COVER PAGE

HYBRID ENERGY INTEGRATION FOR A PASSENGER FERRY: UTILIZING SOLAR POWER IN PASSENGER FERRY DISESL GENERATOR

BY

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MARCH, 2025.

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TO

DEPARTMENT OF MECHANICAL ENGINEERING,FACULTY OF ENGINEERING UNIVERSITY OF BENIN, BENIN-CITY. IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF BACHELOR IN ENGINEERING DEGREE DEPARTMENT OF MARINE ENGINEERING, UNIVERSITY OF BENIN.

MARCH, 2025.

CERTIFICATION

This is to certify that the research project submitted to the Department of Mechanical Engineering was carried out by OKOYE ROSEMARY CHINECHEREM, and ONWUATUELO ONYEBUCHI of the Department of Marine Engineering, University of Benin, Benin City, Edo State, Nigeria, under the supervision of Professor Godfrey O. Ariavie

PROF GO. ARIAVIE **(PROJECT SUPERVISOR)**	**DATE**
ENGR. WISDOM JAJA **(PROJECT COORDINATOR)**	**DATE**
PROE EG. SADJERE **(HEAD OF DEPARTMENT)**	**DATE**

DEDICATION

We dedicate our project to God Almighty for all of his blessings and grace, as well as to our devoted parents and families for their support and affection throughout our time at the University of Benin.

Furthermore, we dedicate this project to everyone who motivates us to dream big, push the envelope of what is feasible, and never accept mediocrity. We hope that our combined efforts will demonstrate the value of cooperation, creativity, and tenacity in accomplishing our objectives and having a significant influence on our industry.

ACKNOWLEDGEMENT

We would like to express our sincere appreciation to all those who have supported us in completing this project. First and foremost, we want to thank God Almighty for watching over us and guiding throughout our life's.

I appreciate the efforts of my parents Mr. and Mrs. Stephen Okoye and Mr. and Mrs .Anthony Onwuatuelo for bringing me up morally and academically, whose unending love, have been our guiding light., your constant encouragement and camaraderie have made this endeavour all the more meaningful. I must register my profound gratitude to my parent for their guide, moral and financial supports. Also, we are grateful to our supervisor, Prof. G.O. Ariavie, for his guidance, feedback, and encouragement throughout this project.

We acknowledge the impact over the years of some of my lecturers and the influence these individuals have had in shaping our lives as a marine engineering student in training, the person of Engr. W. Jaja, Engr. M. Osikhueme, Dr. H. Egware, and others, to name a few,

We express our deepest gratitude to our beloved siblings Kester Eberechukwu Okoye, Oluoma Favour Okoye, Amake Grace Okoye, Makuachukwu Feargod Okoye, Ifeanyi Onwuatuelo and Vincent Onwuatuelo Special thanks to our friends Joy Omamofe Osagehale, Chukz, Tobe and Dybala support, and encouragement throughout this journey.

ABSTRACT

The increasing cost of diesel fuel and the environmental impact of carbon emissions have driven the maritime industry to explore hybrid propulsion systems that integrate renewable energy sources. This research focuses on optimizing the propulsion system of a 8m small passenger ferry by incorporating solar energy alongside a diesel generator to enhance operational efficiency and sustainability. The study examines a 10 kW marine diesel generator and a 48V lead-acid battery system to assess fuel consumption, CO_2 emissions, and cost reduction when supplemented with solar power. A detailed analysis of fuel consumption reveals that the diesel generator alone consumes approximately 2.5 to 3 liters per hour, leading to substantial operational costs. By integrating a solar photovoltaic (PV) system, generator runtime can be reduced, resulting in lower diesel consumption and decreased CO_2 emissions. Calculations show that solar energy can reduce fuel costs by up to 50%, extending generator lifespan and minimizing maintenance costs. The research includes battery runtime calculations, solar energy contribution estimates, and diesel generator sizing to determine optimal hybrid system performance. A comparison of fuel consumption and emissions with and without solar integration demonstrates the system's efficiency improvements. Findings suggest that the hybrid approach offers a cost-effective and environmentally sustainable solution for small passenger ferries, reducing fuel dependency and enhancing energy efficiency. This study concludes that integrating solar power into marine propulsion systems is a viable strategy for improving economic feasibility and environmental sustainability in the maritime sector. The research provides a foundation for further development of hybrid solar-diesel propulsion technologies in passenger ferries and other small vessels

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ABBREVIATIONS

PV – Photovoltaic

COE – Cost of Energy

NPC – Net Present Cost

UHC – Unburned Hydrocarbon

PM – Particulate Matter

SO – Sulfur Dioxide

NO_x – Nitrogen Oxides

CO – Carbon Dioxide

MPPT – Maximum Power Point Tracking

IMO – International Maritime Organization

MARPOL – International Convention for the Prevention of Pollution from Ships

LFP – Lithium Iron Phosphate (Battery Type)

BB – Battery Bank

MSC – Motor Speed Controller

OBC – Optimization-Based Control

RBC – Rule-Based Control

DRL – Deep Reinforcement Learning

ESS – Energy Storage System

SCC – Solar Charge Controller

Li-ion – Lithium-Ion Battery

PWM – Pulse Width Modulation

RPM – Revolutions Per Minute

DC – Direct Current

AC – Alternating Current

HVAC – Heating, Ventilation, and Air Conditioning

SDGs – Sustainable Development Goals

TL – Load Torque

HOMER – Hybrid Optimization Model for Electric Renewables (Simulation Tool)

ROI – Return on Investment

GWP – Global Warming Potential

GHG – Greenhouse Gas

NOx – Nitrogen Oxides

SOx – Sulfur Oxides

DCG – Diesel Cycle Generator

VFD – Variable Frequency Drive

DCM – Direct Current Motor

PMDC – Permanent Magnet Direct Current Motor

CHAPTER ONE

INTRODUCTION

1.1 Background

The maritime industry plays a vital role in global transportation and commerce, enabling the movement of goods and passengers across oceans and waterways. Passenger ferries play a significant role in marine transportation, providing an efficient and cost-effective way to transport people across rivers, lakes, and coastal waterways. These vessels are frequently used in urban and rural locations where bridges and road networks are limited. Ferries provide significant contributions to public transportation networks in many areas, offering an alternative to gridlock and shortening travel times. Traditionally, passenger ferries have been powered by diesel engines, which offer both propulsion and supplementary power. Diesel-powered vessels emit pollutants such as CO_2, NO_x, SO_x, and PM. These emissions have significant environmental repercussions, including air pollution and global warming. The increasing cost of fossil fuels has resulted in higher operating expenses for the boat.

1.1.1 Environmental Impact of Diesel Propulsion Systems

Diesel engines, the cornerstone of marine propulsion, significantly contribute to air pollution and greenhouse gas emissions. The International Maritime Organization (IMO) reports that the shipping industry is responsible for nearly 3% of global CO2 emissions (IMO, 2020). These engines emit not only carbon dioxide but also harmful pollutants such as nitrogen oxides (NOx) and sulfur oxides (SOx), which degrade air quality and negatively impact human health and the environment. Additionally, the combustion of diesel fuel produces particulate matter (PM) emissions, known to cause respiratory issues and other health problems.

1.1.2. Economic Challenges

The operational costs associated with diesel propulsion systems are another area of concern. Fuel expenses constitute a significant portion of a vessel's operating costs, and fluctuating fuel prices can impact the economic viability of maritime operations. Additionally, the maintenance costs for diesel engines are substantial due to the wear and tear of moving parts, the need for regular servicing, and the replacement of components.

1.1.3The Case for Renewable Energy

Given these challenges, there is an increasing interest in integrating renewable energy sources into marine propulsion systems. Solar energy, in particular, presents a promising solution. It is abundant, renewable, and becoming more cost-effective due to advancements in photovoltaic (PV) technology. Solar panels convert sunlight directly into electricity, which can supplement the power generated by diesel engines, thereby reducing fuel consumption and emissions.

Recent developments in solar technology have made harnessing solar energy in the maritime environment more feasible. High-efficiency PV panels, combined with advanced energy storage systems like lithium-ion batteries, allow for the storage and utilization of solar energy even when sunlight is not available. Additionally, the declining costs of solar panels and batteries make the economic case for integrating solar energy increasingly compelling.

1.1.4 Hybrid Propulsion Systems

Hybrid propulsion systems, which combine traditional diesel engines with renewable energy sources like solar power, offer several significant advantages;

supplementing diesel power with solar energy, hybrid systems can substantially reduce fuel consumption. This results in cost savings and a reduced environmental footprint.

Hybrid systems help lower emissions of CO2, NOx, and SOx, contributing to cleaner air and ensuring compliance with international regulations such as the IMO's MARPOL Annex VI, which aims to limit air pollution from ships (IMO, 2020).

These systems enhance the efficiency of propulsion by optimizing power distribution and reducing engine load, leading to lower maintenance costs and extended engine life.

1.1.5 Global Trends and Regulatory Landscape

The maritime industry is increasingly subject to stringent environmental regulations aimed at reducing emissions and promoting sustainability. The IMO has set ambitious targets to cut greenhouse gas emissions by at least 50% by 2050 compared to 2008 levels (IMO, 2020). Compliance with these regulations necessitates the adoption of cleaner technologies and renewable energy sources.

Several countries and regions are implementing policies to support the transition to greener shipping. For instance, the European Union's Green Deal aims for climate neutrality by 2050, with specific measures to address emissions from the maritime sector. These regulatory pressures create a favorable environment for the adoption of hybrid propulsion systems and other renewable energy solutions.

By integrating solar energy into the propulsion systems of Passenger ferry, the maritime industry can make significant strides toward meeting these regulatory goals and contributing to global sustainability efforts. This project aims to explore the potential of using solar energy to optimize the diesel propulsion system of a Passenger ferry, demonstrating the feasibility and benefits of such an approach.

1.2 Aim

The aim of this research project is to enhance the diesel propulsion system of a Passenger ferry by incorporating solar energy. This entails creating a hybrid propulsion system that integrates solar photovoltaic (PV) panels with the existing diesel engines, aiming to reduce fuel consumption, decrease greenhouse gas emissions, and improve operational efficiency.

1.3 Objective

The goal was to create a system where solar panels, diesel generators, and batteries work together to power a ferry more efficiently and sustainably. This can be achieved by:

Installing Solar Panels on the ferry’s roof to capture sunlight during the day and turn it into electricity.

Diesel Generator Used only when the sun isn’t shining enough or when extra power is needed.

Battery Bank Stored the extra electricity made by the solar panels, so the ferry could use it at night or during cloudy weather.

This setup helped the ferry use less diesel fuel, save money, and produce fewer harmful emissions.

1.4 Importance

Integrating solar energy into marine propulsion systems provides numerous environmental and economic benefits:

Utilizing solar energy reduces reliance on diesel fuel, thereby lowering CO2 and NOx emissions, leading to cleaner air and a healthier marine ecosystem.

As a renewable resource, solar energy decreases the overall carbon footprint of maritime operations. This aligns with the United Nations' Sustainable Development Goals (SDGs), particularly Goal 7: Affordable and Clean Energy.

Reduced fuel consumption translates to significant cost savings over the ferry's operational lifespan.

Hybrid systems optimize power usage and decrease engine wear and tear, resulting in lower maintenance costs.

This project supports adherence to international regulations, such as the IMO's MARPOL Annex VI, which aims to reduce air pollution from ships (IMO, 2020).

By leveraging these benefits, this project aims to contribute to a more sustainable and economically viable maritime industry.

1.5 Problem Statement

The maritime industry is a significant contributor to global greenhouse gas emissions and air pollution, with diesel engines being the primary source of propulion for vessels such as Passenger ferry. According to the International Maritime Organization (IMO), shipping accounts for nearly 3% of global CO_2 emissions, alongside substential emissions of nitrogen oxides (NO_x) and sulfur oxides (SO_x) (IMO, 2020). These emissions have adverse effects on air quality, human health, and the environment, contributing to issues such as climate change and ocean acidification.

Despite the availability of advanced diesel engines designed to reduce emissions, the maritime sector continues to face challenges related to fuel consumption and operational costs. The high dependency on diesel fuel not only leads to significant operational expenses but also fluctuates with market prices, making financial planning for shipping companies unpredictable. Maintenance costs associated with diesel engines are another economic burden, as these engines require regular servicing, parts replacement, and repairs due to their complex mechanical nature.

