Available online www.jsaer.com

Journal of Scientific and Engineering Research, 2024, 11(12):95-102

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Hybrid Energy System Characterization of A Catamaran Vessel

Uchenna A. Robinson[1]*, Azubuike J. Chuku[2]

[1,2]Department of Marine Engineering, Rivers State University, Port Harcourt, Rivers State, Nigeria
Uchenna.robinson1@ust.edu.ng

Abstract: This research focuses on the analysis of a hybrid energy system for a catamaran vessel operating in Gulf of Guinea, aiming to enhance energy efficiency, reduce emissions, and promote sustainability in maritime transportation. The proposed hybrid system integrates solar photovoltaic (PV) panels, lead-acid batteries, and a backup diesel generator to meet the energy demands of a 12-meter catamaran operating in Port Harcourt, Nigeria. The system is designed to address the environmental and operational challenges of conventional diesel-powered vessels, offering a cleaner alternative by utilizing renewable energy sources. Through a detailed energy production and consumption analysis, the study demonstrates that the hybrid system can significantly reduce the reliance on diesel fuel, achieving an annual CO_2 emissions reduction of 47.6% compared to a diesel-only system. The solar PV array generates the majority of the vessel's energy during peak solar months, while the diesel generator ensures operational reliability during periods of low solar irradiance. Despite the seasonal variations in solar energy, the system effectively meets the catamaran's energy needs with an estimated annual diesel consumption of 1510 liters. This research highlights the potential of hybrid power systems to enhance the environmental performance of maritime vessels. However, it also identifies limitations in energy storage capacity and suggests further exploration of advanced battery technologies and renewable energy sources. The findings underscore the importance of hybrid systems in advancing sustainable maritime practices while reducing operational costs and emissions.

Keywords: Hybrid, catamaran, emission, solar radiation, photovoltaic

1. Introduction

The marine sector is at a turning point in its history as concerns over environmental sustainability and the pursuit for efficient energy consumption rise. For a long time, this industry has depended heavily on conventional fossil fuels for both onboard power consumption and propulsion systems. However, the pressure to adopt cleaner and more efficient alternatives has been especially pronounced in catamaran vessels, which have emerged as versatile platforms for various maritime operations. Catamarans, with their distinct twin-hull configuration and narrow beam, have seen a surge in popularity across diverse maritime applications. Tracing their roots to ancient Polynesian designs, these vessels have come a long way, evolving from traditional sailing craft to modern motorized variants. Their inherent stability, enhanced speed capabilities, and spacious deck layouts have made catamarans indispensable in sectors like passenger transportation, leisure cruising, and naval operations.

The multi-purpose utility of catamarans is exemplified by their use in ferry services, where they offer increased passenger comfort and reduced transit times compared to conventional monohull ferries. For instance, the introduction of catamaran ferries on routes connecting islands and coastal regions has revolutionized regional transportation networks, enabling rapid and efficient maritime connectivity [1]. Additionally, catamarans have found favor in luxury yacht construction, catering to the discerning preferences of affluent clientele with their expansive interiors and superior stability [2]. Beyond commercial and recreational endeavors, catamarans have also made significant strides in specialized domains like offshore wind farm maintenance and search and rescue operations. Their ability to navigate shallow waters and withstand adverse sea conditions makes them invaluable assets in these critical sectors, where operational efficiency and safety are paramount [3]

Despite the numerous advantages of catamaran vessels, they're not immune to the environmental challenges facing the maritime industry. Concerns about carbon emissions, fuel consumption, and overall environmental impact have prompted maritime stakeholders to explore alternative technologies. In this regard, hybrid power systems have emerged as a promising solution, integrating multiple power sources such power sources like electric motors, internal combustion engines, and renewable energy generators to enhance efficiency and environmental performance. By harnessing the complementary strengths of different technologies, hybrid catamarans offer the potential to reduce reliance on fossil fuels while optimizing energy utilization. Government initiatives aimed at curbing greenhouse gas emissions and promoting renewable energy adoption have further incentivized the development and deployment of hybrid catamarans [4].

