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Conference Paper *in* AIP Conference Proceedings · December 2021

DOI: 10.1063/5.0070707

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Cite as: AIP Conference Proceedings **2403**, 070004 (2021); https://doi.org/10.1063/5.0070707
Published Online: 02 December 2021

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Feasibility on Introducing an Alternative Solar Powered Propelling System for Multi-day Fishing Boats in Sri Lanka

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Abstract. This paper presents a feasibility study on introducing an alternative solar powered propelling mechanism to multi-day fishing boats. Since solar energy is readily available on the sea throughout the year, this free energy could be utilized to power multi-day fishing vessels. Multi-day boats have large deck area where solar panels can be mounted above without much effort. This project involves studying the amount of power that can be generated using onboard solar panels and implementing an independent propelling system to propel the boat. A chain drive system was designed to propel the boat, when the batteries are fully charged, from an electric motor using the same propeller. A 60 feet multi-day fishing boat built by a local boat manufacturer was chosen for the study. The service speed of the boat was around 6 knots with the electric motor and the duration of cruising is 1 hour per day with around 11 hours of charging. 350-watt Mono-crystalline PV module, 75 kW HVH type motor and 10 kWh Lithium-ion Battery packs were chosen for the study. From the calculations, it was obtained that the boat has 30 PV modules (10.5 kW), 5 batteries (47 kWh) and will save around 6475 liters of diesel per annum and around 17094 kg of carbon emissions per annum. The boat dimensions are 20-meter length of water line, 5.51 meter of beam, 1.8 meter of draught, and 77 ton of total displacement with the PV system net present value of USD 12445 for 20 years of operation and a payback period of around 8.2 years.

Keywords. Multi-day fishing boats; Photovoltaic cells; Solar energy; Solar powered boat.

INTRODUCTION

Fishery sector is one of the significant sectors in Sri Lanka. In view of 2016 yearly report of the central bank of Sri Lanka 1.5% of the nation's GDP is contributed by the inland and the marine fishing. Around 350000 people in Sri Lanka are engaged in fishing with the advantage of the coastal area around the country. Considering the nations utilization of fish and the general interest in the international markets there are lot of areas to be enhanced in this sector. Sri Lanka have almost 4,650 multi-day vessels which supply deep-sea tuna to large seafood companies for exporting to Europe, America, and other major foreign markets. Prices of Fish in the local market has increased due to the fuel price in operating cost. Multi-day fishing boats needs 7000-12000 liters of diesel per trip depending on the size of the vessel. At the present setting, cost of diesel is around 3 million Sri Lankan rupees per annum and the total duration around 180 days of fishing in sea per year. Hence by reducing the diesel consumption will drop the fish prices just as uplift the wages of the fishers. As the availability of solar energy at the ocean is high, this solar energy could be utilized to propel multi-day fishing boats with significant roof area which can be used to install solar panels and charging system. Around 236,000 metric tons of hydrocarbons from vessels discovers its way into the water each year around globally and emissions from diesel cause the environment to be polluted and help an Earth-wide temperature boost, hence utilization of PV controlled multi-day boats may advance greener environment. Utilization of this study indirectly provide a viable answer for skippers to bring the vessel to the shore if the engine of the vessel fails in mid sea. The main objective of the study is to determine the feasibility of introducing an alternative solar powered propelling system that could be set up to the same propeller shaft to run the propeller by electrical motor when the batteries are fully charged. Economic Feasibility of the project was determined according to the cost analysis.

THERMOFLUID XI
AIP Conf. Proc. 2403, 070004-1–070004-9; https://doi.org/10.1063/5.0070707
Published by AIP Publishing. 978-0-7354-4167-5/$30.00

DESIGN PROCEDURE

Data Gathering

The required information was collected by interviewing sailors, boat owners and boat manufactures. Results obtained from data gathering by multiple visits to Dikkovita Fisheries harbor, Negombo Fisheries Harbor, and several local multi-day fishing boat builders, allowed the project team to choose a boat to conduct the feasibility study. Considering the deck area of the boat, a boat in 60 feet length was selected for the study.

