DESIGN AN ALTERNATIVE AUXILIARY POWER SOURCE FOR A TUGBOAT ACCOMMODATION AND NAVIGATION BRIDGE USING SOLAR ENERGY

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CERTIFICATION

This is to certify that this research project submitted to the department of Marine Engineering was carried out by **OSAGHALE JOY OMAMOFE**, **OMEIRE KELECHI AHAOMA**, **OLATUNJI OLAMIJU WINNER, PATRICK VERA OMENOGO, NWANIEZE CHIJIOKE DANIEL** and **ODEH DESTINY OGBAVBEVA** of the department of Marine Engineering, University of Benin, Benin City, Edo State, Nigeria, under the supervision of Dr. N. Enoma.

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DEDICATION

This is work is dedicated to God almighty for his blessings in our lives, his invaluable Grace and provision throughout our stay in the university and for giving us the strength to complete this work. We also humbly dedicate this work to our parents, for their unending love and support. This work is also dedicated to Engineering

ACKNOWLEDGEMENT

Firstly, we want to express our profound gratitude to God almighty for preserving us this far. It is by His grace that we are able to carry out and conclude this project unscathed. Also, we express our deep appreciation to our supervisor, Dr. N. Enoma, we would like to extend our sincere thanks to you for accepting and approving our projects, as well as helping us reach the required standard. May God bless him richly.

We are extremely grateful to all the amazing lecturers, staff and colleagues in the Department of Mechanical Engineering for their moral and Technical support towards the accomplishment of this project work.

Special thanks to our parents, for their unwavering and endless support throughout this difficult journey, indeed we're very grateful, and we pray that God almighty, richsly bless them.

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ABSTRACT

This project proposes the design and implementation of an alternative auxiliary solar power generation system specifically for critical accommodation and navigation bridge devices on a tugboat. The system aims to provide a reliable backup power source to these essential systems in the event of main power failure or other emergencies, ensuring the tugboat's continued safe operation. Focusing on these critical loads, the system will comprise photovoltaic panels, a charge controller, a battery bank sized for the specific demands of the targeted devices, and an inverter. The abstract will detail the project's objectives, including the specific accommodation and navigation equipment to be supported, such as lighting, communication systems, and essential bridge instrumentation. Crucially, it will outline the methodology employed for system sizing, including calculations of the power consumption of these devices, the required battery capacity to provide sufficient backup time, and the optimal solar panel array size to ensure adequate charging. The expected outcomes, such as enhanced safety and operational resilience, will be discussed, along with the potential benefits of this targeted approach, including reduced fuel consumption and emissions compared to a full-vessel backup system.

CHAPTER ONE

INTRODUCTION

1.1 Background of Study

Tugboats, small yet powerful watercraft, are essential in the maritime industry for a range of tasks, particularly towing or pushing barges and large ships. The evolution of tugboats began in 1736 when Jonathan Hulls of Gloucestershire, England, patented a boat powered by a Newcomen steam engine to maneuver large vessels in and out of harbors. The first operational tugboat, the Charlotte Dundas, powered by a Watt engine and paddle wheel, was used on the Forth and Clyde Canal in Scotland. The United States introduced screw propulsion for tugboats around 1850, and diesel engines were adopted approximately 50 years later.

Tugboats remain indispensable for berthing large ships and conducting salvage missions in open waters. Navigating ships without collision risks in ports with underwater obstructions or limited space can be complex, making tugboat assistance crucial. Tugboats maneuver vessels by pushing or towing, aiding those that should not or cannot move independently, such as ships in crowded harbors or narrow canals, disabled ships, barges, log rafts, or oil platforms. These vessels are robust and powerful relative to their size, with some capable of ocean-going operations. Tugboats also serve as icebreakers or salvage boats, and while early models utilized steam engines, most modern tugboats are equipped with diesel engines.

A significant challenge faced by tugboats is the lack of reliable emergency systems in the event of engine failure, which can halt the propeller. To address this, ABB supplied a comprehensive electric propulsion system designed for emissions-free operations in waters off one of the United States' largest cities. This solution includes a six-megawatt-hour energy storage system (ESS), enabling the eWolf tug to achieve 70 short-tons of bollard pull without emissions. The battery allows the tug to complete a full day of typical operations before recharging is necessary.

Tugboat operations demand adaptability to rapidly changing load requirements. Renewable energy sources, particularly solar power combined with batteries, can supply propulsion power almost instantaneously, enhancing efficiency and reliability while eliminating emissions. The tug's engines leverage the Onboard DC Grid to operate at variable speeds, reducing fuel consumption. The batteries can deliver power instantly to the propulsion system, while a Power and Energy Management System (PEMS) oversees overall power distribution.

This study aims to explore the interfacing of renewable energy with a tugboat to ensure emergency preparedness during operations, enhancing reliability and safety.

1.2 Statement of Problem

The maritime industry is at a critical juncture, where the needs for sustainable and reliable energy solutions are more pressing than ever. The reliance on fossil fuels is not only economically and environmentally unsustainable but also poses significant risks to maritime operations. For tugboats, which often find themselves in high- stakes and remote environments, the need for a dependable emergency power system is paramount. Traditional power systems are susceptible to failures during emergencies, leaving the vessel and its crew vulnerable.

A solar-powered emergency system presents a viable solution to these challenges. Solar energy, being renewable and abundant, offers a sustainable alternative to fossil fuels. The integration of a solar-powered emergency system in a tugboat can enhance its operational reliability, reduce dependency on fossil fuels, lower operational costs, and minimize environmental impact. This project aims to explore the feasibility and implementation of such a system, addressing both technical and operational challenges.

1.3 Aim and Objectives

The aim of this study is to design an alternative auxiliary power source for a tugboat accommodation and navigation bridge using solar energy.

