin\alpha \quad (4)$$

Furthermore, the hydrodynamic force caused by fluid motion, referred to as Hydrodynamic Force, F_p, can be calculated using Equation 5. The parameter δ, or Turbulent Disturbance Thickness, can be calculated using Equation 6 [17, 18].

$$F_p = \rho_w V^2 \delta \cot(\frac{\alpha}{2}) \quad (5)$$

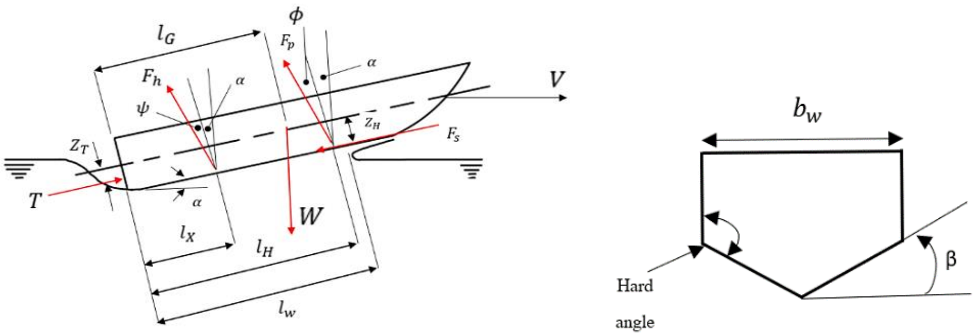
$$\frac{\delta}{L} = \frac{0.382}{Re_x^{\frac{1}{5}}} \quad (6)$$

In the context of the force acting on the surface or hull of the vessel, known as Skin Friction Force, F_s, it is related to the coefficient of drag of the surface, denoted as C_F or the Skin Friction Coefficient. This coefficient is determined by the nature of the turbulent boundary layer, which requires the calculation of the Reynolds number, Re, first using Equation 7. Subsequently, the value of C_F can be obtained using Equation 8 [17, 18].

$$Re_L = \frac{\rho v L}{\mu} \quad (7)$$

$$C_F = \frac{0.455}{(\log Re_L)^{2.58}} \quad (8)$$

In the case of S_w or Wetted Surface Area, it will be related to the angle of the ship's belly or Hard Angle, β from Fig. 4(b). The angle β will be set to 0 since it is very small in size.



(a) (b)

Fig. 4. (a) The free body diagram of the long-tail boat and (b) the dimension of the Wetted Beam, b_w, and the angle β. [17]

Next, calculate the value of S_w using Equation 9 and compute the value of F_s using Equation 10 [17, 18].

$$S_w = l_w b_w \sec\beta \quad (9)$$

$$F_s = \frac{1}{2}\rho_w V^2 S_w C_F \quad (10)$$

4.1.4 Motor Power Calculation

The motor power is selected by considering the range of usage from the Power (kW) and Time (s) graph during the vessel's test run speed. The chosen power will fall within the Continuous Power or Rated Power range, which represents the highest sustained power during testing. As for the Peak Power value, it will be derived from the Maximum Power on the graph or the highest achieved power in each test run cycle, calculated using the formula in Equation 11.

$$P\ (W) = F\ (N) \times V\ (m/s) \quad (11)$$

4.1.5 Battery Capacity Calculation

Initially, it is necessary to determine the battery capacity energy value. This involves calculating the total energy consumed during one test run cycle and then multiplying it by the actual number of cycles per day as defined. This will provide the total energy used for running in a single day. The energy can be calculated using equation 4.12.

$$E\ (kWh) = P(kW) \times \frac{t(s)}{3600} \tag{12}$$

4.2 Testing for Fuel Consumption Rate

4.2.1 Testing of Internal Combustion Engines-Powered Boat

In this case, it is the HONDA GX-200 engine that undergoes testing by filling the fuel tank with a full capacity of 95-octane unleaded gasoline. The boat is then driven from the "Hoi Ka" coffee shop to the Bangmod Tanpeaw Wittayakan School, and then back to the starting point. The distance covered and the amount of fuel consumption are recorded. After that, the fuel tank is refilled to its original level, and the distance and the amount of refueled fuel are recorded. These values are then used to calculate the fuel consumption rate in terms of cost per kilometer.