PV energy

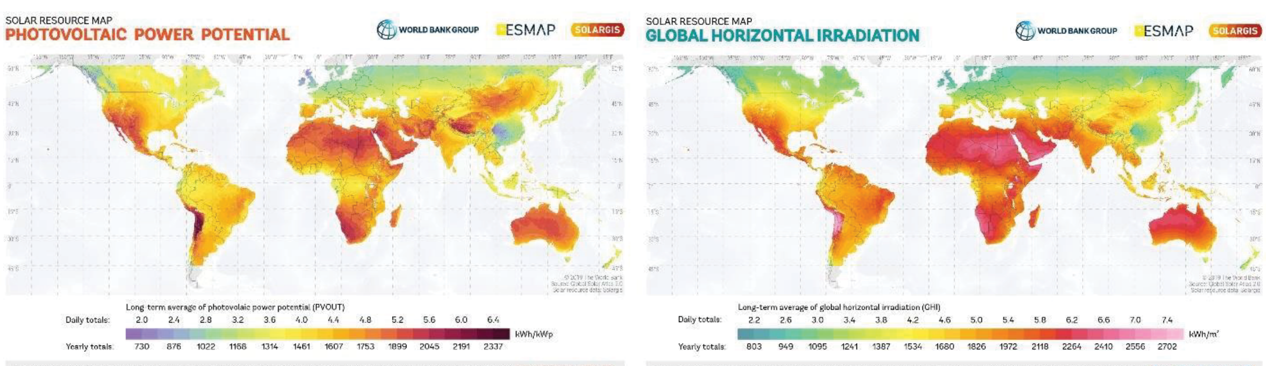
PV energy defines as solar energy harvested by PV modules which is expressed by Eq. (1).

$$E_{PV}(t) = \frac{P_{PV}}{1000}\eta_s \eta_c x_1 \int_0^{1} \frac{I_{rr}(t)}{G_{STC}} dt \tag{1}$$

Where P_{pv} is peak watt power of solar module in watt; I_{rr} is sun irradiance in kW/m2 and G_{STC} is irradiance at standard condition which equals to $1\ kW/m^2$. η_s is solar system efficiency, for incorporating energy losses due to, wiring, temperature, etc. η_c is charging efficiency for incorporating energy losses due to charging of the battery, and $x_1$is number of PV module. In this case, Mono-crystalline PV module with 350 watts produced by Hyundai marine solar was used, while η_s is assumed 80% and η_c is 85%. Irradiance of the sun depends on the boat operational location. In this case, Indian Ocean was chosen as boat operational location [9]. Marine Solar panels were selected to withstand the durability and salt conditions. Two approaches can be used to determine levels of irradiance at any location. The first approach is to use databases with irradiance information for every location. The second approach is the generation of synthesized data, based on physical attributes and location parameters. The first approach was used to determine the irradiation level available at the Indian ocean. Horizontal global irradiance level at Indian ocean is about 6.5 kWh/m^2 [13]. Total solar irradiance is given by Eq. (2).

$$I_\beta = I_{b\beta} + I_{r\beta} + I_{d\beta} \tag{2}$$

I_β is the total irradiance, $I_{b\beta}$ is the direct irradiance, $I_{r\beta}$ is the reflected irradiance and $I_{d\beta}$ is the diffuse irradiance in W/m^2. Fig. 1 shows the Snapshot of the SolarGIS database: (a) annual average photovoltaic power potential. (b) annual average global horizontal irradiation. [9]. According to Eq. (1) 51 kWh can be utilized within 11 hours of time in Indian ocean.



(a) (b)

FIGURE 1. Snapshot of the SolarGIS database: (a) annual average photovoltaic power potential. (kWh/m2) (b) annual average global horizontal irradiation. (kWh/m2) [9]

Battery Energy

The energy of battery is calculated by Eq. (3). The other affecting factors to the battery capacity such as temperature, current of charging or discharging are not considered [3].

$$E_{batt} = \frac{V_{batt} \times C_{batt} \times x_2}{1000 \times \eta_d} \tag{3}$$