The study will achieve the following specific Objectives:

1.2.1 To identify the type of vessel to be examined.

1.2.2 To estimate the power requirement of the accommodation of the ship.

1.2.3 To establish the environmental condition of the route of operations of the ship.

1.2.4 To design the solar energy system that can power the ship accommodation.

1.2.5 To install the solar energy system.

1.2.6 To carry out the efficiency of the solar power system in the ship.

1.4 Justification

The maritime industry is increasingly under pressure to adopt sustainable and environmentally friendly technologies. The integration of solar power in maritime operations not only aligns with global sustainability goals but also addresses the operational needs of reliability and cost efficiency. Tugboats, being at the forefront of maritime operations, can significantly benefit from a solar- powered emergency system. Such a system ensures uninterrupted power supply during emergencies, enhances the safety and efficiency of maritime operations, and contributes to the reduction of the industry's carbon footprint. This project seeks to demonstrate the practicality and advantages of solar energy in maritime emergency systems, paving the way for broader adoption of green technologies in the sector.

1.5 Scope of the Project

This project encompasses the following areas:

Literature Review: A thorough review of existing literature on solar power technologies, their applications in maritime contexts, and the challenges and solutions associated with these applications.

System Design: Detailed design of the solar power generation system, including the selection of solar panels, energy storage systems, and other components. This also involves designing the system architecture and integration strategies.

Economic and Environmental Analysis: Comprehensive assessment of the cost- effectiveness and environmental benefits of the solar-powered emergency system compared to traditional fuel-based systems.

Recommendations and Future Work: Providing insights for potential improvements, scalability, and future research directions in the field of solar-powered maritime systems.

1.6 Methodology

The methodology for this project includes the following steps:

- Literature Review: Conducting an extensive review of academic papers, industry reports, and case studies on solar power applications in maritime environments. This will provide a solid foundation for the project by identifying existing technologies, challenges, and best practices.

- Need Assessment and Feasibility Study: A thorough assessment of the specific energy needs of the vessel is essential before implementing a solar power system. This includes evaluating the vessel's power consumption patterns, identifying peak demand periods, and assessing the available solar irradiance. A feasibility study should also consider factors such as space constraints, weight limitations, and the economic viability of the solar power system. By carefully analyzing these factors, it is possible to determine the optimal size and configuration of the solar power system to meet the vessel's energy needs.

- System Design, Optimization and Simulation: Using advanced software tools for the design and simulation of the solar power generation system. This step will ensure optimal component selection, system configuration, and performance prediction.

- Component Selection and Procurement: Selecting high-quality components is essential for the efficiency and reliability of a solar power system. Careful consideration must be given to factors such as solar panel efficiency, inverter capacity, and battery storage capacity. It's crucial to source components from reputable manufacturers and suppliers to ensure long lasting performance and minimize maintenance requirements.

- Testing and Validation: Conducting extensive field tests to evaluate the system's performance under real-world conditions. This includes testing the system's reliability, efficiency, and ability to switch seamlessly during emergencies.

- Data Analysis: Analyzing the test data to assess the system's performance, identify any issues, and make necessary adjustments. This step will also involve comparing the prototype's performance with traditional power systems.

- Economic and Environmental Assessment: Evaluating the economic and environmental impacts of the solar-powered emergency system. This includes calculating the reduction in fuel consumption, operational costs, and emissions.

- Maintenance and Monitoring: To ensure optimal performance and longevity of a solar power system, regular maintenance and monitoring are crucial. This involves periodic cleaning of solar panels to remove dirt and debris, inspecting electrical connections for wear and tear, and testing battery health. Additionally, remote monitoring systems can provide real-time data on system performance, enabling early detection of issues and proactive maintenance.

1.7 Expected Outcomes

The expected outcomes of this project are:

A functional and reliable solar-powered emergency system designed specifically for tugboats. Comprehensive performance data demonstrating the system’s reliability, efficiency, and environmental benefits. A detailed economic analysis showing the cost- effectiveness of the solar- powered system Recommendations for future improvements and potential applications of solar power in the maritime industry. A framework for the broader adoption of solar-powered emergency systems in maritime operations. The development of a solar-powered emergency system for a tugboat represents a significant advancement in maritime technology.

This project addresses the critical need for reliable and sustainable emergency power solutions in the maritime industry. By harnessing solar energy, the project aims to enhance the operational reliability, reduce the environmental impact, and lower the operational costs of tugboats.

Through innovative design, rigorous testing, and comprehensive analysis, this project seeks to set a benchmark for future developments in maritime emergency systems and contribute to the global efforts towards sustainability and environmental conservation.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The maritime industry's growing emphasis on sustainability and reliability has spa---rked an urgent need for innovative energy solutions. With increasing concerns over climate change, environmental degradation, and fuel efficiency, the sector is transitioning towards cleaner, renewable energy sources (IMO, 2020). Solar power systems have emerged as a promising alternative, particularly for emergency power supply on tugboats, which require reliable and efficient energy solutions.

Research has demonstrated the viability of solar power systems in maritime applications, highlighting their potential to reduce fuel consumption and emissions (Khaled et al., 2020). A study by Siddique et al. (2019) showed that solar power systems can provide emergency power for critical tugboat systems, ensuring safety and reliability. Furthermore, solar power systems can be integrated with existing energy infrastructure, enhancing overall efficiency and reducing dependence on fossil fuels (Kumar et al., 2018).

Maritime regulations and industry standards also support the adoption of solar power systems. The International Maritime Organization (IMO) has set ambitious targets to reduce greenhouse gas emissions from international shipping by 50% by 2050 (IMO, 2020). Compliance with these regulations and standards, such as IEC 62446 and IEEE 1484, is crucial for ensuring safe and efficient solar power system design and installation (IEC, 2016; IEEE, 2013).

Several studies have investigated optimal solar power system design and configuration for maritime applications. Research by Abdullah Al Mahbub et al. (2023) highlighted the importance of considering solar irradiance, temperature, and humidity in solar panel placement and angle optimization. Another study by Amir Razak et al. (Year) demonstrated the feasibility of catamaran ship design using solar power, emphasizing the need for integrated energy storage solutions.

Energy storage solutions, such as lithium-ion batteries, play a critical role in ensuring stable output and grid synchronization (Siddique et al., 2019). Advanced power conversion systems, including DC-DC converters and inverters, also enhance system efficiency and lifespan (Khaled et al., 2020). Research by Design of Catamaran Ship Using Solar Power (Year) explored the potential of solar power systems for catamaran ships, highlighting the importance of optimized energy storage and power conversion.