4.2.2 Testing of Electric Motor-Powered Boat

The propulsion system, including the battery, was installed according to the designed specifications. The testing was conducted with the starting and ending points at the same location as the internal combustion engine vessel testing. Battery percentage was recorded at the beginning and end of a single test cycle, along with the distance and time. Subsequently, the battery was charged to its initial state, using a Power Meter to monitor the incoming power and recording the charging time. Then, the electricity cost was calculated by multiplying the cost in currency per unit by the power in kilowatts. This provided the electricity cost for charging the battery in a single cycle. This value was then divided by the distance covered to obtain the result in terms of currency per kilometer.

4.3 Measuring the Noise Level When the Boat is in Motion

The noise level measurement testing will be performed using the NTI AUDIO SOUND LEVEL METER XL2. This meter will measure decibel values during boat motion. The measurement will be taken at the same location on both the internal combustion engine-powered vessel and the electric motor-powered vessel. The meter will be set to measure and display the maximum sound level and the sound level at that moment. The measurements will be initiated from the same location, the same point, equidistant from the vessels, and at the same height above ground level, mimicking a resident living along the canal.

5. Test Results

5.1 Motor Power Usage

Based on the collected test results and the calculated engine power obtained from the internal combustion engine in each boat testing cycle, these values were plotted on a graph illustrating the relationship between power and time, as shown in Fig. 5. The various values were summarized in Table 3.

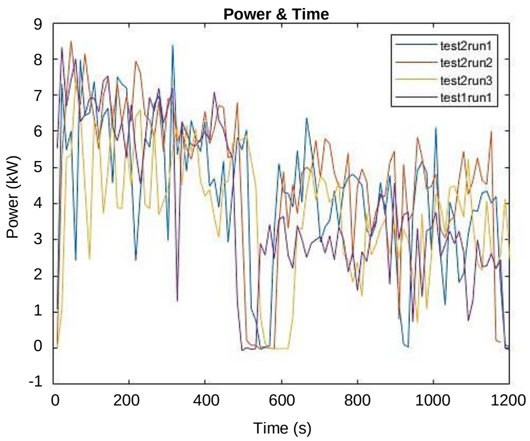


Fig. 5. The power versus time for each test session.

Table 3: The maximum values of computed data from each testing cycle.

Test Number	Direction	Maximum Thrust (N)	Maximum Power (kW)	Total Energy Used (kWh)
TEST1RUN1	Round Trip	2037.38	9.995	1.307
TEST2RUN1	Round Trip	2443.51	13.06	1.466
TEST2RUN2	Round Trip	2042.2	9.73	1.593
TEST2RUN3	Round Trip	1826.82	7.97	1.301

From Fig. 5 and Table 3, it can be observed that in the second test cycle (TEST2RUN1), as indicated by the graph, an anomalous spike in data occurred. This was due to a signal loss and subsequent reconnection while the boat had already passed that position. This led to discrepancies in the recorded values. In summary, considering the results from the four test cycles, a motor size of 5 kilowatts was selected, with a peak value at 13 kilowatts, as the driving power. Subsequently, the total energy consumption per day was calculated, amounting to 6.37 kilowatt-hours. This necessitated a 72-volt battery with a current rating not lower than 45 amperes. Hence, a 72-volt, 50-ampere-hour battery was chosen, minimizing the battery count to only 2 units.

5.2 Simulation of Long Tail Shaft Load

The long tail boat propeller used by the author is the original long tail propeller set from KKK GROUP CO., LTD, specifically the G200 model. Originally, this propeller could withstand a torque from the HONDA GX-200 engine of up to 12.4 newton-meters. However, due to the author's switch to a motor with higher torque output, the consideration of whether the original long tail propeller can handle the new maximum torque from the motor arose. This was done to determine the Factor of Safety for its operation. The motor used is a hub motor with a power of 3000 watts, providing a maximum torque of 145 newton-meters. Therefore, the mentioned values were evaluated to simulate the torque response. The simulation was carried out using SOLIDWORKS 2022 software. The testing conditions will be illustrated in Fig. 6.

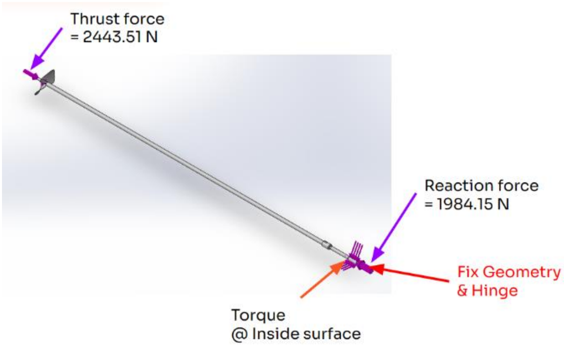


Fig. 6. The simulation setting of the long tail shaft load.