Hybrid power systems, combining multiple energy sources and propulsion technologies, have emerged as a promising solution to address the environmental challenges faced by the maritime industry. These systems typically integrate electric motors, internal combustion engines, and renewable energy sources like wind turbines and solar photovoltaic (PV) panels [5]. The integration of hybrid power systems offers several benefits, including reduced fuel consumption, lower emissions, improved energy efficiency, and operational flexibility. By leveraging the complementary strengths of different power sources, hybrid systems can optimize energy utilization and minimize environmental impact [6]. Research by Reza [7] analyzed the feasibility of using solar PV and wind power for fishing boats in Bangladesh, highlighting the potential for hybrid systems to meet energy demands while reducing fossil fuel dependency. The maritime industry stands to benefit from the approach’s capability to monitor and manage critical energy systems during marine operations. This provides a guide/early warning against total failure of the critical ship systems [17].

Chakraborty et al. [8] conducted a study focusing on the design and implementation of an energy storage system for a fishing trawler. The researchers developed a Maximum Power Point Tracking (MPPT)-based solar PV system integrated with a lead-acid battery bank. This configuration allowed for fast charging and efficient energy storage, meeting the power requirements of the vessel while minimizing reliance on conventional fuel sources. By leveraging energy storage technology, the fishing trawler was able to optimize energy utilization, fuel consumption reduction, and enhance overall effectiveness of operation. They further highlighted the importance of cost-effective solutions in their design of a solar PV system for a fishing trawler, underscoring the need for economic viability. Liu [9] investigated the integration of energy storage systems with solar PV technology on ships, highlighting the potential for significant cost savings associated with battery replacement. Smith et al. [10] conducted a study on the implementation of regenerative braking in a passenger ferry, demonstrating its effectiveness in reducing fuel consumption and emissions. The researchers developed sophisticated control algorithms to maximize energy capture during braking events, highlighting the potential for regenerative braking to enhance the sustainability of maritime operations. A case study of a zero-emission electric propulsion boat with a permanent magnet synchronous motor (PMSM) that is powered by solar PV panels and lithium-ion batteries and intended for use in water sports and public transit was given by Postiglione et al. [11]

A solar-electric tourist boat with sophisticated energy management systems for battery charging and discharging was proposed by Spagnolo et al. [12], allowing for pollution-free operation and inexpensive running expenses. The study highlighted the potential for hybrid catamaran vessels in the tourism sector, catering to environmentally conscious travelers. Furthermore, they presented a comprehensive system architecture involving solar PV arrays, batteries, MPPT controllers, boost converters, inverters, and power management controllers, highlighting the importance of seamless integration and control strategies. Leung et al. [13] conducted case studies on a PV-powered boat, demonstrating the potential cost savings and reductions in CO_2 emissions compared to conventional diesel-powered vessels. Liu [14] explored emission reduction strategies by installing energy storage and photovoltaic systems on ships, highlighting the potential for significant environmental benefits. Hua [15] discussed the feasibility of integrating renewable energies, including solar PV, in the Taiwanese maritime industry, considering the potential impact of government policies and regulations.

2. Materials and Methods

Materials

i. Catamaran Vessel Specifications

The catamaran passenger boat (CPB) considered in this study is a fiberglass polyester vessel with the following dimensions as seen on Mohammad & Tariq [16]:

Length: 12 meters

Width: 4.8 meters

Carrying capacity: 20 passengers

Speed: 10 km/h (5.4 knots)

ii. Solar Photovoltaic (PV) Modules

The solar PV modules employed in the system are polycrystalline silicon modules from Canadian Solar, specifically the CS6U-330P model. Each module has the following specifications:

Rated power: 330 watts

Maximum power point Voltage (V_{mp}): 36.9 volts

Maximum power point Current (I_{mp}): 8.92 amperes

Open-circuit voltage (V_{oc}): 44.98 volts

Short-circuit current (I_{sc}): 8.95 amps

Module dimensions: 1.96 meters × 0.992 meters

Number of cells: 72 (polycrystalline)

The total installed PV capacity is 10.6 kilowatt-peak (kWp), consisting of 16 modules arranged in 8 parallel strings, with two modules in series per string.

iii. Battery Bank

The battery bank comprises 16 lead-acid batteries from Trojan, model SAGM 06 220. The specifications of each battery are as follows:

Nominal voltage: 6 volts

Rated capacity: 220 ampere-hours (Ah)

Battery type: Absorbed Glass Mat (AGM) lead-acid

The batteries are configured in a 48-volt system, with eight batteries connected in series to form a string, and two such strings connected in parallel to achieve the required capacity and voltage.

Design Methodology

i. Load Assessment

Table 1: Energy Demand for the PV System

Equipment	Run time (h)	Power (kW)	Energy Consumed (kWh)
BLDC Motor	8	5.00	40.00
Light 1	1	0.06	0.06
Light 2	3	0.04	0.12
Navigational systems and others	8	0.24	1.92
	Total Load		42.10

The first step in the design methodology was to assess the energy demand of the catamaran passenger boat (CPB). The total electrical load demand was calculated to be 42.10 kilowatt-hours per day (kWh/day). This demand includes the energy required for propulsion (a 5 kW PMDC motor), lighting, control systems, and other auxiliary loads.

ii. Resource Assessment

To accurately size the solar PV array and estimate the system's energy production, an assessment of the solar resource available at the project location in Port Harcourt, Nigeria. The monthly average solar radiation data was calculated using Hargreaves-Samani equation.

$$R_s = k_1 \times R_a \times T_d^{0.5} \quad (1)$$

Where k_1 is a constant obtained as 0.16.

R_a is extraterrestrial solar radiation and T_d is the difference between the max and min temperature. The maximum and minimum temperatures as well as the monthly hours of sunshine for Port Harcourt were obtained via weather-and-climate.com (2024). Their respective values are also shown in the Table 2.

Amadi et al. [17] evaluated the values of the monthly clearness index in Port Harcourt. The monthly values are shown in Table 2

Table 2: Average Monthly Values of Key Parameters in the Study [Weather-and-climate.com (2024)]

Month	Max temp	Min Temp	T_d	R_a KWh/m²/day	Clearness Index	Average solar radiation (R_s)	Hrs of Sunshine
Jan	33	24	9	9.562	0.45	4.59	143
Feb	34	24	10	9.865	0.48	4.99	125
March	33	25	8	10.179	0.42	4.61	115
April	32	25	7	10.404	0.41	4.40	133
May	32	24	8	10.598	0.42	4.80	140
June	30	24	6	10.712	0.41	4.20	104
July	29	23	6	10.543	0.36	4.13	78
August	29	23	6	10.262	0.35	4.02	75
Sept	29	23	6	9.931	0.41	3.89	79
Oct	30	23	7	9.609	0.44	4.07	105
Nov	32	24	8	9.315	0.51	4.22	134
Dec	33	24	9	9.067	0.49	4.35	150

Also, performing manual calculations using the Hargreaves-Samani equation to evaluate monthly average solar radiation, we obtain the values as it appears on the average solar radiation (**R_S**) column of table 2 above.

It can be seen from Table 2 the solar radiation data varies between 3.89 and 4.99 kilowatt-hours per square meter per day (kWh/m²/day), with an annual average of 4.36 kWh/m²/day and a clearness index of 0.52. The highest solar radiation is observed from December to May, with the peak in May (4.99 kWh/m²/day), while the lowest radiation occurs from June to November, with the minimum in September (3,89 kWh/m²/day).

iii. Hybrid System

With the obtained energy demand of the catamaran vessel, calculation must be done to obtain the amount of energy that the PV provides during the course of the year and then evaluate how much diesel would be needed for the general to completely meet up the energy demand of the vessel. This can be calculated using the formula

$$E_{solar} = P \times T_{avg} \times N \qquad (2)$$

Where E_{solar} is the energy provided by the PV system, P is the rated power of each module/panel, T_{avg} is the average hours of direct sunlight, N is the number of modules/panels. Given P is 330W (0.33KW) and N is 16. T_{avg} can easily be calculated by dividing the monthly average hours of sunshine by the number of days of each month.