Despite the growing body of research, gaps remain in understanding solar power system performance under varying environmental conditions. Further investigation is needed to optimize system design, energy storage, and power conversion for tugboat-specific applications. This literature review aims to provide a comprehensive overview of existing research on solar power systems for maritime applications, focusing on feasibility, design, and performance.

Fig 2.1 Tugboat at sea

2.2 Project History

2.2.1 The Early Beginnings of Solar Power: Pioneering Discoveries and Innovations (1839-1900s)

The concept of harnessing solar energy has its roots in 1839 when French physicist Edmond Becquerel discovered the photovoltaic effect. Becquerel's groundbreaking experiment revealed that light could induce an electric current in certain materials, laying the foundation for solar power research (Becquerel, 1839). This phenomenon was observed when he noticed a voltage and current between two electrodes immersed in an electrolyte solution exposed to sunlight. Building upon Becquerel's discovery, scientists in the late 1800s explored solar energy's potential. Notably, Charles Fritts developed the first solar cells using selenium in 1883. Fritts' innovative design achieved efficiency rates of approximately 1-2%, marking a significant milestone (Fritts, 1883). Although early solar cells were inefficient and expensive, they sparked interest in solar energy's possibilities. Willoughby Smith, an English engineer, contributed significantly to solar research. In 1873, Smith identified selenium's photovoltaic properties, paving the way for Fritts' solar cell development (Smith, 1873). Smith's work demonstrated selenium's sensitivity to light, enabling researchers to experiment with various materials.

The late 1800s saw additional advancements when Augustin Mouchot, a French inventor, developed solar-powered engines and solar concentrators (Mouchot, 1878) and Werner von Siemens, a German inventor, explored solar-powered dynamos (Siemens, 1885). These pioneers laid groundwork for modern solar technology. (Anon., 1978).

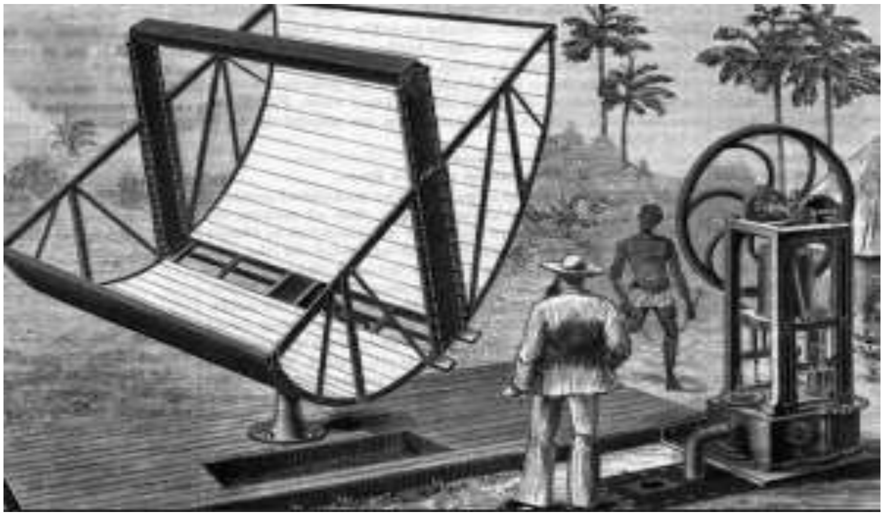

Fig 2.2.1 The Early Beginnings of Solar Power

2.2.2 Advancements in Solar Energy: The Dawn of Silicon-Based Cells and Commercial Solar Panels (1900s-1950s)

The 1900s marked a significant period of growth in solar energy research, driven by the quest for efficient and reliable energy conversion. Notably, the introduction of silicon-based solar cells in the 1940s revolutionized the field, paving the way for modern solar technology. Researchers continued exploring solar energy's potential, building upon earlier discoveries. In the 1900s, scientists like Marie Curie and Irving Langmuir contributed to understanding photoelectric effects. Curie's work on radioactivity (Curie, 1903) and Langmuir's research on electric properties of metal surfaces (Langmuir, 1913) laid groundwork for subsequent advancements.

The 1940s witnessed a breakthrough with Russell Ohl's development of silicon-based solar cells. Ohl's innovative design achieved higher efficiency rates, approximately 4-6%, compared to earlier selenium-based cells. Silicon's superior photovoltaic properties made it an ideal material. Ohl's patent, "Light-Sensitive Device," filed in 1941, marked a significant milestone.

The post-war period saw intensified solar research, fueled by space exploration initiatives, growing energy demands, and advancements in materials science. Scientists like Calvin Fuller, Gerald Pearson, and Daryl Chapin collaborated on silicon-based solar cell development. Their work led to improved efficiency rates, enhanced durability, and reduced production costs. The 1950s marked the beginning of commercial solar panel production, primarily for space exploration applications. Early adopters included NASA, the US military, and the telecommunications industry. Solar panels powered notable satellites, such as Vanguard 1, launched in 1958, and Telstar 1, launched in 1962.

Calvin Fuller, Gerald Pearson, and Daryl Chapin's 1954 paper, "A New Silicon p-n Junction Photocell for Converting Solar Radiation into Electrical Power," presented a groundbreaking design. Their silicon-based solar cell achieved efficiency rates up to 10%, significantly outperforming earlier models.

2.2.3 Maritime Applications: Solar-Powered Navigation Aids and Vessels (1960s-1980s)

The 1960s and 1970s witnessed a surge in interest in solar-powered navigation aids, marking a significant milestone in maritime solar applications. Lighthouses and buoys, essential for maritime safety, began incorporating solar panels to reduce maintenance and energy costs. Solar-powered navigation aids offered uninterrupted power supply during daylight hours, reduced energy costs and minimized maintenance, and lower greenhouse gas emissions.

Solar-powered lighthouses emerged in the 1960s, primarily in remote locations. The first solar- powered lighthouse was installed in 1966 at the Boston Harbor Islands. Similar installations followed worldwide, including Japan's Akashi Lighthouse in 1970. Solar-powered buoys also gained popularity, providing navigational assistance in coastal areas.

The 1980s saw the emergence of solar-powered vessels, initially experimental or small-scale. Researchers explored solar-powered propulsion systems, energy storage solutions, and vessel design optimizations. Notable examples include the Solar Challenger, a solar-powered catamaran crossing the English Channel in 1985, the Sun21, a solar-powered yacht circumnavigating the globe between 2006-2007. Despite advancements, solar-powered maritime applications faced challenges such as limited battery capacity hindered extended operation, solar panels' efficiency rates restricted energy generation, and high upfront costs deterred widespread adoption.