Where V_{batt} is battery nominal voltage in volt and C_{batt} is battery capacity in Ampere-hour, η_d is battery discharging efficiency that represents the energy losses during energy discharging process, and x_2 is the number of batteries. In this case, a compact battery pack with a capacity of 10 kWh was chosen and 80% discharging efficiency was taken. The selected battery is equipped with a battery management system (BMS), which uses MPPT method for charging. The total energy demand (E_{load}) is the energy required to propel the boat. Total energy demand is a function of propulsion power (P_{prop}) and boat's cruising duration [14]. In this case, boat was intended to cruise for 1 hour per day. The battery bank properties are listed in table 1, The total energy demand is expressed by Eq. (4) [14].

$$E_{load}(t) = \int_0^t P_{prop}(t).dt \tag{4}$$

TABLE 1. Properties of the battery bank

Property	Value
Battery Capacity	47 kWh
Voltage	700 V
Current	67 A
Total number of Batteries	5
Weight	240 kg
Charging time	5.2 hours
Discharge Rate	80%
Charging method	MPPT

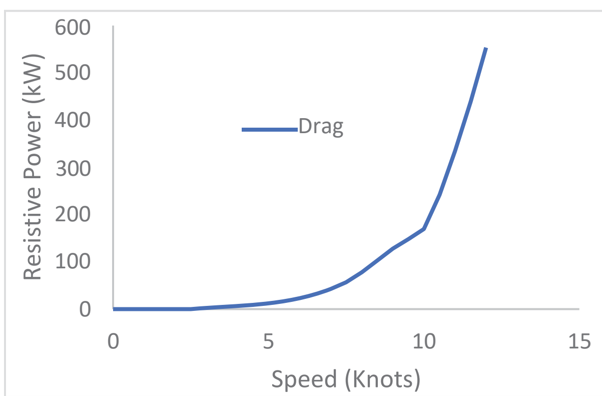


FIGURE 2. Boat Resistance Curve

Motor Selection

Propelling power is the power needed when cruising in particular speeds to overcome the resistance on the boat, supplied by the motor through propellor. Resistive power that the boat must overcome to maintain at a particular speed is illustrated in fig. 2 [14]. Propulsion power required by the motor is calculated with the propeller efficiency from Eq. (5).

$$P_T = \frac{R_T V_S}{\eta_{prop}} \tag{5}$$

P_T is the propulsion power of the boat, R_T is the resistance on the Vessel, η_{prop} is propeller efficiency and V_S is the vessel speed which is 6 knots. Torque required for the motor was calculated according to the propellor speed specified by the local boat builder. [18]. Borg Warner HVH410-150 motor was selected for the study.

Wiring

According to the American wire gauge standards the wire sizes were determined. The current through wires is 67A and the length of the wires is taken as 100 feet. The recommended wire size is 4|0 AWG.

Insulation

The electrical systems inside the boats are to be insulated to prevent damages from salty conditions. Connections must be insulated with polymer nanocomposites. Use of high-density polyethylene nanocomposites in electrical insulation have been recommended by Lau et al [12].

Motor Controller

Motor controller is used to control the operation of the motor. These operations include selecting forward or reverse rotation, speeding up or slowing down. In addition, inverting process is also achieved through the controller. Motor controller compatible to the selected motor was picked. Borg Warner motor controller Gen4 Size 10 was compatible with the Borg Warner HVH410-150 motor.

Solar Panel Installation

Solar panels are to be mounted on a roof above the deck area with a height of 7 feet from the deck. The roof has a total area of 55 square meters. 30 solar panels were mounted on the roof with an offset in height, in between solar panels. Solar panel installation is shown in fig. 3.