From Fig. 6, there is a thrust force acting from the rear, referred to as the Thrust Force, propelling the boat forward. The maximum value of this force is 2443.51 N. Additionally, there is a resistance force, referred to as the Reaction Force, exerted by the water onto the boat, and its value is 1984.15 N. This value coincides with the time of the maximum thrust value. The simulation involves fixing the geometry at the front surface of the long tail propeller's tail joint, known as the PTO SHAFT, and the hinge's inner surface of the tail joint of the boat, referred to as the Fix Hinge. The torque is specified at the inner surface of the tail joint of the boat in the same way. The material used for simulating the long tail propeller is AISI4140. Under Condition 1, a torque of 12.4 newton-meters is applied, derived from the maximum torque of the HONDA GX-200 engine. The results of this simulation are presented in Figs. 7(a) and 7(b), where the maximum stress is 134.48 MPa in the area where the tail joint connects with the coupling. The maximum deflection is 0.332 mm, resulting in a Factor of Safety of 3.086.

For Condition 2, a torque of 145 newton-meters will be applied, obtained from the maximum torque of the hub motor. This value will be used to assess whether the original long tail propeller can withstand the torque without damage.

The testing results are presented in Figs. 7(c) and 7(d). The maximum stress is 275.90 MPa, and the maximum deflection is 0.744 mm. This yields a Factor of Safety of 1.504.

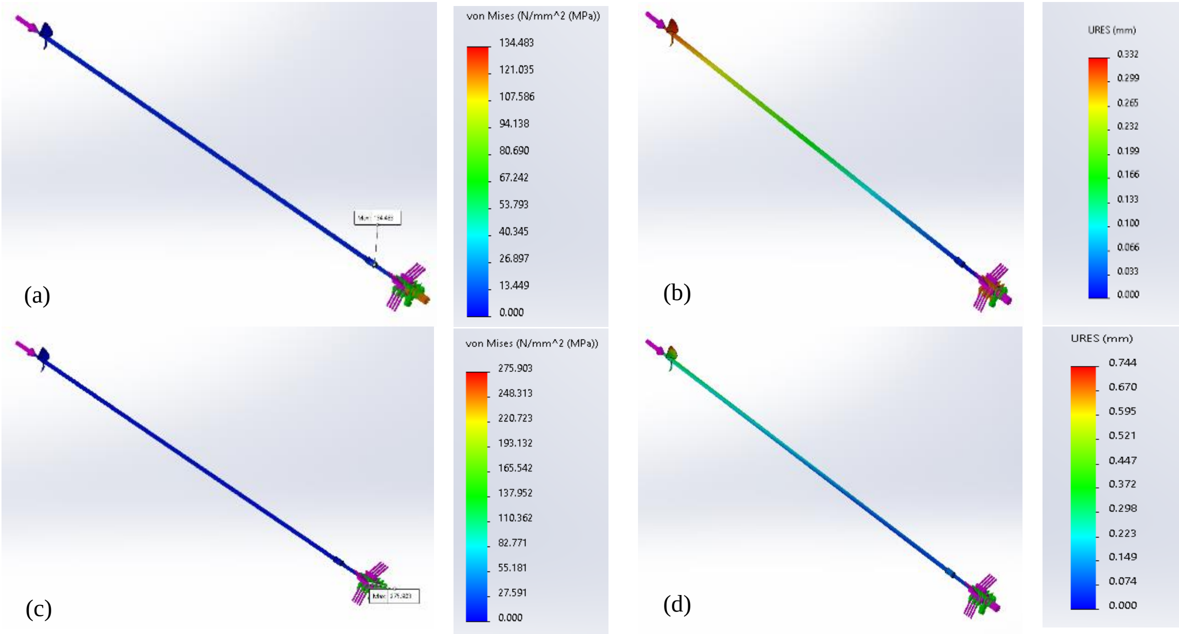


Fig. 7. The simulation results of (a) maximum stress and (b) maximum deflection within the long tail propeller's structure when subjected to a torque of 12.4 N.m and (c) maximum stress and (d) maximum deflection when subjected to a torque of 145 N.m.