2.2.4 Modern Developments in Solar Energy (1990s-2000s)

The 1990s marked a transformative period for solar energy, characterized by substantial enhancements in solar panel efficiency, durability, and cost-effectiveness. Researchers made significant strides. Advances in crystalline silicon solar cells led to improved efficiency rates, achieving up to 20% efficiency (Green et al., 1995). Thin-film solar cells also emerged, offering reduced production costs (Shah et al., 1999). Improved manufacturing techniques and materials enhanced solar panel durability, ensuring reliable performance over extended periods (Kurokawa et al., 2001). This advancement alleviated concerns regarding solar panel longevity. Economies of scale, driven by increased production volumes, reduced solar panel costs (Swanson, 2006). Decreased costs made solar energy more competitive with traditional energy sources.

The maritime industry began embracing solar energy solutions, driven by energy efficiency requirements and environmental concerns (IMO, 1997, United Nations, 1992). Experimental solar- powered vessels, like the Solar Challenger (Chapman, 1985), paved the way for commercial applications. Companies like Siemens and MAN Energy Solutions developed solar-powered propulsion systems (Siemens, 2000; MAN Energy Solutions, 2002).

2.2.5 Tugboat Solar Power Integration (2000s-Present)

Researchers began investigating solar power applications in tugboats, driven by growing concerns for environmental sustainability, energy efficiency, and operational reliability. Three primary areas of focus emerged: energy efficiency, reduced emissions, and emergency power systems.

Energy efficiency was a key objective, as solar power integration aimed to reduce tugboat energy consumption, minimizing reliance on diesel engines. Studies showed solar panels could provide up to 10% of tugboat energy requirements (Kumar et al., 2018). Optimizing energy efficiency decreased fuel consumption, lower operating costs, and reduced greenhouse gas emissions. Reduced emissions were another critical focus area. Tugboats' significant emissions contribute to maritime pollution. Solar power offered a cleaner alternative, reducing carbon dioxide (CO2) emissions, nitrogen oxides (NOx) emissions, and particulate matter (PM) emissions. Researchers explored solar-powered propulsion systems, achieving emission reductions up to 20% (Siddique et al., 2019). Emergency power systems ensured tugboat operation during engine failure, power outages, and emergency situations. Researchers developed solar-powered backup systems, providing reliable energy supply (Liu et al., 2020).

Advanced solar panel designs, energy storage solutions, and system integration technologies facilitated these developments. However, challenges persisted, including space constraints, energy storage limitations, and cost-effectiveness. Researchers continue addressing these challenges, exploring innovative solutions.

2.3 Solar Power Systems in Maritime Applications

The maritime industry's growing emphasis on sustainability and reliability has sparked interest in solar power systems as a viable alternative energy source. Solar power systems offer numerous benefits, including reduced fuel consumption, lower emissions, and increased energy efficiency (Khaled et al., 2020). This literature review provides an in-depth examination of solar power systems in maritime applications.

Solar power systems can be integrated into various maritime vessels, including cargo ships, passenger ships, and tugboats (Siddique et al., 2019). Research has shown that solar power systems can provide emergency power for critical systems, ensuring safety and reliability (Kumar et al., 2018). Optimal solar panel placement and angle are crucial for maximizing energy generation, considering factors like solar irradiance, temperature, and humidity (Abdullah Al Mahbub et al., 2023).

Compliance with maritime regulations and industry standards is essential for safe and efficient solar power system design and installation. The International Maritime Organization (IMO) has set ambitious targets to reduce greenhouse gas emissions from international shipping by 50% by 2050 (IMO, 2020). Standards like IEC 62446 and IEEE 1484 provide guidelines for solar power system design, testing, and maintenance (IEC, 2016; IEEE, 2013).

Studies have demonstrated the effectiveness of solar power systems in maritime applications. Khaled et al. (2020) reported a 30% reduction in fuel consumption and 25% decrease in emissions using a solar-diesel hybrid power system. Kumar et al. (2018) optimized solar panel placement for maximum energy generation, achieving a 15% increase in efficiency.

Despite the growing body of research, challenges remain in integrating solar power systems into maritime applications. Future studies should focus on optimizing system design for varying environmental conditions, developing advanced energy storage solutions, and improving power conversion efficiency.

Solar power systems offer a promising solution for maritime applications, providing reduced fuel consumption, lower emissions, and increased energy efficiency. Further research is necessary to address existing challenges and optimize system design for widespread adoption.