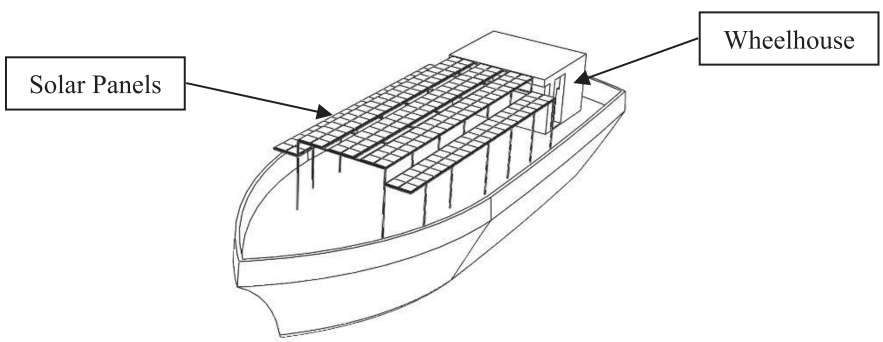


FIGURE 3. Isometric View of Solar Panel Installation

Alternative Propelling System

A chain drive system with two chains of 16B standard were used to propel the boat independent to the engine propelling system but that could be set up to the same propeller shaft to run the propeller by electrical motor when the batteries are fully charged were designed. A disk clutch was used to disengage and engage the motor from the propeller assuming uniform pressure conditions. The designed chain drive system details are listed in table 2.[19]. Vibration analysis and a static stress analysis was performed for the chain drive system. These analyses were performed with Altair hyperworks 2019 software. First order mixed 2D mesh was used with a mesh size of 2 mm. There were no resonance conditions found under operating speeds.

TABLE 2. Properties of the Chain System

Property	Value
Velocity of pinion	600 rpm
Velocity of wheel	200 rpm
Velocity ratio	3
Number of teeth of pinion	24
Number of teeth of wheel	84
Number of chains	2
Pitch Circle Diameter pinion	226.9 mm
Pitch Circle Diameter wheel	679.3 mm
Pitch line velocity	7.2 ms^{-1}
Load on the chain	5366.2 N
Braking Load	68386.9 N
Factor of Safety	12.7
Centre Distance	567 mm
Length of the chain	2646.7 mm

Vessel Stability

Stability of the vessel has a high importance in operational point of view. The change of stability of the vessel must be determined to account the wind moment acting on the vessel with solar roof. The wind lever created by the wind moment was determined by Eq. (6). Wind lever was plotted with the righting lever of the vessel to determine the maximum angle of heel. [20].

$$lw_1 = \frac{P.A.Z}{\Delta} \tag{6}$$

$$lw_2 = 1.5 lw_1 \tag{7}$$

$$P = 0.0514\ (t/m^2) \tag{8}$$

Where lw_1 is wind lever at calm wind, lw_2 is wind lever at gust wind, P is pressure, A is area, Z is height to the center of gravity above waterline and Δ is displacement in tonnes. The righting lever is obtained by Eq. (9) [14].

$$GZ = GM.Sin\theta \tag{9}$$

GZ is the righting lever and GM is the metacentric height and θ is the angle of heel. The wind lever was plotted with the righting lever to determine the equilibrium angle. In this case it was 5 degrees. The boat was assumed to roll at rolling angle to wind from the resulting angle of equilibrium due to the wave action. The rolling angle is determined by Eq. (10). [14].

$$\theta_0 = 109k.X_1.X_2.\sqrt{r.s} \tag{10}$$

Where θ_0 is the rolling angle, k is the keel factor, X_1 is a dimensional factor, X_2 is a factor related with the block coefficient, r is defined as follows,

$$r = 0.73 + 0.6\,.OG/d \tag{11}$$

Where OG is distance between center of gravity and waterline, d is the mean draft. S is determined with the rolling period,

$$T = \frac{C.B}{\sqrt{GM}} \tag{12}$$

Where T is rolling period, B is breadth of the vessel and GM is metacentric height, C is given by Eq. (13),

$$C = 0.373 + 0.023\ (B/d) - 0.043\ (L/100) \tag{13}$$

Where L is length of the vessel. In this case the rolling angle was 22.08 degrees. Fig. 4 shows the vessel is stable in both calm and gust wind conditions at full load.