In response to these environmental and economic challenges, there has been a growing interest in integrating renewable energy sources into marine propulsion systems. Solar energy, in particular, offers a promising solution due to its abundance, renewability, and decreasing cost. Photovoltaic (PV) technology has advanced considerably, providing high-efficiency solar panels capable of generating substantial power even in marine environments.

However, the adoption of solar energy in the maritime industry has been limited, primarily due to technical, economic, and regulatory hurdles.

A hybrid solar-diesel propulsion system could address these challenges by combining the reliability of diesel engines with the environmental benefits of solar energy. Such a system would reduce fuel consumption, lower greenhouse gas emissions, and enhance the operational efficiency of Passenger ferries. The integration of solar power into the existing propulsion infrastructure involves complex engineering and design considerations, including the selection of suitable PV panels, energy storage systems, and control strategies to ensure optimal performance.

The primary problem addressed in this research project is the need for a sustainable and cost-effective propulsion solution for Passenger ferries that mitigates the environmental impact of diesel engines while maintaining operational efficiency. The specific objectives include:

By incorporating solar energy, the hybrid system aims to decrease the reliance on diesel fuel, resulting in lower fuel consumption and cost savings.

The hybrid system seeks to reduce CO2, NOx, and SOx emissions, contributing to cleaner air and compliance with international regulations such as the IMO's MARPOL Annex VI, which mandates strict limits on ship emissions (IMO, 2020).

The project aims to enhance the overall efficiency of the propulsion system through optimized power distribution, reducing the load on the diesel engine and extending its lifespan.

Assessing the cost-effectiveness of the hybrid system, including initial investment, operational savings, and return on investment (ROI), is crucial for the widespread adoption of this technology in the maritime industry.

Evaluating the technical aspects of integrating solar energy into the propulsion system, including the design and installation of PV panels, energy storage, and hybrid controllers, is essential for ensuring the system's reliability and performance.

In conclusion, this research project aims to develop a comprehensive understanding of how solar energy can be integrated into the diesel propulsion system ofa Passenger ferry, providing a sustainable and economically viable solution for the maritime industry. By addressing the identified challenges and demonstrating the benefits of a hybrid solar-diesel propulsion system, the project seeks to contribute to the global effort to reduce the environmental impact of maritime transportation and promote the adoption of renewable energy technologies.

1.6 Scope of the Project

This research focuses on the SolidWorks/AutoCAD design and developing a hybrid propulsion system combining solar energy, battery storage, and diesel power. Selecting of components including solar panels, charge controllers, battery bank, diesel generator, and propulsion motor. Optimal panel positioning on the ferry’s structure to maximize solar energy capture. Calculating the energy demand for propulsion, lighting, navigation, and auxiliary systems. Determining the optimal battery storage capacity based on ferry operational hours. Estimate the power contribution from solar panels under different weather conditions. Battery and Diesel Generator Sizing. Assess the efficiency of PV panels in marine conditions and their impact on overall energy balance. calculate the amount of fuel saved, the operational costs and amount of CO2 gas emissions reduce when solar energy was integrated into the system.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The marine industry is undergoing a major shift as it works to minimize greenhouse gas emissions and reliance on fossil fuels. Ferries, which play an important role in short-distance maritime transportation, are at the forefront of the transition to sustainable energy sources.

Solar energy, with its availability and renewability, is a viable option for powering ferry propulsion systems. This literature review looks at the current status of research, technological achievements, problems, and future prospects for incorporating solar energy into ferry propulsion.

Smith et al, 2020, Investigated the energy savings of a hybrid solar-diesel ferry operating in the Mediterranean. We reduced our gasoline consumption by 15%. The relevance of route planning in maximizing solar energy utilization was highlighted

Kabir et al, 2016, documented the conversion of a normal ferry boat into a solar-powered ferry boat capable of carrying 1200 kg in Bangladesh. This ferryboat was constructed from local wood. They created the PV module, motor, and battery storage system, but did not report on the whole control system. Furthermore, there is no mention of the water drag force used to propel the boat.

Mahmud et al, 2014, presented a solar-powered electric boat for specified load and distance movement; however, no comprehensive design methodology is provided. The light composite material was thought to be suitable for boat construction. They calculated the boat's dimensions and hydrodynamics, as well as its propulsion system, PV capacity, and battery bank size. The boat's movement was accomplished utilizing a motor-driven engine. However, the control mechanism was not observed to maintain steady boat speed with increasing boat passengers.

Postiglione et al, 2012, demonstrated a zero-emission electric propulsion boat powered by a permanent magnet synchronous motor (PMSM) for public transportation and water activities. They introduced two PMSM motors, with each engine rated at 12 kW, as well as a dc-dc converter to provide a constant dc bus voltage. The boat is a wave-penetrating passenger ferry that is powered by lithium-ion batteries and can be charged at the harbor, as well as photovoltaic solar panels. This paper focuses on boat speed and the length of power delivered by the battery; it does not address charge control or motor control procedures.

Simonetti et al, 2000, developed an optimistic control strategy for a solar-powered vessel propelled by an indirect vector-controlled induction motor. To ensure the predicted procedure, a trial drive load was coupled and tested in the laboratory. This research lacks significant field data on solar power and induction motor performance and impact.

Campillo et al, 2019, attempted to evaluate the current trend of electrification for boat propulsion, assessing wind and photovoltaic systems.

Ahmed et al, 2016, investigated the possibility of combining PV and wind power on seafaring. The system consists of a PV array, wind turbine, diesel generator, AC/DC converter, DC/AC inverter, and battery storage. They demonstrated that the solar PV panel could be fitted in available space on the ship, contributing a considerable portion of the energy generation.

Reza et al, 2018, used HOMER, PV syst software, and human calculations to examine a solar-powered marine boat used for fishing in Bangladesh. The key problem is to maximize the output of the solar panel while moving.

J. Hua 2008, described the possibility of renewable energy, as well as its expansion and implementation into maritime transportation. Solar photovoltaic is the first great practical and substitutable source for powering Taiwan's commercial vessels.

Chennai et al, 2019, developed a PV/Diesel/Fuel-cell hybrid power system to suit Dubai passengers' primary and auxiliary power requirements. For configuration and simulation, he used the HOMER software. He demonstrated that his proposed architecture is the most environmentally benign hybrid power system, but there is no discussion of the investment payback schedule.

Leung et a, 2007, created a solar-powered boat with no greenhouse gas emissions. They carried out case studies with variable solar efficiency. This system saved money and reduced carbon emissions.

Chakraborty et al, 2016, developed an MPPT-based solar PV system for rapid charging lead-acid batteries utilizing a buck converter and PID controller to meet the power requirements of a fishing trawler. However, no cost specifics or return period for the investment were revealed.

Liu et al, 2017, investigated a model for reducing CO2 and NOx emissions while increasing energy production on a ship by adding solar PV and storage systems. It has been claimed that the proposed energy storage technology might reduce battery replacement costs by 25% to 35%.

Waleed Obaid et al, 2019, designed a hybrid power source for an electric watercraft. He powered the recommended electric boat's AC motor with a wind turbine system, solar PV panel scheme, and polymer electrolyte membrane (PEM) fuel cell as the first, second, and third renewable energy sources. The suggested electric watercraft was modeled and evaluated using SIMULINK. Throughout the testing, various wind speeds and solar irradiance were evaluated, as was seamless switching, continuous functioning of the hybrid power system mechanism, and steady speed. There is no information on the motor control system or how changing speeds affects the power supply.

Waleed Obaid et al, 2018 and 2019, Developed an electric boat's hybrid power system plan consists of solar PV panels with MPPT technology, a hydrogen storage tank, a polymer electrolyte membrane (PEM) fuel cell with a water electrolyze to produce hydrogen, and a diesel engine connected to a synchronous machine. His weather forecasting system used neural networks to collect environmental temperature, humidity, and wind speed data, and a fuzzy logic-based battery management system to control fuel flow in the fuel cell based on battery charge level. With MATLAB SIMULINK, the system's functionality has been verified. The device has been tested in a variety of weather conditions while maintaining a constant boat speed, but not with variable speed.

In Kuala Terengganu, N. A. S. Salleh et al, 2015, discussed the possibility of using renewable energy sources like as wind and solar PV for grid-connected electric watercraft that charge. He used the HOMER software to simulate various wind turbine, solar PV, converter, battery, and grid power arrangements. He discovered that the hybrid grid-PV configuration is both cost-effective and highly efficient. There is a paucity of information on how to maximize a solar tracking system's output power.

2.2. Solar Energy

Solar energy is a type of renewable energy and solar panel array can capture and convert solar energy to electricity for domestic and industry uses. The practical application of solar energy to vessels is limited, despite the fact that solar energy is becoming more and more viable for on-board electricity generation. The solar energy yield is limited by the vessel's solar energy collection area and the peak solar irradiance available at noon in clear weather, which is approximately 1 kW/m. The vessel's solar energy collection area varies with the solar angle of incidence and is constrained by competing superstructure requirements and available topside. Solar Sailor Holdings Ltd. has improved the solar energy collection area by adding solar cells to the wing sails. Solar photovoltaic (PV) cells can convert solar energy directly into electricity, and solar thermal collectors can convert it into heat energy. Thermal collectors are a well-established technology that can be used to heat water for on-board hotel services.

Solar PV is probably going to be more competitive than concentrated reflective solar thermal technology when it comes to producing electricity on board ships. Among the practical issues preventing it from adapting to the maritime environment are the following; Mirror focusing accuracy issues will be exacerbated by continuous vessel movement and bending. The efficacy of a concentrating receiver lens is likely to be quickly reduced by salt encrustation. Because of these factors, photovoltaics will continue to be the most popular solar energy conversion technology for maritime vessels in the foreseeable future.

Auxiliary systems like lighting, ventilation, and navigational aids can be powered by solar energy, which lessens the need on conventional power sources. Solar energy can augment propulsion systems, improving fuel efficiency and lowering pollutants, even though fully powering propulsion may be difficult.

Case Studies and Examples

2.3 Introduction To Solar Energy In The Maritime Industry

Fossil fuels have long been the maritime industry's main source of onboard energy and propulsion. However, as environmental awareness and government pressure to reduce carbon emissions have grown, there has been a noticeable movement toward integrating renewable energy sources like solar power into maritime operations. Solar-powered ships may power everything from lighting and appliances to propulsion systems, enhancing the sustainability and greenness of the marine industry. The method that ships are propelled has changed significantly with the usage of solar energy in maritime transportation. It is now simpler to integrate solar energy into ship designs because to developments in solar technology, such as lightweight solar panels and highly efficient PV cells.

Over the past few years, solar energy has been used in maritime applications more and more. A number of causes are responsible for this rise. The use of solar electricity on vessels has become more feasible due to technological advancements and ongoing improvements in solar panel durability and efficiency. Solar panels are now more resilient to severe weather and saltwater corrosion thanks to new materials intended for maritime situations.

Fuel consumption is lower on solar-powered ships, which results in considerable cost savings over extended trips. These vessels reduce dependency on fossil fuels, hence reducing the risk of supply chain interruptions and fluctuations in oil prices. After the initial investment in installation, solar panels have low operating expenses and require little maintenance. Ships can save a lot of fuel over time, which will balance the initial costs.

According to the International Maritime Organization (IMO), fleets from member states have increased their use of renewable energy sources by 30%. Strict environmental laws that encourage shipping businesses to invest in green technologies are the driving force behind this development. By using solar panels, ships can produce their own energy and lessen their need on outside fuel sources. This is especially helpful for operations in isolated locations where fuel supplies could be scarce. Marine vessels have a smaller environmental impact thanks to solar panels, which produce electricity without releasing pollutants into the atmosphere. This is in line with international initiatives to lessen shipping's carbon footprint.

Despite its progress, there are still barriers to the widespread use of solar energy in maritime transportation. For example, retrofitting existing fleets with solar technology can cost anywhere from ₦2 to ₦5 million, depending on the size and complexity of the vessel. The efficacy of shipboard solar panels is affected by shifting conditions. The need for systems that can adjust to changing sunlight angles presents technical challenges not seen in static installations.