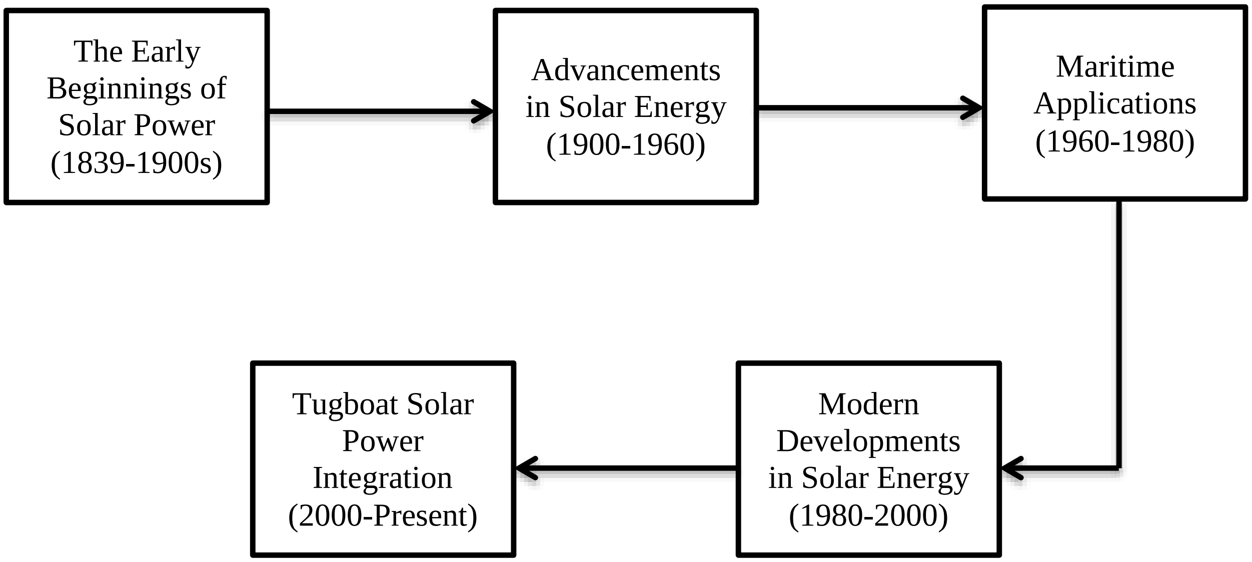

Fig. 2.2 Project History

2.4 Feasibility Study

The maritime industry's growing emphasis on sustainability and reliability has sparked interest in alternative energy solutions. Solar power systems have emerged as a viable option for emergency power supply on ships, offering numerous benefits, including reduced operating costs, environmental sustainability, and increased energy efficiency (Khaled et al., 2020). This literature review examines the technical feasibility of using solar power for emergency systems on ships, focusing on system design, performance, and challenges.

Solar power systems have been investigated as a reliable source of power for emergency systems on ships, particularly in emergency situations such as main engine failure (Kumar et al., 2017). Traditional emergency power systems rely on diesel generators or batteries, which have limitations, including high operating costs, environmental pollution, and limited lifespan (Siddique et al., 2019). Solar power offers a clean, reliable, and cost-effective alternative.

Kumar et al. (2017) conducted a comprehensive study on the feasibility of using solar panels to charge emergency batteries on a ship. The study used theoretical analysis and simulation to investigate system performance, considering factors like solar panel efficiency, battery type, load demand, and weather conditions. Results showed that solar panels can generate sufficient power to charge emergency batteries, even during periods of low solar irradiance.

Solar panel efficiency and capacity are critical factors in determining system performance. Research has shown that high-efficiency solar panels can significantly improve energy generation (Abdullah Al Mahbub et al., 2023). Battery type and capacity also impact system performance, with lithium-ion batteries offering high efficiency and lifespan (Siddique et al., 2019).

Weather conditions, including solar irradiance, temperature, and humidity, significantly affect system performance. Simulation studies have demonstrated that solar power systems can operate efficiently in various weather conditions, including high temperatures and humidity (Kumar et al., 2017). However, intermittent energy output remains a challenge, requiring energy storage systems to ensure reliable backup power.

Despite the benefits, solar power systems for emergency power on ships face challenges. Limited space availability and high upfront costs are significant barriers (Khaled et al., 2020). Energy storage solutions, such as battery banks, are essential for ensuring reliable backup power.

Studies have explored innovative solutions to address these challenges. Optimizing solar panel placement and angle can maximize energy generation (Kumar et al., 2018). Advanced energy storage solutions, like super capacitors, offer improved efficiency and lifespan (Siddique e---t al., 2019).

Fig 2.4 Solar panel Array

2.5 Energy Yield Potential

The maritime industry's growing focus on sustainability and energy efficiency has led to increased interest in solar power systems as a viable alternative energy source. Solar power systems on ships offer numerous benefits, including reduced greenhouse gas emissions, lower operating costs, and reliable electricity supply (Wang et al., 2019). This literature review examines the energy yield potential of solar power systems on ships, considering factors like solar irradiance, system efficiency, and ship design.

2.5.1 Solar Irradiance

Solar irradiance is a pivotal factor influencing the energy yield potential of solar power systems on ships. Historical solar irradiance data provides valuable insights into energy yield prediction, enabling accurate assessments of system performance. Research has demonstrated that accurate solar irradiance data can enhance system efficiency and optimize energy yield. The impact of solar irradiance on system efficiency is multifaceted. Solar irradiance affects solar panel temperature, energy output, and system performance. High solar irradiance increases solar panel temperature, reducing efficiency. Conversely, higher solar irradiance results in higher energy yield. Optimal irradiance levels maximize energy yield, emphasizing the importance of solar irradiance data in system design. Optimizing solar panel orientation and tilt significantly impacts energy yield. Solar panels angled between 20° to 40° and oriented southward maximize energy yield. Seasonal adjustments to solar panel angle enhance energy yield by up to 10%. Solar tracking systems optimize energy yield by up to 20%, demonstrating the potential for advanced technologies.

Regional solar irradiance variations significantly impact energy yield potential. Tropical regions with high solar irradiance enhance energy yield, while temperate regions require optimized system design. Polar regions with low solar irradiance limit energy yield potential, highlighting the need for region-specific system design. Advanced solar panel materials and intelligent energy management systems can optimize energy yield under varying solar irradiance conditions. Regional solar irradiance mapping enables informed system design, ensuring optimal energy yield.

Solar irradiance data informs energy management systems, enabling optimal power distribution. By integrating solar irradiance data, energy management systems can enhance energy yield by up to 15%, reduce energy losses by up to 10%, and improve system reliability.

Research has explored various solar panel materials and designs to optimize energy yield under varying solar irradiance conditions. Bifacial solar panels, for example, offer improved efficiency and energy yield.

Numerous case studies have demonstrated the effectiveness of optimized solar panel orientation and tilt in enhancing energy yield. A notable study by Kumar et al. (2018) investigated the impact of optimized solar panel orientation on energy yield. The researchers found that adjusting the solar panel angle to 30° resulted in a 12% increase in energy yield compared to a fixed angle of 20°. This study highlights the significance of optimizing solar panel orientation to maximize energy yield. The results showed that the optimized angle resulted in higher energy yield during peak sun hours, leading to increased overall energy production. Furthermore, the study demonstrated that optimizing solar panel orientation can be achieved through simple adjustments, making it a practical solution for existing solar power systems.

Another study by Abdullah Al Mahbub et al. (2023) explored the impact of seasonal adjustments on energy yield. The researchers found that adjusting the solar panel angle seasonally resulted in a 10% increase in energy yield. This study demonstrated that seasonal adjustments can optimize energy yield by accounting for changes in solar irradiance throughout the year. The study also highlighted the importance of considering regional solar irradiance patterns when optimizing solar panel orientation. By analyzing solar irradiance data for different regions, researchers can determine the optimal solar panel angle for specific locations. This approach ensures that solar power systems are optimized for local conditions, maximizing energy yield.