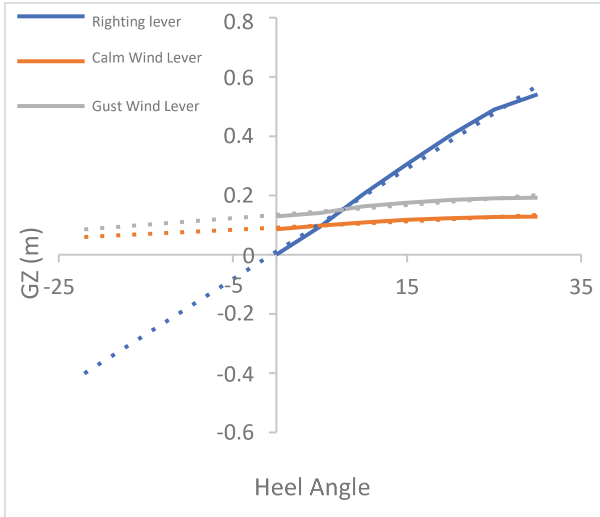


FIGURE 4. Plot of the heel angle and wind lever in clam and gust wind conditions compared with righting lever

Cost Analysis

A Cost analysis was performed to determine economic feasibility of the project. Payback period was calculated by identifying the cash outflows and cash inflows. Simple payback period is given by Eq. (19),

$$Payback\ Period = \frac{Cash\ outflows}{Cash\ inflows} \tag{14}$$

Life cycle cost analysis was performed to determine the cost spend on the assets over the course of its useful life. Life cycle costing was performed for Cost of Installing and Cost of maintenance. Life cycle cost of batteries is given by Eq. (20) [15].

$$LCC = \frac{C_{in}.1000+C_{o\&m}}{n.E} \tag{15}$$

Where, C_{in} is the capital expenses, $C_{o\&m}$ is the operation and maintenance cost, n is the lifetime and E is energy stored. Life cycle cost of solar panels is given by Eq. (16).[16].

$$LCC=C_{in}+C_{o\&m} \tag{16}$$

Where, C_{in} is capital expenses and $C_{o\&m}$ is operation and maintenance cost. Discount rate of 4.5% is used in calculations and a lifetime of 10 years. Maintenance cost of batteries are assumed to be 2% [17] and for solar panels 1% of the initial investment. The present value of the future operating cash flows is given by Eq. (17).

$$PV = \frac{FV}{(1+r)^t} \tag{17}$$

Where FV is future value, r is discount rate and t are the time in years [16]. Net present value was obtained for utilizing the solar powered system for 20 years, to confirm the economic feasibility of the project. According to the net present value the economic feasibility of the project was determined. A positive NPV value will make the project feasible, but the implementation of the system is up to the operators of the boat due to the uncertainties.