5.3 Fuel Consumption Rate

5.3.1 Boat Propelled by Internal Combustion Engine

The long tail boat propelled by an internal combustion engine, in this case, is powered by the Honda GX-200 engine. It is a 4-stroke engine with a single cylinder, having a displacement of 196 cc and a maximum horsepower of 5.8 horsepower at 3600 revolutions per minute. From conducting three round trips of the boat and recording the values, the average distance covered was 4.41 kilometers. The average gasoline consumption of 95 octane gas used was 583.33 milliliters, resulting in a fuel consumption rate of 7.56 kilometers per liter. These values align with the data presented in Table 4.

Table 4: Fuel Consumption Rates

Number of Tests	Distance (km)	Fuel Consumption Gasohol 95 (liters)	Fuel Consumption Rate (liter/km)
Test 1	4.35	0.45	9.66
Test 2	4.47	0.7	6.39
Test 3	3.84	0.6	6.41
Average Value	4.41	0.58	7.56

Dividing the fuel consumption rate in kilometers per liter by the gasoline price of 36.5 Baht per liter, the result will yield the cost of consumption in Baht per kilometer, which is 4.83 Baht per kilometer.

5.3.2 Boat Propelled by Electric Motor

This long-tail boat, propelled by an electric motor, is a system that has been designed to use a 3-kilowatt electric motor. The power is transmitted through a pulley and a belt to the propeller, which is connected to the tail set of the boat. From the results of the electric boat tests as shown in Table 5, it is found that the distance, time, and maximum speed in each round are close in value to each other, as well as the battery percentage decreasing in a similar manner.

Table 5: Electric boat testing.

Number of Tests	Battery Percentage (%)		Controller Temperature (°C)	Maximum Speed (km/h)	Distance (km)	Testing Time (min)
	Beginning	End	End			
Test 1	81	44	71	16.37	4.11	27.64
Test 2	100	69	66	15.23	4.19	28.15
Test 3	69	37	69	14.11	4.09	29.07

After charging the battery using the household electricity, record the power and time used for charging. This was based on the starting and ending battery percentage during charging. This information enabled the calculation of the electricity cost. The calculation was performed using Equation 13 with an electricity rate of 4.43 Baht per unit. The results are shown in Table 6.

$$Electricity\ cost\ (Baht) = \frac{(Electric\ Power\ (Watts) \times Charging\ Time\ (hours))}{1000} \times Electricity\ Rate\ per\ unit \quad (13)$$

Table 6: Battery charging and the corresponding charging cost.

Number of Tests	Battery Charging				
	Voltage (Volts)	Current (Amperes)	Power (Watts)	Charging Time	Price (Baht)
Test 1	232.7	3.417	435.5	2 hours 12 minutes	4.24
Test 2	231.8	3.547	431.3	1 hour 47 minutes	3.41
Test 3	231.1	3.367	424.7	2 hours 25 minutes	4.55

After calculating the charging costs for each test round, the energy consumption rate was calculated in terms of Baht per kilometer. This was obtained by dividing the charging cost by the distance covered in each test round. The result is an average energy consumption rate of 0.986 Baht per kilometer, as shown in Table 7.

Table 7: Energy Consumption Rate.

Number of Tests	Distance (km)	Battery Charging Cost (Baht)	Energy Consumption Rate (Baht per kilometer)
Test 1	4.11	4.24	1.032
Test 2	4.19	3.41	0.814
Test 3	4.09	4.55	1.112
Average Value			0.986

In terms of estimating the achievable distance, based on the test results, Table 8 displays the battery capacity reduction in each test round. When these capacities are summed up, they amount to 100 percent. Combining the total distances covered results in 12.39 kilometers. Considering the presence of two batteries, it is evident that the cumulative usability is 24.78 kilometers. This exceeds the predefined threshold of 14 kilometers per day.

Table 8: The diminishing battery capacity in each test round.

Number of Tests	Battery Percentage (%)			Distance (km)
	Start	End	Used	
Test 1	81	44	37	4.11
Test 2	100	69	31	4.19
Test 3	69	37	32	4.09
Total			100	12.39

5.4 Sound Intensity Level of the Boat

The sound level testing was conducted using the NTI AUDIO SOUND LEVEL METER XL2 device, and the results are shown in Table 9.

Table 9: The Results of Sound Level Measurements.