2.4 Challenges Of Using Solar Energy At Sea

The quantity of energy that may be produced by solar panels on marine vessels may be limited due to their small surface area. Creating effective design is crucial to maximizing the coverage of solar panels. The production of solar energy depends on sunshine, which varies depending on the time of day, location, and weather. Reliable energy storage technologies are necessary to guarantee a steady power supply because of this fluctuation. Saltwater exposure from the maritime environment can corrode solar panels and eventually lower their efficiency. Choosing materials that are resistant to corrosion and putting strong protection measures in place are essential for durability. In order to store solar energy for usage when there isn't any sunlight, effective storage technologies are needed. Creating long-lasting, high-capacity batteries that can survive in maritime environments is a difficult task.

2.5 Solar Photovoltaic (PV) Array selection

Solar photovoltaic (PV) arrays are made up of hundreds of photovoltaic cells, also known as solar cells, which are semiconducting. A PV array is made up of several PV modules. PV modules are connected in parallel and series (string) based on the energy consumption. Electrons in solar cells are energized and transformed into electrical current when bright sunlight reaches them. A typical photovoltaic module has 60 or 72 cells connected in series. In contrast, the 72-cell modules can be set up to function as either two 12-V modules, which consist of two parallel strings with 36 series cells each, or as a single 24-V module by maintaining 72 cells in series. In order to simulate the solar PV-powered boat, polycrystalline silicon cells have been taken into consideration. The following part will involve the sizing of solar PV panels. Three primary types of photovoltaic cell technology are currently at the forefront of the global market.

2.6 Monocrystalline Silicon Cell

A Single-crystal silicon is used to make monocrystalline panels, which have great durability and efficiency. Because of their high-power production per square foot, they are appropriate for vessels with limited room.

It was also the world's first solar cell to be introduced commercially. Although the production process is sluggish, this form of cell is advantageous. Usually, has a high efficiency between 20-25%. long lifespan and reliable performance. Power output Often exceeds 300W per panel. Perfect for locations with little room for installation. Compared to thin-film and polycrystalline silicon cells, it is more expensive. The monocrystalline silicon cell is shown in Fig. 1.1.

2.7 Polycrystalline Silicon Cell

Several small crystal particles make up the polycrystalline (or multi-crystalline) structure, as seen in Fig. 1.3, and fig.1.4. By manufacturing 70% of photovoltaic polycrystalline silicon cells, it helped lead the global PV cell market in 2015 despite the fact that these cells are less efficient but less expensive. In direct sunlight, polycrystalline panels typically produce less per square inch, may be less responsive to shading, and are less costly. with an efficiency rating between 15 -20%. The performance of some monocrystalline panels in full sun is within 10% of that of the more recent, high-quality polycrystalline panels. Power output ttypically between 250W and 300W per panel. Lower manufacturing costs. Suitable for larger installations where space is not as limited.

Fig1.3 Canadian Solar's CS6U-330P Polycrystalline Silicon Solar PV Modules (https://www.solaris-shop.com/canadian-solar-maxpower2-cs6u-330p-330w-poly-solar-panel/)

2.8 Thin-Film Solar Panels

Thin-Film Solar Panels are flexible, lightweight, and can conform to curved surfaces. These panels are made by depositing photovoltaic materials onto a substrate. They have lower efficiency (7% to 13%) but are lightweight and flexible, making them ideal for marine environments where installation surfaces may not be flat. They are easy to install on a variety of surfaces and can be mounted on decks, Biminis, or other curved areas.

2.9 Solar Charge Controller (SCC)

The function of the solar charge controller (SCC) maximizes the amount of solar power that is available. In this study, the captured power will power the motor and charge the battery.

Maximum Power Tracking (MPPT) and pulse width modulation (PWM) solar charge controllers are currently widely used in the industry. PWM-based SCC modifies the pulse size to regulate the PV module's output voltage. It is possible to use the PWM-SCC with a 2kW solar power system.

Solar Charge Controllers (SCCs) are critical components in marine photovoltaic (PV) systems, ensuring efficient and safe battery charging by regulating the voltage and current from solar panels. Their role is especially important in the maritime environment, where factors such as space constraints, exposure to harsh conditions, and the need for dependable power supply pose unique challenges.

SCCs prevent batteries from being overcharged or over discharged, extending battery life and maintaining system efficiency. Advanced SCCs use MPPT algorithms to continuously modify the modules' electrical working point, ensuring maximum power extraction from the solar panels under variable conditions. SCCs protect the system from potential problems such short circuits, reverse polarity, and overheating, which are crucial in the harsh marine environment.

A study on the integration of solar battery charging systems in marine vessels emphasizes the role of SCCs in lowering fuel consumption and reliance on generator-based power sources. Using solar energy, vessels can obtain a more sustainable and cost-effective power source.

Research on the naval vessel Blue Star Delos revealed the use of MPPT charge controllers to match PV array voltage to battery voltage, efficiently managing the charging process. This implementation demonstrated the practical benefits and limitations of implementing SCCs in maritime contexts.

SCCs play an important role in the design of solar-powered Passenger ships because they manage the energy generated from solar panels, ensuring optimal storage and usage. The study underlines the need for SCCs to handle the particular power needs and climatic conditions faced at sea.

Selecting SCCs with strong protection features and marine-grade construction is crucial because marine environments present challenges like saltwater corrosion, temperature fluctuations, and constant motion that can affect the performance and longevity of SCCs. To ensure compatibility and optimal performance, integrating SCCs into existing marine electrical systems requires careful planning, which includes taking into account space constraints, wiring complexities, and the vessel's unique energy requirements.

Fig 1.5 PowMr 140A 48V MPPT Solar Charge Controller

(https://www.aliexpress.com/i/1005005200174757.html)

2.10 Solar Energy in Marine Applications

A Research published in 2023 examined the viability of using solar energy on marine passenger ships. The research indicated that 17 passenger ships might generate around 1,240 MWh of power yearly, potentially lowering CO_2 emissions by around 325.56 tons per year. This demonstrates the tremendous environmental benefits of using solar energy in maritime transportation. A detailed assessment in 2023 studied the principal applications of solar energy as the dominant power source in the maritime sector, with an emphasis on current advancements. The study identified three key sectors for developing solar-powered boats: maritime drones, sporting boats, and short-range tourist vessels. This demonstrates the versatility and increasing interest in solar-powered maritime vessels for a variety of purposes.

A 2019 review examined several elements of solar photovoltaic (PV) use on ships. The paper focused on the technical and economic challenges of integrating PV energy into ship power systems, as well as future research opportunities in marine photovoltaics. Key problems include correct connection with current ship electrical systems as well as maritime environment considerations. Researchers have looked on the deployment of floating photovoltaic (FPV) plants in marine environments. While FPV systems are typically placed on lakes and dams, their use in low-wave offshore protected waters opens up new possibilities for renewable energy generation in marine contexts. This strategy takes advantage of the huge surface area of water bodies to deploy solar panels without competing for land space.

A 2021 study described a low-cost Unmanned Surface Vehicle (USV) driven by wave and solar energy. The design features an electrically powered winch for deploying underwater units and employs additive manufacturing for cost savings. Such advances show the potential for autonomous, solar-powered vessels to collect ocean data and monitor the environment.

Advances have been made in determining the best photovoltaic technology for underwater applications.

A 2021 study tested different solar cell technologies and discovered that certain materials, like as Gallium Indium Phosphide (GaInP), have higher efficiency at depths greater than 2 meters. This study is critical for developing undersea solar energy collection systems. These studies collectively demonstrate the increased interest and breakthroughs in incorporating solar energy into marine applications, opening the path for more sustainable and efficient shipping.

2.11 Efficiency of solar panels on vessels

A study looked at the practical implementation of solar panels on a container vessel, with an emphasis on energy savings and efficiency gains. Adding solar panels to a vessel can save fuel and reduce CO_2 emissions, improving overall energy efficiency, according to study.

An investigation of a tourist ship's power system in the Bay of Kotor using PVsyst software to assess the effectiveness of solar energy integration. The study found that solar panels may meet a significant percentage of the vessel's energy requirements, increasing energy efficiency and reducing dependency on traditional fuel sources.

A review looked at various aspects of solar photovoltaic (PV) applications on ships, highlighting technical and economic challenges. The paper emphasized that while pure solar vessels have been demonstrated, most applications involve supplementing existing power systems to increase energy efficiency and reduce emissions.

The research looked into the use of photovoltaic (PV) systems on ship retrofits to reduce hazardous gas emissions. The study discovered that incorporating solar panels into existing vessels can contribute to decarbonization efforts by boosting energy efficiency and reducing the environmental effect of marine operations.

These studies highlight the potential for solar panels to improve energy efficiency on marine boats, resulting in more sustainable and ecologically friendly maritime operations.

Monocrystalline panels are the most efficient (20-25%) and best suited for marine applications due to their small size and high output. Polycrystalline panels are less efficient (15-20%) but more cost-effective, making them ideal for bigger vessels with plenty of room. Flexible solar panels are great for curved or uneven surfaces, however they perform significantly less efficiently. Solar irradiation, shade, and seawater corrosion have a substantial impact on panel efficiency. Regions with high solar exposure, such as tropical and subtropical zones, produce the highest results. Wave-induced shadowing and the limited surface area available for installation can both reduce the effectiveness of solar panels aboard vessels. Hybrid systems that combine solar panels with diesel generators or batteries improve overall energy efficiency. While the initial installation costs may be significant, the long-term benefits of lower fuel usage and pollutants outweigh the expenditure. Many studies indicate that solar energy systems aboard vessels can have a payback period of 5-10 years, depending on operating conditions.

2.12 Solar energy output and limitations in maritime environments

Solar panels on vessels can harness significant amounts of energy, depending on environmental conditions and system design. Some noteworthy findings include;

Passenger Ships: Research has shown that passenger ships equipped with photovoltaic (PV) systems can generate substantial electricity annually. For example, a case study involving 17 ships highlighted an annual production of approximately 1,240 MWh of electricity, reducing CO_2 emissions by 325.56 tons per year.

In cargo vessels, solar systems on cargo ships have been used to power auxiliary systems, such as lighting and navigation equipment. Studies estimate that solar panels can meet up to 30% of total auxiliary power demands, significantly reducing diesel generator usage.

In ferries, Solar-powered ferries operating in sunny regions like India and Scandinavia demonstrate that energy output can cover nearly 100% of the propulsion and onboard energy requirements for short-distance trips.

For long voyages vessels operating in international waters with extended sunlight exposure, solar power can supplement engine loads and reduce fuel consumption by 10–25%, depending on solar irradiance and ship orientation.

Solar panel efficiency on vessels varies between 15–25%, depending on the type of panel used (monocrystalline, polycrystalline, or thin-film) and environmental factors such as solar irradiance and shading Seasonal variations and geographic location are key determinants of energy output. For example:

Vessels operating in the Mediterranean and tropical regions achieve higher efficiency due to abundant sunlight.

In northern or polar regions, energy output is limited during the winter months but can still contribute during the summer.

2.13 Limitations of Solar Energy in Maritime Environments

Saltwater corrosion, high humidity, and extreme weather conditions (e.g., strong winds, heavy rain) reduce the lifespan and performance of solar panels. Biofouling, caused by algae and salt deposits, requires frequent cleaning to maintain efficiency. Shadows from ship masts, lifeboats, and antennas can create significant power losses. Studies show that even 10% shading can reduce solar panel output by up to 40%. Deck space for installing solar panels is often limited, particularly on commercial vessels with complex superstructures. Researchers have explored innovative solutions such as flexible solar panels that can be installed on curved surfaces, but these are less efficient than rigid panels.

Batteries are essential for storing solar energy, but their weight and size pose challenges for ships. Lithium-ion batteries are commonly used but require careful management to prevent overheating or failure.

Some vessels integrate ultra-capacitors to improve energy storage and distribution efficiency.

The installation of solar PV systems on vessels is capital-intensive. For instance, retrofitting a medium-sized cargo ship with solar panels can cost between ₦500,000 and ₦1 million, depending on the system size. Regular inspections, cleaning, and repairs are required to prevent system degradation in harsh maritime conditions. These maintenance costs can add up over time. Solar installations must adhere to International Maritime Organization (IMO) standards to ensure they do not compromise ship safety or navigational capabilities. Systems must also withstand the dynamic stresses of sea travel, such as vibrations and impacts from waves. Integrating solar energy systems into existing electrical grids on older ships is technically challenging. Modern vessels are better equipped for such adaptations.