The table below gives the calculated values of T_{avg} and E_{solar} for each month.

Table 3: Monthly calculated values of T_{avg} and E_{solar}

Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
T_{avg}(hrs)	4.6	4.5	3.7	4.4	4.5	3.5	2.5	2.4	2.6	3.4	4.5	4.8
E_{solar} (KWh)	24.3	23.8	19.5	23.2	23.8	18.5	13.2	12.7	13.7	18.0	23.8	25.3

The amount of energy that need be supplied by the generator E_{gen} can be calculated thus:

$$E_{gen} = E_{total} - E_{solar} \qquad (3)$$

Where E_{total} is the energy demand of the vessel a day, previously assessed to be 42.1KWh/day

Table 4: Calculated Monthly Values of E_{gen}

Month	Jan.	Feb.	Mar.	Apr.	May	June	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.

E_{gen} (KWh/day)	17.8	18.3	22.6	18.9	18.3	23.6	28.9	29.4	28.4	24.1	18.3	16.8

Spagnolo et al. [12] established a relationship that can be used to ascertain the quantity of diesel fuel that would be needed to meet and cover up the energy demand of the generator.

$$Q_{Diesel} = \frac{E_{gen}}{\eta_{gen} \times \rho_{DE} \times \rho_D} \qquad (4)$$

Where Q_{Diesel} is the quantity of diesel fuel in litres, η_{gen} is the efficiency of the generator (30-40%), ρ_{DE} is the diesel energy density (13.8 KWh/kg), ρ_D is the diesel density (0.85kg/ltr)
After calculations taking efficiency of generator as 30%, we have

Table 5: Calculated Monthly Values of Quantity of Diesel

Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Q (ltrs/day)	5.1	5.2	6.4	5.4	5.2	6.7	8.2	8.4	8.1	6.8	5.2	4.8
Q (ltrs)	102	104	128	108	104	134	164	168	162	136	104	96

Hence annually, the quantity of diesel needed would be;

$$Q_{Diesel} = \sum_{i=1}^{12} Q_i \qquad (5)$$

$Q_{Diesel} = 1510 ltrs$
Finally, using the general formula for calculating the amount of CO_2 emissions given the amount of diesel fuel consumed

$$CO_2 \text{ emission} = Q_{Diesel} \times e_{f,diesel} \qquad (6)$$

Where $e_{f,diesel}$ is the CO_2 emission factor of diesel taken as 2.64kg CO_2/litre according to ICCP (2006)
$CO_2 \text{ emission} = 1510 \times 2.64$
$CO_2 \text{ emission} = 3986.4 kg\ CO_2/year$

Conventional Diesel Only System

For the Diesel only system, the energy demand of 42.1KWh would need to be met solely on the diesel generator. Using **Equation (3)** once again, we can estimate the quantity of fuel needed as;

$$Q_{Diesel} = \frac{42.1}{0.3 \times 13.8 \times 0.85}$$

$$Q_{Diesel} = 12 \text{ litrs/day}$$

Hence the annually, that is for 240 working days, the quantity of diesel needed would be

$$Q_{Diesel} = 240 \times 12$$
$$= 2880 \text{ litrs}$$

Calculating the amount of CO_2 emissions given the amount of diesel fuel consumed

$$CO_2 \text{ emission} = 2880 \times 2.64$$
$$CO_2 \text{ emission} = 7603.2\ CO_2/year$$

3. Results & Discussion

Hybrid System Production

The hybrid system's solar photovoltaic (PV) array serves as the primary source of energy, with a rated capacity of 10.6 kW. As observed, the PV system's production varies throughout the year due to changes in solar irradiance. The highest energy output occurs during the summer months when solar irradiance and daylight hours are maximized. On the other hand, the system relies more heavily on the diesel generator during the winter months when solar irradiance is lower (Table 3).