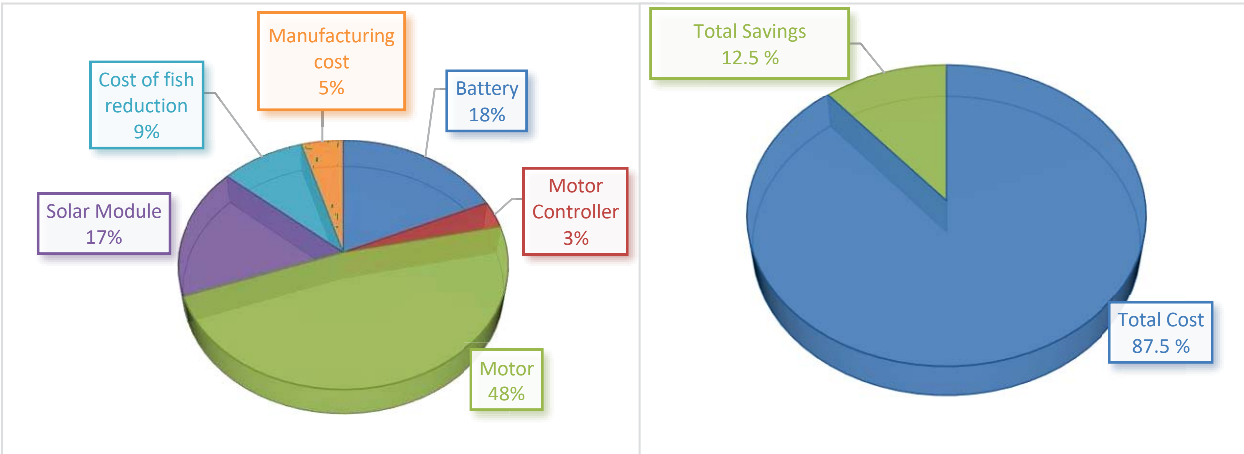
RESULTS AND DISCUSSION

Based on the procedure as described in the section of design procedure, the results of cost analysis are summarized in Table 3. This configuration can produce the propulsion power around 51 kW from PV system, the number of PV modules were around 30 modules (10.5 kW) and the number of batteries was 5 battery packs (47 kWh), with the available PV energy the boat can run for continuous operation of 1 hour per day at a speed of 6 knots with 11 hours of charging. When determine the feasibility of the project the payback period was determined. There were several cash outflows identified, Cost of solar panels, cost of the motor and controllers, cost of batteries, cost of manufacturing structures and cost of fish load reduced due to overfittings. When calculating the cost of fish, average price of fish was considered. Cash inflow was identified as the savings from fuel. Calculated simple payback period was around 8.2 years (Table 3), when the payback period is 8.2 years the batteries will be deteriorated about 80%, therefore the batteries must be replaced in the 10th year of commissioning. The total life of the components was assumed to be 20 years, to recover the initial investment. Factors affecting the performance of the system components were assumed to be ideal, hence in the practical scenario the calculated payback period will vary about 10% to 15%. The inflation rate of Sri Lanka is about 4.67% and it is predicted that the price of a dollar will be increased to 198 Lankan rupees from the current rate of 184 Lankan rupees in 2021 [22]. Thus, these cost values will be increased about 8% in a year. Table 3 shows a positive net present value; thus, the project is economically feasible when used for a period of 20 years. Utilization of solar power will save around 6475 liters of diesel per annum and around 17094 kg of carbon emissions per annum [24].

TABLE 3. Summary of the Cost Analysis.

Property	Value
Battery	\$5280
Motor Controller	\$996
Motor Purchase Cost	\$13924
Motor Operation Cost	\$85
Solar Module	\$4950
80A28 Sprocket	\$70
80A84 Sprocket	\$758
Chain	\$84
Shaft	\$8.487
Motor Cage	\$236.88
Clutch Plate	\$40
Clutch Assembly	\$120
Manufacturing Cost	\$1317.5
Cost of fish reduction	\$2638.8
Total Cost	\$29099.5
Total Savings Per Trip	\$1214
Total Savings Per Annum	\$3640
Total Savings	\$69160
Payback Period	8.2 years
Net Present Value	\$12,445.23

Fig. 5(a) shows the percentage of the total costs incurred throughout the project. Battery (around 16% of total cost) and the motor (around 43% of total cost) are the major components which directly influence the total cost of the project. The size of the battery and the motor was determined by the total resistance acting on the boat. Therefore, the cost of these components for a specific boat is limited. To reduce these costs, the design of the hull and the service speed must be optimized to reduce overall resistance. The return on investment (ROI) of utilizing this project is around 12.5% per annum illustrated in fig. 5(b).



(a) (b)

FIGURE 5. (a) Average cost of system components (% of total cost). (b) The return on investment of the project.

Total savings of the project depends on the amount of solar power harvested. Hence the possibility of propelling the boat with electricity generated from a smaller prime mover assisted with solar power must be carried out. With fossil fuels being depleted at a rate of 66.48 billion barrels of oil per year [23] and the environmental issues arising because of burning of fuels, boat operators should move into these alternative energies.

CONCLUSION

Solar powered alternative propelling system for multi-day fishing boats has been studied. Regarding the solar system, the system has 30 solar modules (10.5 kW), 5 li-ion battery packs (47 kWh) and powered with a 75 kW HVH type motor. The economic feasibility of the introduced system was evaluated. Considering the cost analysis, the project is economically feasible with a payback period of 8.2 years and a positive net present value for 20 years of utilization. Comparing to the existing vessel, solar powered vessel will save around 6475 liters of diesel per annum and around 17094 kg of carbon emissions per annum. This is a preliminary study where the results were obtained with assumptions on some factors such as environmental conditions, cost of the components of solar powered system and ideal working conditions. For future studies, multi objective optimization of the components and use of diesel electrical system to propel the boat with assistance of solar power may be carried out. It is concluded that the project has a high potential as an alternative to be developed in the future.

ACKNOWLEDMENTS

Our gratitude goes to Dr. W.K. Wimalsiri for supervising the work presented in this paper and Mr. Harshana Seneviratne for co-supervising the work presented in this paper.

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