In polar regions, vessels experience months of limited sunlight, making solar panels less effective. These vessels rely more heavily on diesel generators during such periods. Similarly, ships that operate primarily during night time hours cannot fully utilize solar energy. Cloud Cover and Weather: Overcast skies and storms can reduce solar panel output by up to 50–80%, significantly impacting energy generation.

2.14 Future Outlook and Recommendations

The development of high-efficiency solar cells, such as perovskite and bifacial panels, can significantly improve energy output. Some researchers propose floating solar panels attached to the ship or deployed at ports to increase energy collection areas. Combining solar energy with wind turbines, fuel cells, and energy storage can create more robust and reliable power systems for vessels.

Integration with Hybrid Systems where solar energy used alongside diesel generators and batteries to create hybrid systems. For example: Solar panels can handle daytime energy needs, while diesel generators or batteries provide backup at night or during cloudy conditions. Hybrid systems on a container ship resulted in 20% fuel savings annually, according to a study conducted in the South China Sea.

2.15 Diesel Propulsion Systems Of A Passenger Ferry

Diesel propulsion technologies have formed the foundation of Passenger ferry operations, providing dependability and efficiency for both passenger and car transportation. Recent research has focused on various components of these systems, with the goal of improving performance while reducing environmental effect. The study "Propulsion System Matching Analysis of a Passenger Ship by Changing the Gear Ratio" investigated how changing the gear ratio in diesel engines influences the propulsion efficiency of passenger ferries. The study discovered that adjusting the gear ratio can result in considerable gains in fuel efficiency and overall vessel performance.

A comparison research comparing the emissions of a diesel-powered passenger ferry with its totally electric equivalent operating on the same route was conducted in an effort to reduce greenhouse gas (GHG) emissions. The results showed that compared to the diesel-powered ferry, the electric vessel's greenhouse gas emissions were only 25% higher. Nonetheless, the study underlined that the energy sources utilized to generate power in the operating location have a significant impact on the environmental advantages of electric propulsion.

In order to lessen the environmental impact of high-speed passenger ferries, alternative propulsion systems were examined in another research article, "The Study of an Innovative Propulsion Plant for a High-Speed passenger Ferry for Decarbonization in the Marine Industry." The study showed how cutting-edge propulsion plants can achieve notable emission reductions, aiding in the decarbonization of maritime transportation. Modern lithium batteries and propulsion systems have made it possible for passenger ferries and other vessels of all sizes to have sophisticated hybrid propulsion systems. According to research, electric motors are more efficient than conventional diesel engines across a broad range of loads and speeds. They also have the advantage of being lighter and requiring less maintenance.

Although passenger ferry operations have historically relied heavily on conventional diesel propulsion systems, current research and technology developments are guiding the sector toward more effective and ecologically friendly substitutes. Among the developments advancing marine transportation are hybrid systems, totally electric propulsion, and gear ratio optimization.

2.16 Overview of Marine Diesel Generators selection

Marine diesel engines and generators are essential parts of the marine sector since they give ships electrical and propulsion power. Enhancing their effectiveness, dependability, and environmental performance has been the main focus of recent study. Thanks to advancements, "smart" camshaft less engines with electronically controlled fuel injection and exhaust valve actuation systems have been developed. Variable timing is provided by these clever technologies for enhanced performance and fuel economy. Data-driven fault diagnostic techniques have been surveyed to improve the maintenance and reliability of marine diesel engines, ensuring safer maritime operations and contributing to the development of cleaner technologies. Studies have measured exhaust emissions from marine diesel engines in dynamic states, offering insights into their environmental impact.

To help with the design of more resilient power systems, dynamic models of marine diesel generators have been created to examine voltage and frequency fluctuations during failure scenarios. Thorough approaches to choosing ship electric power system generators have been put forth, taking into account variables that affect the equipment's efficiency and life-cycle cost. Fuel-efficient operation and the integration of variable speed diesel generators with energy storage systems have been the main topics of research on the modelling and real-time scheduling of DC platform supply vessels.

New techniques for evaluating the technical state of marine diesel engines powering synchronous generators have been introduced, improving maintenance plans. In order to provide novel references for health monitoring, research has investigated fault early warning systems for marine diesel engines based on variational modal decomposition and singular value entropy. In order to improve performance under a variety of operating settings, adaptive state observer-based control techniques have been developed for marine diesel engine speed regulation.

Fig 1.4 Kubota 10 kW Marine Diesel Generator

2.17 Integration with Hybrid Systems

Numerous studies have been conducted on the integration of hybrid propulsion systems in maritime boats, with an emphasis on increasing operational flexibility, lowering emissions, and improving energy economy.

Hybrid Systems in Series: In this setup, the vessel is propelled by electric motors after the internal combustion engine powers a generator to create electricity. This configuration minimizes pollutants and fuel consumption by enabling the engine to run as efficiently as possible.

Parallel hybrid systems allow either or both of the electric motor and internal combustion engine to supply propulsion power because they are mechanically attached to the propeller shaft. Under a variety of operational circumstances, this adaptability can improve performance and efficiency.

In order to maximize hybrid propulsion systems, efficient energy management is essential. In order to ensure optimal performance and fuel efficiency, sophisticated control algorithms—such as those based on deep reinforcement learning—have been created to regulate power distribution between engines, generators, and energy storage devices. The potential for hybrid propulsion systems to lower greenhouse gas emissions and other pollutants has been shown to be substantial. By regulating engine load and integrating energy storage options, hybrid systems have been shown to reduce emissions and promote more environmentally friendly maritime operations.

Both series and parallel hybrid architectures might significantly lower emissions, according to research on hybridizing Venice's waterborne transportation system; nevertheless, the series hybrid offered the biggest advantages.

RBC, or rule-based control to switch between power sources, fundamental decision-making procedures are applied, depending on operational conditions (e.g., using batteries in ports and diesel engines during cruise). For example, waterbuses in Venice. OBC, or optimization-based control Model predictive control (MPC) and other advanced algorithms optimize energy distribution dynamically, lowering emissions and fuel consumption. For example, the modified ferries in Norway. DRL, or deep reinforcement learning Machine learning algorithms estimate optimal energy use patterns by analysing both historical and present data. One example is the use of hybrid cargo ships that function under different load scenarios. The viability of hybrid propulsion systems in smaller marine applications was highlighted by a South Korean study on the use of these systems in small fishing vessels, which showed increases in fuel economy and decreases in operating expenses.

Emissions of CO_2, NOx, and SOx are significantly reduced by hybrid systems. This is in line with the 2020 IMO sulfur cap and the 50% reduction in GHG emissions by 2050. Because electric motors and batteries run quietly, marine life is less impacted by underwater noise pollution. Depending on the type of vessel and its operational profile, studies have indicated fuel efficiency improvements of up to 30–50%.

Equipment, batteries, and energy management systems for hybrid systems come with a hefty initial cost. Capacity, weight, and longevity are issues with current battery technologies. Advanced control systems are necessary for the efficient integration and management of different energy sources. International safety and environmental regulations must be met by vessels, which complicates the design of hybrid systems. Solid-state and high-energy-density batteries are being developed to increase capacity and decrease weight. Numerous pilot projects are already in progress, and hydrogen fuel cells provide a zero-emission substitute for hybrid systems. Performance optimization for hybrid systems will be greatly aided by artificial intelligence.

Notwithstanding the benefits, there are still issues like high upfront costs, complicated system integration, and the requirement for sophisticated energy management systems. Research is being done to address these issues by creating more effective energy storage solutions, better control algorithms, and economical system designs. The integration of hybrid propulsion systems in marine vessels offers a promising path to environmental sustainability and energy efficiency in the maritime sector. To overcome current obstacles and enable broad adoption, more research and technological developments are needed.

2.18 Battery selection

A battery is a compact device that converts stored chemical energy into electrical power, allowing a variety of devices to function. It is composed of one or more electrochemical cells, each containing a positive electrode (anode), a negative electrode (cathode), and an electrolyte. When electrodes and electrolyte are joined in a circuit, the chemical reaction between them generates electrical current.

Reliable battery systems are vital for both recreational and commercial vessels. Inadequate power supply can cause disruptions, jeopardizing both the vessel's function and the safety of its inhabitants. Thus, choosing the right batteries for maritime applications is crucial.

Marine batteries must withstand harsh conditions such as seawater immersion and temperature fluctuations. Effective performance ensures that vital systems continue to function, which is critical for efficient maritime operations.

Furthermore, advancements in battery technology have an immediate influence on maritime fuel efficiency and sustainability. Emphasizing the importance of batteries in marine applications can lead to advancements that help to save the environment while also improving the overall efficiency of maritime transportation.

Batteries for marine applications are classified into numerous varieties, each with unique properties suitable to specific nautical purposes.

2.18.1 Lead-acid batteries

Lead-acid batteries are one of the oldest technologies utilized in marine applications, noted for their durability and low cost. They are often useful for applications that require consistent power delivery, such as starting engines and powering onboard electronics.

Lead-acid batteries are a popular energy storage alternative in marine applications. These batteries are made of lead dioxide and sponge lead immersed in a sulfuric acid electrolyte. This design creates electrical energy via a chemical reaction during discharge and is reversible when an external voltage is applied during charging.

Lead-acid batteries are known for their low cost, dependable performance, and durable design, making them suited for a variety of marine situations. In nautical situations, common applications include starting engines, powering lights, and supporting navigational systems.

2.18.2 Lithium-ion batteries

Lithium-ion batteries are a more advanced alternative, gaining popularity due to their better energy density and efficiency. These batteries use lithium ions to travel between the anode and cathode, resulting in better performance and lighter weight. They are lighter than lead-acid batteries and charge faster, making them perfect for modern marine applications requiring dependable power in a compact package. Because of its high energy density and efficient charging capabilities, lithium-ion batteries are popular in marine applications.

Furthermore, lithium-ion batteries have reduced self-discharge rates, ensuring that energy is efficiently preserved during storage. This function is especially useful in marine applications, where batteries may not be used for long periods of time.

Environmental concerns also favor lithium-ion batteries. They are increasingly being made with recyclable materials, which helps to promote sustainable practices in the marine industry. The use of this battery technology in marine applications is a big step toward increased efficiency and environmental responsibility.

2.18.3 Nickel-cadmium batteries

Nickel-cadmium batteries are another option, known for their endurance and performance in severe temperatures. These batteries use nickel oxide hydroxide and cadmium as active ingredients, making them ideal for marine applications that require high reliability. They can resist deeper discharges better than lead-acid batteries and are commonly used in specialized marine conditions where dependability is critical. Nickel-Cadmium batteries are rechargeable energy storage devices renowned for their durability and performance in severe situations.

One distinguishing feature is their capacity to deliver high discharge rates, which makes them ideal for starting engines and heavy-duty applications. Furthermore, they are very resistant to deep discharge, ensuring longevity in tough marine circumstances.

2.19 Criteria for Marine Battery Selection

To achieve best performance and reliability when selecting batteries for maritime applications, numerous criteria must be taken into consideration. These parameters have a considerable impact on the efficiency, safety, and longevity of batteries used in marine applications.

Capacity and voltage are important considerations in the selection process. The battery must provide enough power to support onboard systems while maintaining voltage stability, especially during peak loads, to ensure that all electronic devices function properly and without interruption. The capacity of batteries for marine applications is the amount of energy they can store, which is typically measured in ampere-hours. This specification is critical because it determines how long a battery can supply power to onboard systems before requiring a recharge. Thus, choosing a battery with adequate capacity is critical for meeting operational demands. Voltage is a measure of electrical potential and has a direct impact on the performance of marine batteries. Most marine applications run on 12V, 24V, or 48V systems. For example, a 12V battery may be utilized for smaller vessels, however larger ships frequently require multiple batteries to accommodate higher voltage needs.