This trend highlights the seasonal dependency of solar power and the crucial role of hybrid systems in ensuring continuous operation. The analysis shows that during periods of high irradiance, the PV array is able to cover most of the vessel's energy demand, thus significantly reducing diesel consumption. As illustrated in Figure 4.2, PV energy production peaks from November to February and April to May, covering nearly 50-70% of the daily demand. The optimized integration of the PV system ensures efficient utilization of renewable energy while minimizing fuel usage during optimal months.

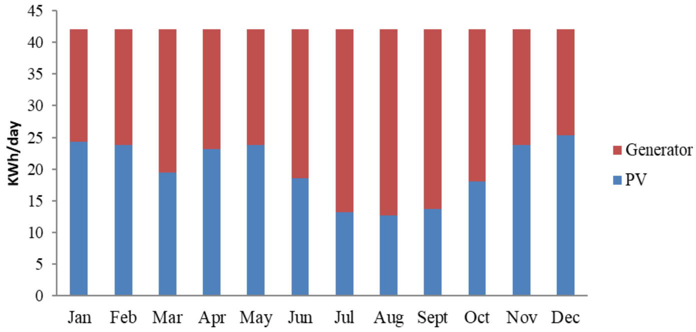

Figure 1: Monthly Solar PV and Generator Energy Production

Figure 1 illustrates the monthly energy production of the solar component as compared with that of the generator to meet the energy demand of the catamaran throughout the year. As expected, higher PV production is observed during summer months due to increased solar irradiance and longer daylight hours, while winter months require higher usage of generator due to low solar irradiance and lesser daylight hours.

Solar Radiation and Energy Deficit Analysis

This section examines the relationship between monthly solar radiation and the energy deficit that is the energy that must be covered by the diesel generator. While the hybrid system relies on solar energy as the primary source, seasonal variations in solar radiation significantly affect energy production.

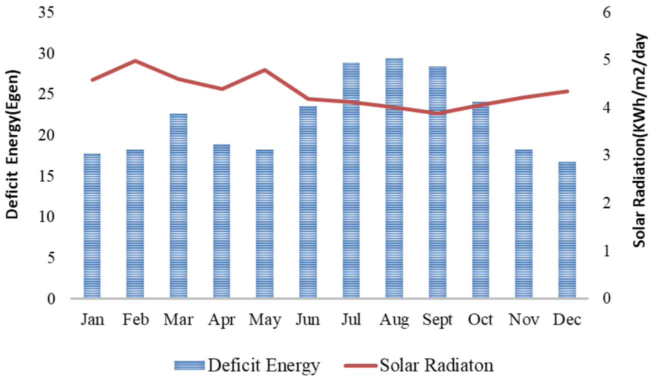

Figure 2: Solar Radiation to Deficit Energy Analysis

By comparing the solar radiation data (Table 2) with the vessel's daily energy demand of 42.1 kWh, it becomes clear that the solar PV system cannot fully meet the demand, resulting in an energy deficit. This deficit, as shown in Figure 2, highlights the months where the generator is most heavily utilized due to low solar production.

For example, during July and August, where irradiance drops to its lowest (4.02 and 3.89 kWh/m²/day respectively), the PV system's output is insufficient, and the energy deficit reaches its peak. This analysis provides insights into why generator usage spikes during these months (Figure 2), and further underscores the limitations of the solar PV system in periods of low irradiance.