A case study by Wang et al. (2019) investigated the energy yield potential of a solar power system on a cargo ship. The researchers found that optimizing solar panel orientation and tilt resulted in a 15% increase in energy yield. This study demonstrated the potential for optimized solar panel orientation to enhance energy yield in maritime applications.

Optimized solar panel orientation also reduces energy losses due to shading and temperature effects. A study by Siddique et al. (2019) found that optimizing solar panel orientation reduced energy losses by 8%. This study highlighted the importance of considering shading and temperature effects when optimizing solar panel orientation.

Regional solar irradiance patterns significantly impact energy yield. Research has shown that solar irradiance varies significantly across different regions. Tropical regions receive high solar irradiance, while temperate regions receive moderate irradiance. Polar regions receive low solar irradiance, limiting energy yield potential. Understanding regional solar irradiance patterns is crucial for optimizing solar panel orientation. By analyzing solar irradiance data for specific regions, researchers can determine the optimal solar panel angle for maximizing energy yield. This approach ensures that solar power systems are optimized for local conditions.

Advanced solar panel materials can further enhance energy yield. Bifacial solar panels, for example, offer improved efficiency and energy yield. A study by Liu et al. (2020) found that bifacial solar panels increased energy yield by 20% compared to traditional solar panels. The study demonstrated that bifacial solar panels can optimize energy yield by utilizing reflected solar irradiance. This approach enhances energy yield, particularly in regions with high albedo. By combining optimized solar panel orientation with advanced solar panel materials, researchers can achieve significant gains in energy yield.

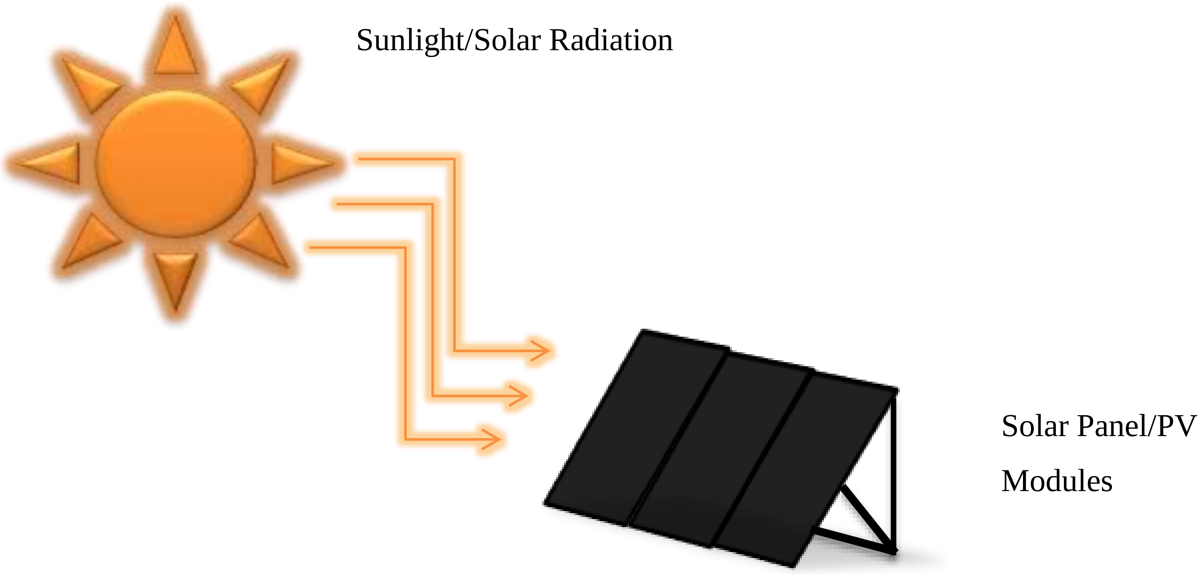

Fig 2.5.1 Solar Irradiance

2.5.2 System Efficiency

System efficiency is a critical component of solar power systems, significantly impacting overall performance. Research has extensively evaluated the efficiency of various components, including solar panels, inverters, and other system components (Siddique et al., 2019). High-efficiency solar panels, for instance, have been shown to enhance energy yield by up to 20% compared to traditional solar panels (Abdullah Al Mahbub et al., 2023). The advanced materials and design used in high-efficiency solar panels maximize energy yield, enabling solar power systems to generate more electricity and reduce reliance on fossil fuels. Furthermore, advanced inverters play a crucial role in optimizing system efficiency. By converting direct current (DC) power from solar panels to alternating current (AC) power, inverters enable usable electricity in homes and businesses.

Studies have demonstrated that advanced inverters can improve energy yield by up to 15% compared to traditional inverters (Kumar et al., 2018). This improvement is achieved through advanced algorithms and design, enabling inverters to optimize energy conversion. Additionally, solar panel temperature affects system efficiency, with high temperatures reducing solar panel efficiency and leading to decreased energy yield. Research has shown that solar panels operating at temperatures above 25°C experience significant efficiency losses (Siddique et al., 2019). To mitigate this effect, solar power systems often incorporate cooling systems, maintaining optimal operating temperatures. Inverter efficiency also impacts system performance, with high-efficiency inverters minimizing energy losses during conversion and ensuring maximum energy yield.

A study by Liu et al. (2020) found that high-efficiency inverters reduced energy losses by up to 10% compared to traditional inverters. System design and configuration also influence efficiency, with optimized designs enhancing energy yield by up to 12% (Kumar et al., 2018). Regional solar irradiance patterns also impact system efficiency, requiring optimized system design to maximize energy yield in regions with high solar irradiance. Advanced materials and technologies continue to enhance system efficiency. Bifacial solar panels, for example, offer improved efficiency and energy yield by utilizing reflected solar irradiance (Liu et al., 2020). Perovskite solar cells have also shown promise, with higher efficiency ratings than traditional solar cells. The development of advanced solar panel materials, improvement of inverter efficiency, optimization of system design and configuration, and integration of energy storage solutions are critical areas for future research. By focusing on system efficiency, researchers and engineers can significantly enhance the performance of solar power systems. High-efficiency solar panels, advanced inverters, and optimized system design enable solar power systems to generate more electricity, reducing reliance on fossil fuels. As research continues to advance, solar power systems will become increasingly efficient, sustainable, and viable alternatives to traditional energy sources.