Due to vessel space constraints, weight considerations are also important. Lighter batteries have the potential to improve fuel efficiency and performance. To meet the energy needs of maritime applications without overloading the vessel, weight must be balanced with power output. Weight is an important factor to consider when choosing batteries for marine applications because it affects a vessel's overall performance and efficiency. The weight of a battery influences not just marine vehicle fuel consumption, but also stability and mobility on the water. As a result, lighter batteries are typically selected for best performance. Weight differences become obvious when different battery types are compared, such as lead-acid, lithium-ion, and nickel-cadmium. Lead-acid batteries, while inexpensive, are heavy, which can be a disadvantage for smaller vessels. In comparison, lithium-ion batteries have a substantially higher energy density, allowing for significant weight reduction while maintaining power output. Furthermore, reducing weight improves load distribution in marine applications. This is critical for vessels that perform specific jobs, such as fishing or research missions, where balance and agility are essential. Thus, understanding weight issues enables informed selections about the best batteries for marine applications, resulting in increased efficiency and performance.

It is important to consider charging efficiency. Optimal charging decreases downtime and increases battery life, which is critical for long-distance travel. High-quality marine batteries should have short charge times and be compatible with a wide range of charging technologies used in the marine sector. Charging efficiency is the efficiency with which a battery may be charged in relation to the amount of energy input. This metric is critical in marine applications for optimising battery performance and assuring long-term use during journeys. High charging efficiency reduces energy loss and the need for frequent recharges. In general, lead-acid batteries have poorer charging efficiency than lithium-ion equivalents. Lithium-ion batteries have efficiency more than 90%, making them the ideal choice for modern maritime vessels. Enhanced charging efficiency correlates to decreased operational costs and increased reliability on water.

Fig 1.2 Trojan battery (https://www.solaris-shop.com/trojan-sagm-06-220-agm-6v-220ah-battery/)

2.20 Storage capacity, lifecycle, and safety considerations of Battery for Marine Use

Advances in battery technology are critical to improving marine vessel efficiency and sustainability. Storage capacity, lifetime, and safety are all important factors to consider when selecting marine batteries. Storage capacity is the quantity of energy that a battery can store, which is commonly measured in kilowatt-hours (kWh). A large storage capacity is required for marine boats to ensure adequate energy for propulsion and aboard systems during voyages. Recent research has focused on increasing battery energy density to improve storage capacity and hence extend the operational range of electric and hybrid marine vessels.

The lifecycle of a battery refers to the number of charge-discharge cycles it can go through before its capacity declines considerably. A longer lifecycle minimizes the frequency of battery changes, resulting in lower maintenance costs and higher vessel uptime. Lifecycle tests of lithium iron phosphate (LFP) batteries have shown that they are suitable for large-scale energy storage in maritime conditions, providing a good mix of cost and endurance.

Safety is critical in marine applications due to the possible hazards of battery failures, such as thermal runaway, fires, and explosions. According to studies, the dangers associated with Li-ion batteries vary with battery size and volume, underlining the importance of robust safety measures in big energy storage systems.

Recent evaluations have highlighted the development of several ESS specialized for marine conditions, with an emphasis on enhancing overall performance, safety, and dependability. Data-driven state of health monitoring for maritime battery systems is boosting predictive maintenance capabilities, resulting in increased safety and battery longevity. Optimizing storage capacity, prolonging lifetime, and assuring safety are all essential considerations in the development and deployment of battery technology for maritime boats. Ongoing research continues to address these issues, hence advancing sustainable maritime operations.

2.21 Ferry selection

Ferries are boats that transport people and cars over waterways like rivers, lakes, and oceans. They have been a popular means of transportation for ages and are still in widespread use today.

2.21.1 Hydrofoil Ferry

A hydrofoil ferry is a type of boats that uses wing-like structures known as hydrofoils to raise its hull out of the water as it speeds up, reducing drag and allowing for faster speeds. As the hydrofoil craft accelerates, the hydrofoils generate lift, propelling the boat's hull out of water. This minimizes the amount of hull in contact with the water, resulting in less hydrodynamic drag. Hydrofoils are often smaller and lighter than conventional ferries. They have a characteristic structure, featuring wing-like features on the lower half of the load-bearing surfaces. Some recent hydrofoils have entirely submerged inverted T-shaped foils. Hydrofoils are noted for their superior speed than ferries. Hydrofoil ferries typically range in length from around 12 meters (39 feet) to more than 27 meters (89 feet). The beam length can range from 4.5 meters (14.8 feet) to 6.4 meters (21 feet). These vessels may accommodate anywhere from 30 to 150 passengers, depending on the design. Hydrofoil ferries have engines with power outputs ranging from around 320 kW to 810 kW. Onboard electrical systems typically use voltages of 220V, with power outputs of roughly 50 kW for auxiliary systems. They can achieve speeds of 25-36 knots. Hydrofoils are also more maneuverable and stable than traditional ships. Hydrofoils can retain their speed and maneuverability even in rough seas, making for a more comfortable working environment for the crew. The ship's automated control system (ACS) ensures constant dynamic control throughout takeoff, landing, and all foilborne operations. Hydrofoils are commonly utilized to travel shorter and more frequently between coastal destinations. Hydrofoils, on the other hand, may be more sensitive to wave motion, making for a less enjoyable flight experience in poor weather situations. In addition, hydrofoils are typically smaller vessels with no cabins or car decks for motor vehicle transit.

2.21.2 Ro-Ro ferries

Ro-Ro (roll-on/roll-off) ferries are cargo ships designed to transport wheeled cargo, such as cars, lorries, buses, and train wagons, which are driven onto and off the ship via ramps. This effective loading/unloading mechanism sets them apart from LoLo (lift-on/lift-off) vessels, which require cranes. Ro-Ro ferries have built-in or shore-based ramps that allow cars to easily board and exit the vessel. Ro-Ro vessels have many decks for parking wheeled cargo and can accommodate a huge number of cars. Ro-Ro ferries range in length from about 62 to more than 265 meters. The beam can range from 16 to 32 meters. Typically ranges from 2.3 to 11 meters, depending on the vessel's construction and cargo capacity. Smaller Ro-Ro ferries may transport approximately 600 passengers, whereas bigger vessels can carry up to 2,500 passengers. Vehicle capacity varies greatly, with some ferries intended to carry around 100 automobiles, while larger vessels may take up to 1,216 cars or 165 trucks. Ro-Ro ferries use numerous diesel engines with total power outputs ranging from about 1,600 kW to more than 33,600 kW. Service speeds normally range between 11.5 to 22.5 knots, depending on the vessel's design and propulsion system, onboard electrical systems often run at voltages of 6.6 kV or 11 kV, especially for bigger vessels that require significant power for propulsion and auxiliary systems. Capacity is measured in CEU (vehicle equivalent units), and most boats hold between 4,000 and 5,000 CEU. Ro-Ro ships are thought to be a more efficient way to move wheeled freight, saving time and resources over regular cargo ships. The simplified freight movement helps to reduce port congestion and wait times.

2.21.3 High-speed ferries

High-speed ferries, also known as fast ferries or fast craft, are specialized vessels that can transport passengers and vehicles at much higher speeds than traditional ferries. These ferries have transformed marine transportation by providing faster, more efficient routes that connect towns and countries across bodies of water. There are several types of high-speed ferries.

Monohull These ferries have a single hull and are frequently stabilized with ballast. They were popular during the 1990s.

Catamarans have two hulls and offer greater stability and speed. They are the most popular form of high-speed ferry.

Trimarans, like catamarans but with three hulls, offer increased stability and speed. Hovercraft These vessels use air pressure to hover above the water surface, allowing them to move.

High-speed ferries exist in a variety of sizes, typically ranging from 24 to 130 meters long. Smaller catamarans measure 24-60 meters, whereas bigger monohulls and catamarans can reach 130 meters. High-speed ferries can attain speeds surpassing 40 knots (74 km/h or 46 mph). Some of the fastest ferries, such as the Francisco, may reach speeds of up to 58 knots (107 km/h/67 mph). High-speed ferries are often powered by multiple diesel engines, with total power outputs ranging from 7,274 horsepower to more than 36,400 kW. Onboard electrical systems typically use standard marine voltages, such as 440V or 690V, to power auxiliary equipment and passenger amenities. High-speed ferries can transport a variety of passengers and vehicles. Passenger-only ferries can hold hundreds of people, whereas larger ferries meant to transport vehicles can transport hundreds of people as well as cars, buses, and trucks. For example, certain huge catamarans can transport up to 1,200 passengers and 417 automobiles.

2.21.4 Passenger ferries

These ferries are only designed to transport passengers and not automobiles. Passenger ferries are vessels built expressly to transport people over bodies of water, such as rivers, lakes, and seas. They play an important role in public transit systems around the world, providing an efficient and often scenic alternative to driving and rail travel. passenger ferries typically measure 12 to 200 meters in length. Depending on the design, the beam might be anywhere from 5 to 35 meters long. Capacity can range from 20 to 2000 passengers, depending on the vessel's size and arrangement. These ferries are typically powered by either single or dual diesel engines with individual power outputs ranging from around 6000 kW to 30,000 kW. Service speeds typically range from 8 and 30 knots, depending on the vessel's design and intended usage. Onboard electrical systems typically use standard marine voltages, such as 24V to 690V, to power auxiliary equipment and passenger amenities.passenger ferry can be monohull or twin hull.

2.22 Propeller selection

A propeller is a mechanical device with revolving blades that transfers rotational power from an engine or motor into thrust and propels a vehicle (such as a boat, ship, or ferry) through water. It is a fundamental component of marine propulsion systems, influencing a vessel's speed, efficiency, and maneuverability.

2.22.1 Fixed Pitch Propeller

The blade angle (pitch) is fixed and cannot be changed during operation. They are simple and cost-effective. Reliable and low-maintenance, ideal for steady speed operation. Less efficient at different speeds and loads. They are used on small boats, ferries, and vessels that operate under regular conditions. Types of Fixed Pitch Propeller;

- **3-Blade fixed pitch Propeller**

Provides an excellent balance of thrust, efficiency, and maneuverability. When compared to 2-blade propellers, it produces less cavitation (low-pressure bubbles), resulting in a smoother and quieter operation. Offers greater acceleration and performance at low speeds, making it perfect for passenger ferries. The propeller is built of stainless steel, with a diameter of 30-35 cm and a pitch of 20-25 cm, making it suitable for a 5kW motor and this size ferry. This ensures perfect energy transfer from the motor to the water, resulting in maximum efficiency. The propeller generates enough thrust to propel the ferry at the necessary speed (6-8 knots) without overloading the motor. The three-blade design reduces cavitation and vibration, resulting in a pleasant and quiet journey for guests.

Fig 1.8 Michigan Wheel Vortex Series Propeller

(https://www.zoro.com/michigan-wheel-prop-145x19-rh-3bl-al-vortex-992004-992004/i/G204944145/)

- **2-Blade Propeller**

2-Blade Propeller fewer blades minimize drag, allowing the propeller to rotate quicker and reach higher speeds. They are more efficient at high speeds because of lower drag and cavitation. They have Fewer blades imply less weight, which can boost overall vessel performance. They are generally less expensive to manufacture and buy. They are less efficient at producing thrust at low speeds or under heavy loads. They can increase vibration and noise, particularly at lower speeds. They provide less control and maneuverability than multiblade propellers.

- **4-Blade Propeller**

4-Blade Propeller have more blades which produce more thrust at low speeds, making it excellent for vessels that require rapid acceleration or operate at low speeds. It Reduces vibration and noise for a smoother, quieter ride. It provides improved control and maneuverability, particularly in tight situations or while docking. 4-Blade Propeller are more effective when the vessel is carrying high loads or operating in severe waters. More blades create drag, which limits the vessel's top speed. Additional blades add weight, which might impact overall performance. Generally more expensive to create and buy.

2.22.2 Variable-Pitch Propeller (VPP)

The blade angle can be changed during operation to improve performance at various speeds and loads. They improve efficiency across a wide range of speeds, offer better maneuverability and control, and are more sophisticated and expensive. They demand more maintenance. They are appropriate for large ships, tugboats, and vessels with exceptional maneuverability.

2.22.3 Controllable-Pitch Propeller (CPP)

A variable-pitch propeller whose blade angle is controlled hydraulically or electronically. They provide optimal performance under different speeds and loads. They can reverse the thrust without changing the motor's direction. They are complex and pricey. They require regular maintenance. They are ideal for commercial ships, ferries, and vessels that require precision control.

2.23 ferry Hull selection

The hull is the ferry's main body or frame, which includes its bottom, sides, and deck. It is the most important structural component of any boat or ship since it provides buoyancy, stability, and shape. The hull design of a small passenger ferry has a considerable impact on its performance, efficiency, and passenger comfort.