Sound Level Measurement	
Internal combustion engines-powered boat	Electric motor-powered boat
82.1 decibels	69.1 decibels

Based on the results of the sound level measurements when the vessels were in motion, it was found that vessels powered by internal combustion engines had a decibel level of 82.1 decibels, while vessels powered by electric motors had a sound level of 69.1 decibels. According to sound level standards, sounds greater than 80 decibels are categorized as loud and can cause irritation, whereas sounds within the range of 40-60 decibels fall into the category of general conversational noise. Electric vessels produce a much gentler sound compared to vessels powered by internal combustion engines.

5.5 Vessel Speed of Both Types of Boats

From the tests conducted by running the vessels from the same starting point to the same destination, both for the vessel powered by an internal combustion engine and the vessel powered by an electric motor, the speed values of the vessels were measured using the DEWESOFT software. Satellite images with high angles are shown in Fig. 8. The test results revealed that the average speed of the vessel powered by an internal combustion engine was 17.55 kilometers per hour, which is higher than the vessel powered by an electric motor, with a maximum speed of 15.24 kilometers per hour, as shown in Table 10.

It should be noted that the lower speed of the electric motor-powered vessel during the test was due to the fact that the test was conducted on a day with reduced water current. This prevented the consistent immersion of the vessel's tail or propellers in water, as it would have led to entanglement with aquatic plants and underwater debris, as well as the slower flow of lighter-than-normal water currents. As a result, the vessel's movement was slower, and its maximum attainable speed was lower. However, these conditions still fall within the prescribed research boundaries.

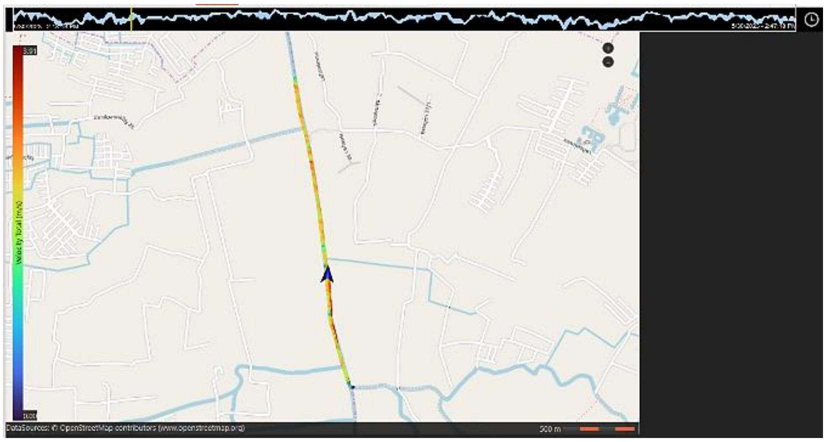


Fig. 8. The image of tracking the vessel's speed through the DEWESOFT software.

Table 10: The maximum speeds achieved in each test round for the two types of vessels.

Maximum Vessel Speed (kilometers per hour)		
Number of Tests	Internal combustion engines-powered boat	Electric motor-powered boat
Test 1	19.3	16.37
Test 2	17.21	15.23
Test 3	16.13	14.11
Average Value	17.55	15.24

5.6 Investment Comparison

Regarding the initial investment, the vessel powered by an internal combustion engine incurs a starting investment cost of 34,280 baht. On the other hand, the electric-powered vessel has an initial investment cost of 85,883 baht, resulting in a difference of 51,603 baht in investment. These investment expenses will be used to calculate energy consumption rates for determining cost savings, as shown in Table 11.

Table 11: Cost Comparison between Internal Combustion Engine-Powered Vessel and Electric-Powered Vessel

Costs	Internal combustion engines-powered boat	Electric motor-powered boat
Investment Costs	34,280 Baht	85,883 Baht
Energy Costs	36.5 Baht per liter	4.43 Baht per kilowatt-hour
Energy Consumption Rate	4.83 Baht per kilometer	0.986 Baht per kilometer
Daily Cost	67.62 Baht per day	13.80 Baht per day
Annual Cost	24,681 Baht per year	5,037 Baht per year
Potential Energy Cost Savings	19,644.3 Baht per year with the use of the electric-powered vessel	

From Table 10, the energy consumption rate for the internal combustion engine-powered vessel is 4.85 Baht per kilometer, while the electric-powered vessel has an energy consumption rate of 0.986 Baht per kilometer. This results in a difference of 3.844 Baht per kilometer. When calculated as annual energy savings, it amounts to 19,644.30 Baht. This can be used to determine the break-even point of the investment, which is at 2 years and 8 months.