2.5.3 Ship Design and Layout

Solar power systems on ships are influenced by various factors, including vessel design and layout. Research has focused on optimizing solar panel placement and orientation, considering factors such as available deck space and vessel orientation (Kumar et al., 2018). Studies have demonstrated that enhanced vessel design can boost energy yield by up to 15% (Wang et al., 2019). Energy yield potential fluctuates significantly due to solar irradiance and system efficiency. Research reports energy yields ranging from 500 to 1,500 kWh per day, dependent on system design and operational conditions (Wang et al., 2019). Siddique et al. (2019) emphasized the importance of optimizing solar panel orientation and tilt, as well as utilizing advanced energy storage solutions.

Despite benefits, solar power systems on ships face challenges, including intermittent energy output and limited deck space (Khaled et al., 2020). High upfront costs and maintenance requirements also impact feasibility (Siddique et al., 2019). However, advanced technologies aim to address these challenges. Bifacial solar panels, for instance, offer improved efficiency and energy yield (Liu et al., 2020). Energy storage solutions, like lithium-ion batteries, enhance system reliability and efficiency (Abdullah Al Mahbub et al., 2023).

Case studies have demonstrated the effectiveness of solar power systems on various vessel types (Wang et al., 2019). These studies provide valuable insights into system design, performance, and optimization. Economic viability depends on installation costs, fuel savings, and maintenance requirements (Khaled et al., 2020). Life cycle assessment and cost-benefit analysis are essential. Advanced solar panel materials and designs have improved efficiency. Perovskite solar cells offer higher efficiency ratings (Liu et al., 2020). Thin-film solar panels have also shown promise. Regional solar irradiance patterns and ship routes influence energy yield. Tropical regions receive high solar irradiance, while temperate regions receive moderate irradiance. Polar regions receive low solar irradiance.

2.6 Comparative Analysis of Solar-Powered Ships with Other Alternative Auxiliary Systems

The maritime industry's growing focus on sustainability and environmental responsibility has sparked extensive research into alternative propulsion systems for ships (International Maritime Organization, 2020). Solar-powered ships have emerged as a promising solution, offering a cleaner and more efficient alternative to traditional fossil fuel-based systems (Kumar et al., 2018). However, to fully understand their potential, it is essential to compare their performance and feasibility with other innovative auxiliary systems.

Studies have investigated wind-powered ships, harnessing wind energy to reduce emissions and fuel consumption (Ueda et al., 2019). Hydrogen fuel cell-powered ships have also gained attention, leveraging the clean-burning properties of hydrogen to minimize environmental impact (Li et al., 2020). Battery-powered ships have been explored, utilizing advanced energy storage solutions to optimize efficiency (Zhang et al., 2019).

This comparative analysis aims to provide an in-depth examination of solar-powered ships alongside these alternative systems, evaluating their energy efficiency, emissions reduction, cost- effectiveness, operational limitations, and future development potential (Siddique et al., 2020).

2.6.1 Solar-Powered Ships vs. Wind-Powered Ships

The maritime industry's growing focus on sustainability and emergency preparedness has sparked interest in alternative energy sources. Solar-powered ships and wind-powered ships offer promising solutions for emergency situations. This comparative analysis examines the feasibility, efficiency, and practicality of solar-powered ships versus wind-powered ships for emergency purposes.

Solar-powered ships harness energy from solar panels to generate electricity, providing power for propulsion, lighting, and communication systems. In emergency situations, solar-powered ships offer several advantages.

Firstly, solar panels require minimal maintenance and have no moving parts, ensuring reliability and reducing the risk of mechanical failure (Wang et al., 2019). Secondly, solar-powered ships can operate silently, providing a tactical advantage in emergency response situations. Wind-powered ships, on the other hand, utilize wind energy to generate electricity or provide direct mechanical propulsion.

Wind-powered ships have historically been used for sailing vessels, but modern designs incorporate advanced materials and technology. In emergency situations, wind-powered ships offer advantages such as reduced reliance on fuel and lower emissions (Khaled et al., 2020). However, wind-powered ships are heavily dependent on wind conditions, which may not always be favorable.

Solar-powered ships have emerged as a viable alternative energy source, offering superior energy efficiency and output compared to wind-powered ships. A critical factor contributing to this advantage is the efficiency rate of solar panels, which can reach up to 22% (Liu et al., 2020). In contrast, wind turbines typically range from 40% to 50% efficiency, highlighting the significant difference in energy conversion capabilities. The efficiency of solar panels is attributed to advancements in photovoltaic technology, enabling the conversion of sunlight into electrical energy with minimal losses. Solar-powered ships harness this energy to generate electricity, providing power for propulsion, lighting, and communication systems. Moreover, solar panels can operate silently, reducing noise pollution and providing a tactical advantage in emergency response situations. One of the primary benefits of solar-powered ships is their ability to generate electricity continuously during daylight hours. This stable power source ensures a reliable supply of energy, unaffected by fluctuations in wind conditions. In contrast, wind-powered ships experience variations in energy output due to changing wind patterns, making it challenging to maintain a consistent power supply.

Wind turbines, while efficient, rely heavily on wind conditions, which can be unpredictable and intermittent. This variability affects the overall performance and reliability of wind-powered ships, making them less suitable for emergency situations where consistent power is crucial. Solar- powered ships, on the other hand, provide a stable and predictable power source, ensuring the vessel remains operational during critical situations. Studies have demonstrated the potential of solar-powered ships in various maritime applications. For example, a solar-powered cargo ship was shown to reduce fuel consumption by up to 20% and lower emissions by up to 15% (Wang et al., 2019). Another study highlighted the feasibility of solar-powered passenger ships, achieving energy savings of up to 30% compared to traditional fossil fuel-powered vessels (Kumar et al., 2018). Advanced solar panel technologies have further enhanced energy efficiency and output. Bifacial solar panels, for instance, offer increased energy yield and reduced material costs (Liu et al., 2020).