Fiberglass polyester is a composite material created by mixing glass fibers and polyester resin. This combination produces a material that is strong, durable, and light. Fiberglass helps ships become lighter while maintaining their strength. Its high strength-to-weight ratio is useful in boat construction.

Fig 1.1 Fiberglass polyester boat (https://lianyagroup.en.made-in-china.com/product/qjDmlCTOlukN/China-Liya-19FT-Classic-Fiberglass-Boat-Passenger-Boats-for-Sale.html)

2.24 Electric Motor

Electric Motor produces power making it appropriate for small ferries that require low to moderate power. It generates enough propulsion for speeds of 5-7 knots, making it ideal for calm waters such as lakes, rivers, and harbors.

Fig 1.6 Golden Motor BLDC Motor (https://goldenmotorcz.en.made-in-china.com/product/hveQZRoWfqUV/China-2020-Golden-motor-brushless-5kw-motor-48V-electric-motorcycle-BLDC-motor.html)

CHAPTER THREE

METHODOLOGY

3.1 Ferry Sizing

The proposed hybrid power-driven boat has a hull speed of 14.816km/hr, while diesel-powered country boats typically travel at 7km/hr (3.78 knots) to 12km/hr (6.48 knots) cross rivers. Therefore, a boat speed of 10km/hr (5.4 knots) is sufficient for the crossing.

SPECIFICATIONS OF FERRY AND POWER REQUIREMENT

Boat Hull Type	passenger ferry type of passenger boat
Boat materials	Fiber glass Polyester materials
The gross weight of the boat (full load capacity)	2000kg (5291lb)
Passenger on board	20 people
Boat length	8m (39.37ft)
Boat beam (the transverse distance between the outer sides of the boat)	3.5m (15.75ft)
Draft height (DH)	0.04m (0.13ft)
Boat depth	0.4m (1.64ft)
The displaced volume of water	2.41m^3
Displacement of water by fully loaded boat	2000kg (5291lb)
Maximum and the safest Hull speed	14.816kwh (8 knots)
Considered Hull speed	10kwh (5.4 knots)
Maximum boat speed by propeller	10.056kwh (5.43 knots)
and propeller efficiency	99.43%

3.2 Load Assessment

Table 1: Energy Demand for the PV System

Equipment	Run time (h)	Power (kW)	Energy Consumed (kWh)
BLDC Motor	6	5.00	30.00
Light 1	1	0.06	0.06
Light 2	3	0.04	0.12
Navigational Systems and others	6	0.24	1.44
Total Load			31.62

The first step in the design methodology process is to determine the energy requirements of the passenger ferry. The overall electrical load demand was calculated to be 31.62kWh. This requirement accounts for the energy needed for propulsion (a 5 kW PMDC motor), lights, control systems, and other auxiliary loads.

Theoretically The solar boat will be in operation for eight hours per day, beginning at 8:00 a.m. and ending at 04:00 p.m., with the boat resting at 01:00 p.m. In this research, a small BLDC motor with a 5kW capacity is used to drive the boat at 10 km/hr, with a constant daily load demand of 31.62kWh, an average load of 1.3175 kW.

3.3 Generator Capacity

A diesel generator typically consumes 0.25 to 0.3 liters per kWh at full load.

Calculation for a 10 kW Generator: At Full Load (100%)

Diesel consumption per hour = 10 kW × 0.25 to 0.3 L/kWh

= 2.5 to 3 liters per hour

At 75% Load (7.5 kW)

Diesel consumption per hour = 7.5 × 0.25 to 0.3 L/kWh

= 1.875 to 2.25 liters per hour

At 50% Load (5 kW)

Diesel consumption per hour = 5 × 0.25 to 0.3 L/kWh

= 1.25 to 1.5 liters per hour

A 10 kW diesel generator at full load will consume approximately 2.5 to 3 liters of diesel per hour.

Time Period	Fuel Consumption (liters)
Per Hour	2.5 - 3 L
Per Day (24 hours)	2.5 × 24 = 60 L to 3 × 24 = 72 L
Per Month (30 days)	60 × 30 = 1,800 L to 72 × 30 = 2,160 L
Per Year (365 days)	60 × 365 = 21,900 L to 72 × 365 = 26,280 L

CO_2 Emissions from a Diesel Generator (10 kW) in One Hour

The amount of CO_2 emissions produced by a diesel generator depends on fuel consumption and the carbon content of diesel fuel.

From our previous calculation, a 10 kW diesel generator consumes 2.5 to 3 liters of diesel per hour at full load.

CO_2 Emission Factor for Diesel

Diesel Density: ~ 0.832 kg/L

Carbon Content in Diesel: ~ 86.2%

CO_2 Emission Factor: 2.68 kg of CO_2 per liter of diesel

CO_2 Emission Calculation

CO_2 emitted per hour:

$$CO_2 \text{ Emission} = \text{Diesel Consumption} \times CO_2 \text{ Emission Factor}$$

At 2.5 L/h: $2.5 \times 2.68 = 6.7$ kg CO_2 per hour

At 3 L/h: $3 \times 2.68 = 8.04$ kg CO_2 per hour

Time Period	CO_2 Emissions (kg)
Per Hour	6.7 - 8.04 kg
Per Day (24 hours)	6.7 × 24 = 160.8 kg to 8.04 × 24 = 193 kg
Per Month (30 days)	160.8 × 30 = 4,824 kg to 193 × 30 = 5,790 kg
Per Year (365 days)	160.8 × 365 = 58,692 kg to 193 × 365 = 70,445 kg (≈ 58.7 to 70.4 metric tons)

Time Period	Fuel Used (Liters)	CO_2 Emissions (kg)
Per Hour	2.5 - 3 L	6.7 - 8.04 kg
Per Day (24h)	60 - 72 L	160.8 - 193 kg
Per Month (30d)	1,800 - 2,160 L	4,824 - 5,790 kg
Per Year (365d)	21,900 - 26,280 L	58,692 - 70,445 kg

3.4 Battery Capacity

Battery Type: Lead-Acid (AGM)
Number of Batteries: 16
Voltage per Battery: 6V
Capacity per Battery: 220Ah
System Configuration: 48V (likely 8S2P configuration → 8 batteries in series, 2 parallel strings)

Total Stored Energy (Capacity in Wh)

Stored energy in watt-hours (Wh) is given by:

$$\text{Total Energy} = \text{Total Voltage} \times \text{Total Capacity}$$

Since we are using 8 batteries in series (to form 48V) and then two parallel strings, the total capacity increases while the voltage remains 48V.

$$\text{Total Capacity} = 220\text{Ah} \times 2 = 440\text{Ah}$$

Total Stored Energy $=48V \times 440Ah = 21{,}120$ Wh or 21.12 kWh

Usable Energy (Considering Depth of Discharge)

Lead-acid batteries should not be fully discharged. Typically, 50% Depth of Discharge (DoD) is recommended for longer life.

Usable Energy $=21.12 \times 0.5 = 10.56$ kWh

Runtime of Battery for a 5 kW Motor

The runtime (hours) is calculated as:

Runtime= Load Power(kW)/Usable Energy(kWh)

Runtime = 10.56/5=2.11 hours(about 2 hours and 6 minutes)

3.5 Solar Panel Capacity

Power rating:	330 watts.
Maximum power point Voltage (Vmp):	37.2 volt
Maximum power point Current (Imp):	8.88 amp
Open-circuit voltage (VOC):	45.6 volts
Short-circuit current (ISC):	9.45amps
Temperature coefficient of Isc (%/deg.C)	0.05
Temperature coefficient of Voc (%/deg.C)	-0.31
Module dimensions are	1.96 meters × 0.992 meters
Number of cells:	72 (polycrystalline) cells.

Battery Type: Canadian Solar's CS6U-330P Polycrystalline Silicon Solar PV Modules

Configuration:32 solar panels (330W each) connected to form a 48V system

Total Battery Capacity: 330W per PANEL × 2 series strings × 16 parallel strings = 10.6KW total.

Solar Contribution: During daytime operations, solar can reduce diesel and battery usage significantly.

3.5 Hybrid System

A hybrid power system with a 5 kW electric motor, solar PV (10.56 kW), DC gas generator (10kW), and battery bank (220 Ah) is ideal for typical water boats. A 8 meter long and 3.5 meter-wide passenger ferry boat manufactured of fiberglass polyester was considered. The passenger ferry boat has a speed of 10 km/h (5.4 knots) and can carry up to 20 passengers. Figure 2.1 shows a schematic diagram of a hybrid-powered passenger ferry boat. The solar photovoltaic (PV) panel will be mounted in such a way that it may serve as both an energy source and the roof of the proposed system boat. PV power is controlled by an MPPT controller and its output is fed into the battery via a constant current and constant voltage charge controller and boost converter. The dc gas generator is coupled to the battery bank (BB). BB is connected to the motor speed controller (MSC) via an overcurrent protection device (140 A DC relay). A manual ON/OFF switch is proposed between the motor speed controller and the motor.

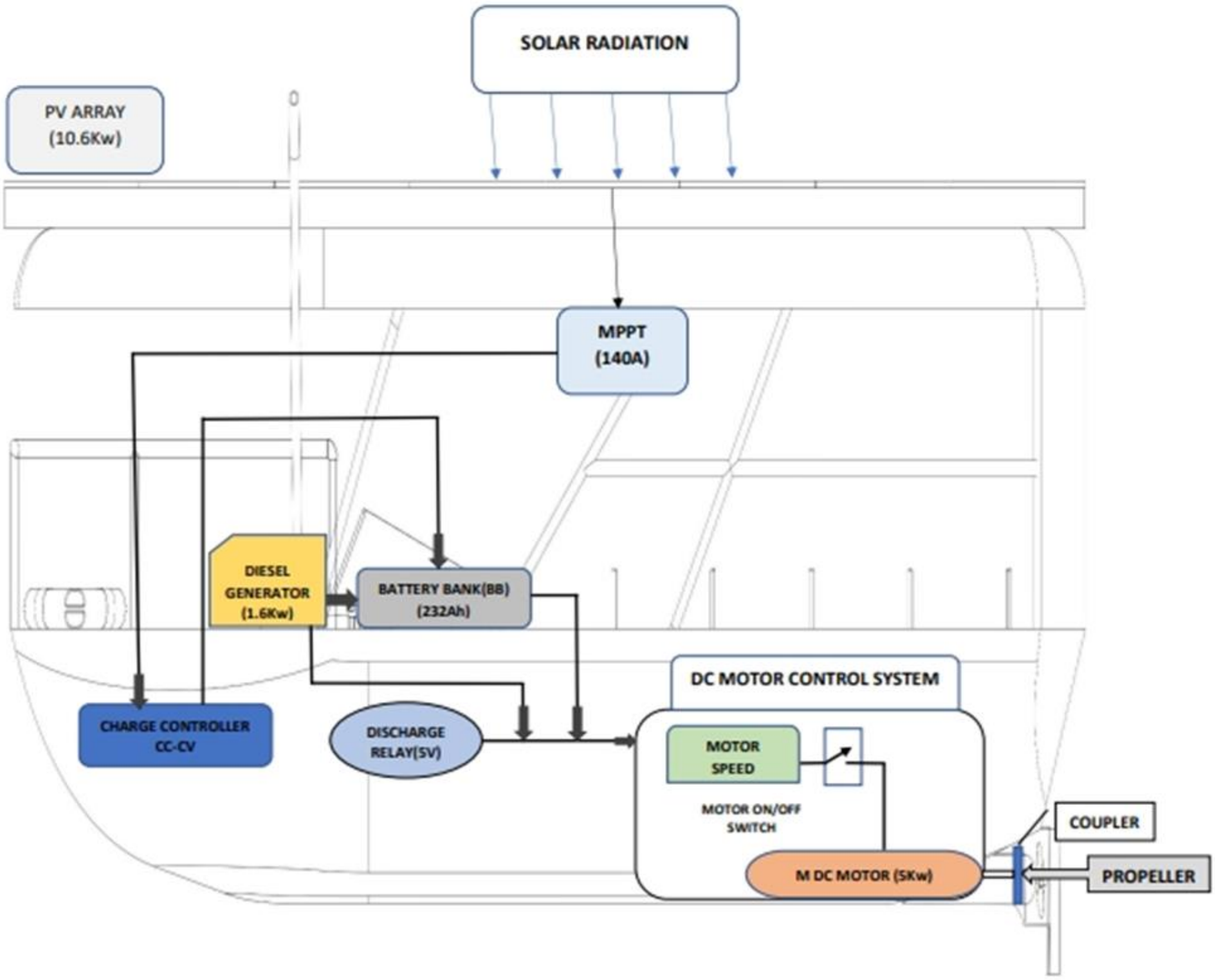

Fig1.15. The schematic diagram of a hybrid-powered passenger ferry boat.