Diesel Generator Usage

The 1.6 kW diesel generator acts as a backup during periods of insufficient solar production, particularly in the rainy and winter months. The analysis reveals that annual diesel consumption for the hybrid system is approximately 1510 liters, representing a considerable reduction compared to a diesel-only system that would consume 2880 liters annually. This reduction is largely attributable to the hybrid system's reliance on solar power during peak irradiance months, which reduces the need for diesel-generated electricity by nearly half.

Notably, the diesel consumption spikes in months with lower solar production, such as July and August, when solar irradiance drops below 3.5 kWh/m²/day (Table 2). However, even during these months, the hybrid system manages to optimize fuel consumption by balancing energy production between the PV array and the generator.

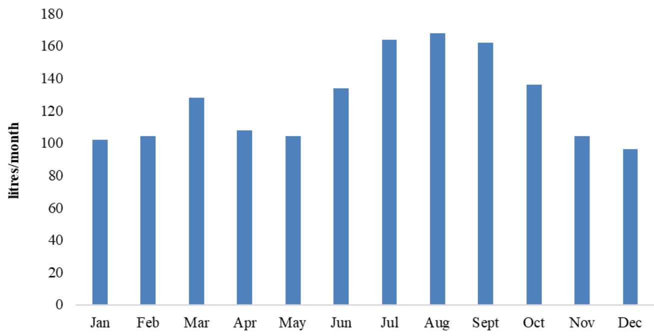

Figure 3: Monthly Diesel Generator Diesel Consumption

Figure 3 shows the monthly diesel consumption of the diesel generator. Higher quantity is observed during rainy months when solar irradiance is typically lower.

Emissions Reduction

A critical benefit of the hybrid system is its significant reduction in carbon dioxide (CO_2) emissions compared to a diesel-only system. The annual CO_2 emissions for the hybrid system amount to approximately 3986.4 kg, a 47.6% reduction from the 7603.2 kg emitted by the diesel-only system (Figure 3). This considerable decrease in emissions underscores the environmental advantages of hybrid systems, particularly in maritime applications where vessels operate in environmentally sensitive areas.

By relying primarily on renewable solar energy for a substantial portion of the energy demand, the hybrid system not only reduces operational costs but also minimizes the vessel's carbon footprint. This is particularly important in the context of global efforts to curb greenhouse gas emissions in the maritime industry, as highlighted by the International Maritime Organization's (IMO) 2020 regulations.

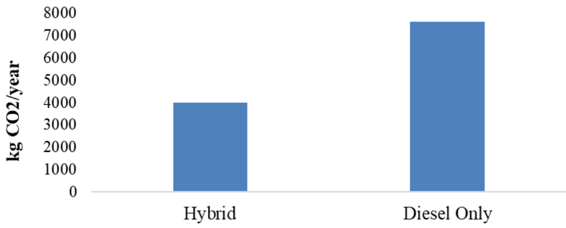

Figure 4: Annual Emissions Comparison of the Hybrid and Conventional diesel system

Figure 4 compares the annual emissions of the hybrid system with a conventional diesel-only system. As seen, the Hybrid emits 3986.4 kg CO_2/year as compared with the Conventional Diesel emitting 7,603.2 kg CO_2/year. This represents a significant 47.6% reduction in CO_2 emissions, significantly lowering the catamaran's carbon footprint.

4. Conclusion

The integration of hybrid power systems in catamaran vessels, as explored in this study, presents a promising solution for improving energy efficiency, reducing operational costs, and minimizing environmental impact. By combining solar photovoltaic (PV) systems, energy storage, and a backup diesel generator, the hybrid system provides a balance between sustainability and reliability, reducing the overall dependence on fossil fuels. The performance analysis demonstrates that the hybrid system can supply a significant portion of the catamaran's energy demand, especially during peak solar months, leading to a notable reduction in fuel consumption and greenhouse gas emissions compared to a conventional diesel-only system.