Moving forward, the calculation will involve assessing the investment profitability using the Internal Rate of Return (IRR) as an analytical tool. The Discount Rate is set at 6%. Maintenance costs are not considered in this calculation. The results can be seen in Table 12.

Table 12: Calculation of Internal Rate of Return (IRR)

Year	Investment Value (Baht)
0	-51,553
1	19,644.3
2	19,644.3
3	19,644.3
4	19,644.3
5	19,644.3
IRR	26.20%

From the table, it can be observed that the investment value calculation is only done for the difference in investment between the electric-powered vessel and the internal combustion engine-powered vessel. In terms of annual expenses, the calculation is performed for the difference in fuel consumption rates for the internal combustion engine-powered vessel and the energy consumption rate for the electric-powered vessel. The calculation employs a time frame of 5 years since components or parts of both the electric-powered vessel and the internal combustion engine-powered vessel need replacement after the span of 5 years. This information reveals that the Internal Rate of Return is 26.20%, which is a high percentage, indicating that our electric-powered vessel is a worthwhile investment.

As mentioned in the introduction section, the previous work pertaining to long-tail boat conversion especially in Thailand is relatively limited [12-14]. Thus, we find it quite difficult to compare our findings with previous research as the vessel arrangement and equipment specification were not directly comparable to our specific use cases. However, we did try to elucidate based on their finding and make common observations of the trend in that the conversion from petrol engine to electric motor in general could save fuel cost, lower air pollution, and reduce noise. In this case, the results in this work also follow the trend as reported elsewhere [3-11].

6. Conclusions and Recommendations

6.1 Conclusions

From the design and construction of the electric-powered vessel system, it results in a total vessel weight of 449 kilograms, which is greater than the internal combustion engine-powered vessel. However, upon testing the actual vessel, it was found to be operational. The testing of the motor system and wiring kit revealed that they function effectively on the vessel, provided proper positioning and placement to ensure good air ventilation and avoid water exposure. Subsequent analysis indicated that the electric-powered vessel is cost-effective in terms of cost per kilometer, at 0.96 Baht per kilometer. This is significantly lower than the internal combustion engine-powered vessel's cost of 4.85 Baht per kilometer, showing a difference of almost fivefold. The sound produced by the electric vessel is gentle and environmentally friendly, measuring at 69.1 decibels. While the speed during the test was lower than the internal combustion engine-powered vessel, it can be improved by adjusting the motor's rotation and testing under equal canal flow conditions. Additionally, feedback from drivers who used both vessel types indicated that the electric-powered vessel performs well even at high speeds without causing discomfort or instability. The motor size calculation determined that using a 3-kilowatt motor is suitable, as it provides smooth propulsion, and the selection of components such as pulleys and bearings was efficient. Bearing noise could be addressed by compressing grease and lubricant. Regarding vibration in the propulsion system, it occurs at low speeds and diminishes at higher speeds. Gripping the control handle can help mitigate this vibration, ensuring user safety.

6.2 Recommendations

The heat and air ventilation of the equipment on the boat are important factors due to the fact that boat operation takes place outdoors, and the boat itself lacks a roof for sun protection. This exposes the equipment directly to sunlight. Most of the equipment is black, which allows it to absorb solar energy effectively. This results in increased temperature of the equipment, affecting its performance and operation duration. For instance, high temperatures from the sun can damage materials inside the control units, impacting their functionality. In the case of batteries, elevated temperatures lead to heat-related losses, causing quicker battery depletion and reduced efficiency. To address this, an air ventilation system should be installed to enhance heat dissipation. This could involve placing a fan within the protective casing, particularly around the control units, and even installing a sunshade to mitigate direct sunlight exposure.

Regarding the arrangement and storage of various equipment on the boat, the boat's electrical power system necessitates the presence of wires and batteries, consuming a significant amount of space. Moreover, since the boat floats on water, movement generates water splashes that could potentially damage the equipment, posing risks to users. To prevent this, protective enclosures or fastening points should be implemented to secure the batteries, and flexible conduit systems should be used for wire management. Additionally, extra protective measures for connectors and plug heads should be sought.

The heavy weight of the power distribution system is primarily attributed to the substantial weight of iron plates and the added weight of batteries. Consequently, the total weight is significantly greater compared to the original engine, which weighed only 16 kilograms. Therefore, it's advisable to opt for materials that can withstand the forces and are lighter in weight to replace the existing components. This might involve using the same materials but reducing their thickness, among other strategies.

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