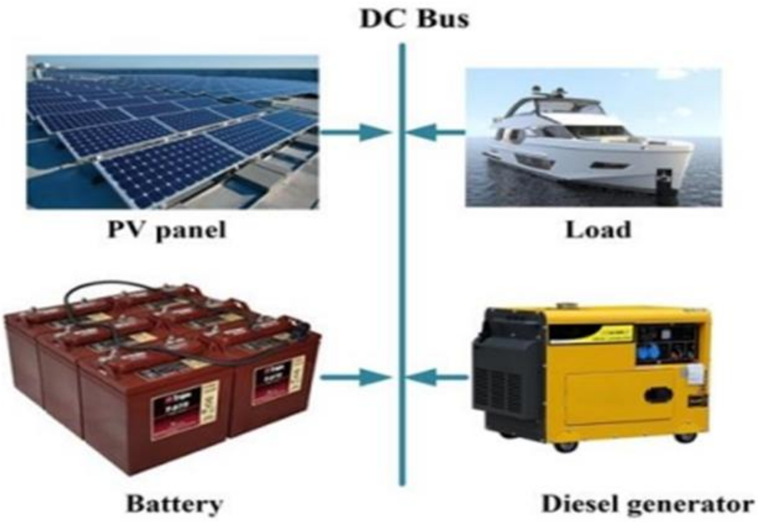

Fig1.16. illustrates a schematic architecture of the proposed hybrid power system for a b.

PV modules are employed in this study to generate baseload power. A diesel generator, on the other hand, is utilized as a backup power source when there is insufficient supply of electricity from PV due to solar inaccessibility, boosting its reliability. Excess energy from PV modules and diesel generators is fed into the battery and used to meet load demand until it reaches a minimum state of charge (SOC). Because there are no alternating current components in the system, no bidirectional converter is required. The next subsections provide a brief description of the mathematical models presented for each system component. In order to reach the specified power of 10.6 kW, the total number of PV strings is increased to 16 parallel and 2 series each string.

CHAPTER FOUR

RESULTS & DISCUSSION

4.1 Hybrid System Production

4.1.1 Fuel And CO2 Gas Emission Reduction By Battery Usage

Fuel & CO_2 Reduction for 2.1 Hours of Battery UsageSince the battery system powers the ferry for 2.1 hours, the diesel generator remains off during that period. This means we save the fuel and CO_2 emissions that the generator would have produced.

Diesel Fuel Saved

Diesel consumption per hour: 2.5 to 3 liters

For 2.1 hours: 2.5×2.1=5.25 to 3×2.1=6.3 liters saved

Total Diesel Saved: 5.25 to 6.3 liters

CO_2 Emissions Reduced

CO_2 emission per liter of diesel: 2.68 kg CO_2

CO_2 reduction for 2.1 hours: 5.25×2.68=14.07 to 6.3×2.68=16.88 kg CO_2 saved

Total CO_2 Saved: 14.07 to 16.88 kg

By running the ferry on batteries for 2.1 hours, the system saves 5.25 to 6.3 liters of diesel And 14.07 to 16.88 kg of CO_2 emissions.

Reduction in CO_2 Emissions and Diesel Fuel Consumption Using Solar Energy

We assumed that the Solar power replaces the need for diesel during the day.

The generator consumes 2.5 to 3 liters of diesel per hour when running at full load.

CO_2 emission factor for diesel = 2.68 kg CO_2 per liter.

Solar energy runs the system for X hours per day (assume 6 hours of sunlight per day).

Reduction in Diesel Fuel Consumption Per Hour

Diesel Saved: 2.5 to 3 liters

Per Day (6 Hours of Solar Usage): 2.5×6=15 to 3×6=18 liters saved per day

Per Year (365 Days): 15×365=5,475 to 18×365=6,570 liters saved per year

Reduction in CO_2 Emissions

Using the CO_2 emission factor (2.68 kg CO_2 per liter of diesel):Per Hour

$$2.5\times2.68=6.7 \text{to} 3\times2.68=8.04 \text{ kg } CO_2 \text{ saved per hour}$$

Per Day (6 Hours of Solar Usage)

$$6.7\times6=40.2 \text{to} 8.04\times6=48.24 \text{ kg } CO_2 \text{ saved per day}$$

Per Year (365 Days)

$$40.2\times365=14,673 \text{to} 48.24\times365=17,613 \text{ kg } CO_2 \text{ saved per year}$$

Time Period	Diesel Saved (Liters)	CO_2 Reduced (kg)
Per Hour	2.5 - 3 L	6.7 - 8.04 kg
Per Day (6 hours of solar)	15 - 18 L	40.2 - 48.24 kg

Per Year (365 days of solar)	5,475 - 6,570 L	14,673 - 17,613 kg

Solar Energy Reduces diesel consumption by up to 6,570 liters per year. Preventing over 17.6 metric tons of CO_2 emissions per year. Cost savings on diesel fuel and extended generator lifespan.

4.2 Long-Term Impact of Hybridization

If the ferry operates for 12 hours daily, with 6 hours powered by solar and 2.1 hours powered by batteries, the generator would only be needed for the remaining 3.9 hours per day instead of running continuously. Over a year, this would result in Significant diesel fuel savings (thousands of liters per year), CO_2 emissions reduction of several metric tons, Lower operational costs and maintenance expenses for the generator. Integrating solar panels to charge the batteries during the day could further increase runtime without using diesel, making the system even more sustainable

4.3 Operational Cost Reduction with Solar Energy Integration

As of February 27, 2025, the average price of diesel fuel in Nigeria is approximately ₦1,033.2 per liter. However, prices can vary by region; for instance, in Abuja, diesel is priced at ₦1,200 per liter

Integrating solar energy into your ferry's power system can significantly reduce operational costs associated with diesel fuel consumption. Here's how:

Fuel Cost Savings:

Daily Diesel Consumption: A 10 kW diesel generator consumes approximately 2.5 to 3 liters per hour.

Daily Operating Hours: Assuming the generator operates 12 hours daily, the total daily consumption is:

$$2.5\text{liters/hour}\times 12\text{hours}=30\text{liters}$$

Daily Fuel Cost: At ₦1,033.2 per liter, the daily fuel expense is:

$$30\text{liters}\times \text{₦}1{,}033.2\text{/liter}=\text{₦}30{,}996$$

By incorporating solar panels, you can offset a portion of this consumption. For example, if solar energy reduces generator usage by 6 hours daily, the fuel savings would be:

$$15\text{liters}\times \text{₦}1{,}033.2\text{/liter}=\text{₦}15{,}498\text{per day}$$

This translates to an annual savings of approximately ₦5,656,770.

4.4 Maintenance Cost Reduction

Extended Equipment Lifespan: Reduced operational hours for the diesel generator lead to less wear and tear, decreasing maintenance frequency and costs.

Lower Operating Expenses: Solar energy systems have minimal moving parts, resulting in lower maintenance requirements compared to diesel generators.

Long-Term Financial Benefits:

Return on Investment (ROI): While the initial installation cost of solar panels and associated equipment can be substantial, the ongoing savings in fuel and maintenance costs can lead to a favorable ROI over time.

Cost Competitiveness: Studies have shown that over a 15-year period, solar photovoltaic (PV) systems can be up to 89.8% more cost-effective than diesel generators

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

The integration of hybrid power systems in Passenger ferry, as investigated in this work, offers a promising approach for increasing energy efficiency, lowering operational costs, and reducing environmental effect. The hybrid system achieves a mix of sustainability and reliability by combining solar photovoltaic (PV) systems, energy storage, and a backup diesel generator, lowering total reliance on fossil fuels. The hybrid system can meet the Passenger ferry's energy requirement, particularly during peak solar months, resulting in lower fuel usage and greenhouse gas emissions than a diesel-only system.

This study evaluated the fuel consumption, CO_2 emissions, and energy savings associated with integrating batteries and solar power into a 10 kW diesel generator-powered ferry. The results showed that:

The diesel generator consumes 2.5 to 3 liters per hour, leading to high operational costs and emissions.

A fully charged battery bank provides 2.1 hours of motor runtime, saving 5.25 to 6.3 liters of diesel per cycle.

This results in a CO_2 emission reduction of 14.07 to 16.88 kg per battery cycle.

Hybridization with solar energy further reduces generator dependence, leading to significant fuel savings and lower emissions over time.

Thus, integrating solar power and battery storage into the ferry's propulsion system is a highly effective strategy for reducing fuel consumption, lowering environmental impact, and improving energy efficiency. Further optimizations, such as increasing battery capacity or solar panel efficiency, could enhance these benefits even further.

Recommendations

Exploring Lithium-Ion Batteries for longer lifespan and higher efficiency. Increasing Solar Panel Coverage to further reduce diesel dependency. Use Smart Energy Management Systems to optimize power usage. Pilot Testing & Scaling for larger ferries in the future.

REFERENCE

1. Ahmed S., Castellazzi A., and Williams A. (2016), "Multi-source energy networks for cargo vessels," Trans. Environ. Electr. Eng., vol. 1, no. 4, DOI: 10.22149/teee. v1i4.52.
2. Aijjou, Bahatti L. , and Raihani A. (2019) “Influence of Solar Energy on Ship Energy Efficiency: Feeder Container Vessel as Example”.
3. Bangladesh Petroleum Corporation, "Imported Petroleum Products (From 2001-02 to 2019-20)." http://www.bpc.gov.bd/site/page/bc0b4f85-c680-4d6f-866cce034d357324/- (accessed October. 30, 2024).
4. Templin J. Brown, ,Sperstad I. B. , Steen A. and Nelsion U. (2019) , "Utilization of catamarans in offshore wind farm maintenance," Journal of Renewable Energy, pp. 131, 1111-1123.
5. Bruna Bacalja Bašić , Maja Krčum and Gudelj Anita . (2023) “Adaptation of Existing Vessels in Accordance with Decarbonization Requirements—Case Study—Mediterranean Port”.
6. Hossain C. A. , Chowdhury N. , Longo M. , and Yaïci W. (2019) , "System and Cost Analysis of Stand-Alone Solar Home System Applied to a Developing Country," Sustainability, vol. 11, no. 5, Art. no. DOI: 10.3390/su11051403.
7. Leung C. P. and Cheng K. W. E. (2017) , "Zero emission solar-powered boat development," in 2017 7th International Conference on Power Electronics Systems and Applications - Smart Mobility, Power Transfer Security (PESA), pp. 1–6, DOI: 10.1109/PESA.2017.8277736.
8. Smith C. , Burrows J. , Scheier E. , Young A. , Smith J. , Young T. , Gheewala S.H.,(2015). Comparative Life Cycle assessment of a Thai Island's diesel/PV/wind hybrid microgrid. Renewable Energy 80, 85 - 100. Http://dx. dox.Org/1016/ j.renene.2015.01.003.
9. Campillo J., Domínguez-Jimenez J. A., and Cabrera J. (2019), "Sustainable Boat Transportation Throughout Electrification of Propulsion Systems: Challenges and Opportunities," in 2019 2nd Latin American Conference on Intelligent Transportation system (ITS LATAM), pp. 1–6, DOI: 10.1109/ITSLATAM.2019.8721330.
10. Canadian Solar MaxPower2 CS6U-330P 330w Poly Solar Panel," Solaris. https://www.solaris-shop.com/canadian-solar-maxpower2-cs6u-330p-330w-poly-solar-panel/ (accessed December 3, 2024).