The findings indicate that the hybrid system can achieve a 47.6% reduction in CO_2 emissions annually, positioning it as a viable option for eco-friendly maritime operations. Despite seasonal variations in solar energy production, the diesel generator ensures continuous operation, highlighting the system's reliability. However, the study also recognizes challenges, such as limitations in energy storage capacity and the intermittent nature of solar energy, which call for further technological advancements.

Reference

[1]. J. Smith, "Economic impact of catamaran ferry services: A case study of the Mediterranean region," Maritime Economics Review, pp. 15(1) 78-92, 2018.

[2]. R. Jones, "Luxury yacht trends: The growing popularity of catamaran designs," Yachting Today, pp. 12(2), 45-50., 2021.

[3]. A. Brown, J. Templin, I. B. Sperstad, A. Steen and U. Nelsion, "Utilization of catamarans in offshore wind farm maintenance," Journal of Renewable Energy, pp. 131, 1111-1123., 2019.

[4]. IMO, "Global regulations on maritime emissions: Overview and implications for hybrid catamarans," IMO Publication No. 12345., 2020.

[5]. J. Campillo, F. Walenny, R. Diaz, D. Fernandez and J. P. Garcia-Quesada, "Trends and Emerging Marino Renewable Energy Powered Motorized Vehicles: A Review. Journal of," Journal of Maritime Research, pp. 14(1) 75-88, 2017.

[6]. M. Spagnolo, E. Servidio, F. Papini and S. Cassese, "Design and implementation of a solar powered catamaran for tourist applications. IEEE International Conference on," in IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Europe, 2018.

[7]. S. M. Reza, M. I. Hossain and F. Ahmad, "Performance analysis of an integrated system of solar photovoltaic and wind energy for fishing boat: Bangladesh perspective," in 9th International Conference on Electrical and Computer Engineering (ICECE), Bangladesh, 2016.

[8]. M. K. Chakraborty, S. Sharma and R. Singh, "Design and analysis of an MPPT-based solar photovoltaic system for fishing trawlers," Renewable Energy Focus, pp. 27-37, 2020.

[9]. J. Liu, "Application of solar photovoltaic energy and advanced energy storage technology in ships," Ships and Offshore Structures, pp. 16(5), 497-509., 2021.

[10]. T. W. Smith, P. Ranjitkar, R. Bucknall and P. Fricke, "Feasibility study of solar assisted marine propulsion system for a short-route passenger ferry," Journal of Marine Science and Engineering, pp. 6(2), 39., 2018.

[11]. F. Postiglione, M. Mattei and P. Troisi, "A new electric propulsion system with PMSM for catamaran boat," in AEIT International Annual Conference, Bari, Italy, 2018.

[12]. M. Spagnolo, E. Servidio, F. Papini and S. Cassese, "Design and implementation of a solar powered catamaran for tourist applications," in 18th IEEE International Conference on Environment and Electrical Engineering, Palermo, Italy, 2018.

[13]. P. K. Leung, N. Stratton, P. Hills, Y. Miao, W. Yuan and Y. Zhang, "Fuel saving and emission reduction potential of a solar photovoltaic system on a marine vessel," International Journal of Naval Architecture and Ocean Engineering, pp. 12(1), 165-177, 2020.

[14]. J. Liu, "Application of solar photovoltaic energy and advanced energy storage Technology in Ships," Ships and Offshore Structures, pp. 16(5), 497-509, 2021.

[15]. J. Hua, "Feasibility study of introducing renewable energy into Taiwan's maritime industry," Maritime Policy and Management, pp. 44(8), 1005-1019, 2017.

[16]. A. Mohammad and I. M. Tariq, "Optimal design, dynamic modeling and analysis of a hybrid power system for a catamarans boat in Bangladesh," European Journal of Electrical Engineering and Computer Science, pp. 5-10, 2021.

[17]. S. Amadi, T. Dike and S. Nwokolo, "Global Solar Radiation Characteristics at Calabar and Port Harcourt Cities in Nigeria," Trends in Renewable Energy, vol. 6, no. 2, pp. 111-130, 2020.