11. catamaran for tourist applications," in 18th IEEE International Conference on Environment and Electrical Engineering, Palermo, Italy, 2018. (Accessed November 10, 2024).
12. 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. (Accessed November 3, 2024).
13. Deutsche Gesellschaft Für Sonnenenergie. (2012) "Planning and Installing Photovoltaic Systems: A Guide for Installers, Architects and Engineers. UK: Earthscan.
14. Equivalent Circuit Model - an overview science direct topics. Https:// science direct.Com/topics/engineering/equivalent-circuit-model.(Accessed November 4, 2024).
15. system with PMSM for catamaran boat," in AEIT International Annual Conference, Bari, Italy. (Accessed October 9, 2024)
16. Ghenai C., Al-Ani I., Khalifeh F., Alamaari T., and Hamid A. K. (2019), "Design of Solar PV/Fuel Cell/Diesel Generator Energy System for Dubai Ferry," in 2019 Advances in Science and Engineering Technology International Conferences (ASET), pp. 1–5, DOI: 10.1109/ICASET.2019.8714292.
17. Giangiacomo Minak (2023) "Solar Energy-Powered Boats: State of the Art and Perspectives"
18. Green A. Martin, Emery Keith, King L. David, Hishikawa Yoshihiro and Warta Wilhelm (2006). "Solar cell efficiency tables (version 28) - Wiley Online Library," moam.info.https://moam.info/solar-cell-efficiency-tables-version-28-wiley-online library_59989beb1723dd97bdd00e8d html. (Accessed September 2, 2024)
19. Liu H. , Zhang Q. , Qi X. , Han Y. , and Lu F. (2017) , "Estimation of PV output power in moving and rocking hybrid energy marine ships," Appl. Energy, vol. 204, pp. 362–372, DOI: 10.1016/j.apenergy.2017.07.014.
20. Hua J., Wu Y. H., and Jin P. F. (2008), "Prospects for renewable energy for seaborne transportation—Taiwan example," Renew. Energy, vol. 33, no. 5, pp. 1056–1063, DOI: 10.1016/j.renene.2007.06.002.
21. Ilija Knežević, Snezana Dragicevic, Drasko Kovac, Nemanja Pudar. (2022) "Energy Efficiency Analysis of Solar Powered Ship - The Case of Bay of Kotor".
22. IMO, (2020) "Global regulations on maritime emissions: Overview and implications for hybrid catamarans," IMO Publication No. 12345.
23. Ćatipović Ivan , Alujević Neven , Smoljan Darko , Mikulić Antonio . (2022) " A review on marine applications of solar photovoltaic systems"
24. Campillo J. , Walenny F. , Diaz R. , Fernandez D. and Garcia-Quesada J. P. (2017) , "Trends and Emerging Marino Renewable Energy Powered Motorized Vehicles: A Review. Journal of," Journal of Maritime Research, pp. 14(1) 75-88.
25. Eskew J. , Ratledge M. , Wallace M. , Gheewala S.H. , Rakkwamsuk P. (2018). An environmental Life Cycle Assessment of rooftop solar in Bangkok, Thailand. Renewable Energy 123, 781 - 792. https://dx.doi.org/10.1016/j. renene.2018.02.045.
26. Hua J. (2017) , "Feasibility study of introducing renewable energy into Taiwan's maritime industry," Maritime Policy and Management, pp. 44(8), 1005-1019.
27. Liu J. (2021) , "Application of solar photovoltaic energy and advanced energy storage technology in ships," Ships and Offshore Structures, pp. 16(5), 497-509.
28. Smith J. (2021), "Economic impact of catamaran ferry services: A case study of the Mediterranean region,"

29. Röhr A. Jason , Sartor Ed , Duenow N. Joel , Zilun Qin, Juan Meng, Lipton Jason , Maclean A. Stephen , Römer Udo , Nielsen P. Michael , Suling Zhao, Jaemin Kong, Reese O. Matthew , Steiner A. Myles , Ekins-Daukes N. J., Taylor D. André., (2022). “optimal photovoltaic technologies for underwater applications”.
30. Hussein K. H. , Muta I. , Hoshino T. , and Osakada M. (1995), "Maximum photovoltaic power tracking: an algorithm for rapidly changing atmospheric conditions," Transm. Distrib. IEE Proc. - Gener., vol. 142,no. 1, pp. 59–64,, DOI: 10.1049/ip-gtd:19951577
31. Kabir S. M. L., Alam I., Khan M. R., Hossain M. S., Rahman K. S., and Amin N. (2016), "Solar powered ferry boat for the rural area of Bangladesh," in 2016 International Conference on Advances in Electrical, Electronic and Systems Engineering (ICAEES), pp. 38–42, DOI: 10.1109/ICAEES.2016.7888005.
32. Hussain M. , Gawate S. P. , Prasad P. S. , and Kamble P. A. (2015) , "Smart irrigation system with three level access mechanisms," International Conference on Computation of Power, Energy,Information and Communication(ICCPEIC),pp.0269–0275,DOI:10.1109/ICCPEIC.2015.725944.
33. Chakraborty M. K. , Sharma S. and Singh R. (2020) , "Design and analysis of an MPPT-based solar photovoltaic system for fishing trawlers," Renewable Energy Focus, pp. 27-37.
34. Spagnolo M., Servidio E., Papini F., and Cassese S., Design and implementation of a solar powered".
35. Jacobson M.Z., Delucchi M.A., Bazouin G. , Dvorak M.J. , Arghandeh R. , Bauer Z.A.F. , Cotte A. , de Moor G.M.T.H. , Goldner E.G. , Heier C. , Holmes R.T. , Hughes S.A. , Jin L. , Kapadia M. , Menon C. , Mullendore S.A. , Paris E.M. , Provost G.A. , Romano A.R. , Srivastava C. , Vencill T.A. , Whitney N.S. , Yeskoo T.W. , (2016). A 100% wind, water, sunlight (WWS) allsector energy plan for Washington State. Renewable Energy 86, 75-88.
36. Tawfik Magdy , Shehata Ahmed S , Amr Ali Hassan, Mohamed A Kotb. (2023) “Renewable solar and wind energies on buildings for green ports in Egypt”.
37. Mahmud K., Morsalin S., and Khan M. I. (2014), "Design and Fabrication of an Automated Solar Boat," Int. J. Adv. Sci. Technol., vol. 64, pp. 31– 42.
38. Maritime Economics Review, (2018), pp. 15(1) 78-92.
39. Abdullah-Al-Mahbub Md, Abu Reza Md, Towfiqul Islam, and Mahbuba Redowan Asha. (2023)“Sustainable solar energy potential on marine passenger ships of Bay of Bengal: A way of reducing carbon dioxide emissions and disaster risk reduction”
40. Michail Serris, Paraskevi Petrou, Isidoros Iakovidis and Sotiria Dimitrellou. (2023) “Techno-Economic and Environmental Evaluation of a Solar Energy System on a Ro-Ro Vessel for Sustainability”.
41. Midhu Paulson, Dr.Chacko Mariamma (2019) “Marine Photovoltaics: A review Of Research And Developments, Challenges And Future Trends”.
42. Mohammad A. and I. M. Tariq, (2021) "Optimal design, dynamic modeling and analysis of a hybrid power
43. Elkolali Moustafa , Al-Tawil Ahmed , Much Lennard , Schrader Ryan , Masset Olivier , Sayols Marina , Jenkins Andrew , Alonso Sara , Carella Alfredo , Alcocer Alex, (2021). “A low-cost wave-solar powered Unmanned Surface Vehicle”.
44. Salleh N. A. S. , Muda W. M. W. , and Abdullah S. S. (2015) , “Feasibility study of optimization and economic analysis for grid-connected renewable energy electric boat charging station in Kuala Terengganu,” in 2015 IEEE Conference on Energy Conversion (CENCON), pp. 510– 515.

45. Petrychenko Olga , Levinskyi Maksym , Goolak Sergey , Lukoševičius Vaidas . (2024) “Solar Energy: Revolutionizing Shipping Industry Towards Sustainability and Environmental Stewardship”.
46. Leung P. K. , Stratton N. , Hills P. , Miao Y. , Yuan W. and Zhang Y. (2020) , "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.
47. Postiglione C. S., Collier D. A. F., Dupczak B. S., Heldwein M. L., and Perin A. J. (2012), "Propulsion system for an all-electric passenger boat employing permanent magnet synchronous motors and modern power electronics," in Railway and Ship Propulsion 2012 Electrical Systems for Aircraft, pp. 1–6, DOI: 10.1109/ESARS.2012.6387441.
48. Gupta R. , Gupta G. , Kastwar D. , Hussain A. , and Ranjan H. (2010) , "Modeling and design of MPPT controller for a PV module using PSCAD/EMTDC," 2010 IEEE PES Innov. Smart Grid Technol. Conf. Eur. ISGT Eur.
49. Jones R. (2021) , "Luxury yacht trends: The growing popularity of catamaran designs," Yachting Today, pp. 12(2), 45-50.
50. Reza S., Shiblee M. S., Mawla M. R., Jein J. N., and Rahman M. M. (2018), "Design and Analysis of Solar PV System for Marine Fishing Trawlers in Bangladesh," in 2018 4th International Conference on Electrical Engineering and Information Communication Technology (iCEEiCT), pp. 677–680, DOI: 10.1109/CEEICT.2018.8628166.
51. Amadi S., Dike T. and Nwokolo S., (2020), "Global Solar Radiation Characteristics at Calabar and Port Harcourt Cities in Nigeria," Trends in Renewable Energy, vol. 6, no. 2, pp. 111-130.
52. Chakraborty S., Hasan M. M., Das S. , and Razzak M. A. (2016), "A novel MPPT-based synchronous buck converter for solar power system in fishing trawler," in 2016 IEEE 7th Power India International Conference (PIICON), pp. 1–6, DOI: 10.1109/POWERI.2016.8077296.
53. Harishankar S., Kumar R. S., Vignesh U., and Viveknath T. (2014), "Solar Powered Smart Irrigation System," Advance in Electronic and Electric Engineering, vol. 4, No. 4, pp. 341–346.
54. Reza S. M., Hossain M. I. and Ahmad F. (2016) , "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.
55. Sharma C. and Jain A. (2014)."Simulink Based Multi-Variable Solar Panel Modeling," Indones. J. Electrical. Eng. Computer. Sci., vol. 12, no. 8, Art. No. 8.
56. Solar Battery Charge Controller “https://a1solarstore.com/canadian-solar-330w-solar-panel.html”. (Accessed January 22, 2025).
57. Solar Battery Charge Controller “https://www.ecodirect.com/Canadian-Solar-CS6U-330P-330-Watt-Solar-Panel-p/canadian-solar-cs6u-330p.htm”.(Accessed January 22, 2025).
58. Sousa G. C. D., Simonetti D. S. L., and Norena E. E. C. (2000), "Efficiency optimization of a solar boat induction motor drive," in Conference Record of the 2000 IEEE Industry Applications Conference. Thirty Fifth IAS Annual Meeting and World Conference on Industrial Applications of Electrical Energy (Cat. No.00CH37129), vol. 3, pp. 1424–1430 vol.3, system for a catamarans boat in Bangladesh," European Journal of Electrical Engineering and Computer Science, pp. 5-10, 2021.

59. "Trojan SAGM 06 220 AGM 6V 220Ah Battery," Solaris. https://www.solaris-shop.com/trojan-sagm-06-220-agm-6v-220ah-battery/(Accessed January 22, 2025).
60. Smith T. W. , Ranjitkar P. , Bucknall R. and Fricke P. (2018), "Feasibility study of solar assisted marine propulsion system for a short-route passenger ferry," Journal of Marine Science and Engineering, pp. 6(2), 39.
61. Tommaso Zito, Park Chybyung & Jeong Byongug. (2022), “Life cycle assessment and economic benefits of a solar assisted short route ferry operating in the Strait of Messina”.
62. “Types of photovoltaic cells - Energy Education.” /Types of photovoltaic cells https://energyeducation.ca/encyclopedia./Typesofphotovoltaiccells. (accessed Feb. 01, 2021).
63. Vorobiev P. and Vorobiev Y. (2010), “Automatic sun tracking solar electric systems for applications on transport,” in 2010 7th International Conference on Electrical Engineering Computing Science and Automatic Control, pp.66–70, doi: 10.1109/ICEEE.2010. 5608582.
64. Obaid W. , Hamid A.-K. , and Ghenai C. (2018), “Hybrid PEM Fuel-Cell-Diesel-Solar Power System Design with Fuzzy Battery Management System and Weather Forecasting for Electric Boats,” in 2018 6th International Renewable and Sustainable Energy Conference (IRSEC), pp. 1–7.