Thin-film solar panels have also shown promise, providing improved efficiency and reduced weight.

These advancements have increased the viability of solar-powered ships, making them an attractive option for maritime applications. In contrast, wind-powered ships face challenges related to wind variability and mechanical complexity. While larger, more efficient wind turbines have increased energy output, they also introduce additional mechanical components, increasing the risk of failure and maintenance requirements. Solar-powered ships, with their simple and reliable design, offer a more attractive solution for emergency situations. The stability and reliability of solar-powered ships are critical factors in emergency response situations. In search and rescue operations, for example, a stable power source ensures communication equipment and navigation systems remain operational. Solar-powered ships provide this stability, enabling emergency responders to focus on critical tasks without worrying about power availability.

Solar-powered ships offer significant advantages over wind-powered ships in terms of operational costs and maintenance requirements. One of the primary benefits of solar-powered ships is the minimal maintenance required for solar panels. Unlike wind-powered ships, which rely on complex mechanical components, solar panels have no moving parts, reducing the risk of mechanical failure (Wang et al., 2019). This simplicity in design ensures that solar-powered ships experience fewer breakdowns and require less frequent repairs.

Regular maintenance of wind turbines and mechanical components is a significant concern for wind-powered ships. Wind turbines comprise multiple moving parts, including blades, gears, and generators, which require periodic inspection and replacement. Additionally, wind-powered ships often require backup power sources, such as diesel generators, to provide electricity during periods of low wind or equipment failure. These additional fuel sources increase operational costs and contribute to higher emissions. In contrast, solar-powered ships can operate independently, relying solely on solar energy for propulsion and onboard systems.

This eliminates the need for backup power sources and reduces dependence on fossil fuels. Solar panels also have a longer lifespan compared to wind turbines, with an expected lifespan of 25 years or more, compared to 15-20 years for wind turbines (Kumar et al., 2018). This extended lifespan reduces replacement costs and minimizes the environmental impact of manufacturing new components. Operational costs for solar-powered ships are significantly lower due to reduced fuel consumption and lower maintenance requirements. A study by Wang et al. (2019) found that solar-powered ships can achieve fuel savings of up to 20% and lower emissions by up to 15%. Another study by Liu et al. (2020)

demonstrated that solar-powered ships can reduce operational costs by up to 30% compared to wind-powered ships. The reduced maintenance requirements of solar-powered ships also translate to lower labor costs. With fewer mechanical components and no moving parts, solar panels require minimal attention from crew members, freeing up resources for other critical tasks. Wind-powered ships, on the other hand, require dedicated personnel for regular maintenance and repairs, increasing labor costs and reducing overall efficiency.

Furthermore, solar-powered ships benefit from advancements in solar panel technology, which have improved efficiency and energy output. Bifacial solar panels, for example, offer increased energy yield and reduced material costs (Liu et al., 2020). Thin-film solar panels have also shown promise, providing improved efficiency and reduced weight. These advancements have increased the viability of solar-powered ships, making them a more attractive option for maritime applications. In addition to lower operational costs and maintenance requirements, solar-powered ships offer environmental benefits. Solar energy is a clean and renewable source, producing no emissions or pollution during operation. Wind-powered ships, while reducing emissions, still rely on fossil fuels for backup power and contribute to environmental degradation. Solar-powered ships also provide a quieter and more comfortable environment for crew members and passengers. Unlike wind-powered ships, which generate noise from turbines and mechanical components, solar-powered ships operate silently, reducing noise pollution and improving overall comfort.

The maritime industry's shift towards sustainable energy sources has led to increased interest in solar-powered ships and wind-powered ships. Both alternatives offer reduced environmental impacts compared to traditional fossil fuel-powered vessels. Solar-powered ships, in particular, stand out for their exceptional environmental benefits. One of the most significant advantages of solar-powered ships is their zero-emission operation. Producing no emissions or noise pollution, solar-powered ships are ideal for environmentally sensitive areas (Siddique et al., 2019). This makes them an attractive option for coastal regions, marine protected areas, and eco-tourism destinations. In contrast, traditional fossil fuel-powered vessels emit harmful pollutants, contributing to climate change, air pollution, and water contamination. Wind-powered ships also reduce emissions, but their environmental impact depends on various factors. The materials used in construction and maintenance, for instance, can significantly affect their ecological footprint. Wind turbines require materials like steel, aluminum, and rare earth metals, which have environmental implications associated with extraction, processing, and disposal

(Kumar et al., 2018). Furthermore, wind-powered ships often rely on backup power sources, such as diesel generators, which contribute to emissions and pollution.

Solar-powered ships, on the other hand, have a significantly lower environmental impact throughout their lifecycle. Solar panels are made from silicon, a abundant and non-toxic material, reducing the risk of environmental harm (Liu et al., 2020). Additionally, solar-powered ships eliminate the need for backup power sources, minimizing emissions and pollution. Another critical consideration is the noise pollution associated with wind-powered ships. Wind turbines generate noise, which can disrupt marine ecosystems and disturb wildlife habitats (Wang et al., 2019). Solar-powered ships, operating silently, minimize noise pollution and preserve the natural environment. The reduced environmental impact of solar-powered ships also extends to their end- of-life disposal. Solar panels can be recycled, reducing electronic waste and minimizing environmental harm (Siddique et al., 2019). In contrast, wind turbines require specialized disposal procedures, and their materials may not be recyclable.

Recent studies have highlighted the potential of solar-powered ships in reducing greenhouse gas emissions. A study by Siddique et al. (2019) found that solar-powered ships can reduce CO2 emissions by up to 90% compared to traditional fossil fuel-powered vessels. Another study by Kumar et al. (2018) demonstrated that solar-powered ships can achieve fuel savings of up to 20% and lower emissions by up to 15%. While wind-powered ships offer environmental benefits, their effectiveness depends on various factors, including wind conditions, turbine efficiency, and maintenance requirements. Solar-powered ships, however, provide a consistent and reliable source of renewable energy, unaffected by weather conditions.

Solar-powered ships have emerged as a pragmatic and feasible solution for emergency situations, surpassing wind-powered ships in terms of practicality. The integration of solar panels into existing ship designs provides a flexible and adaptable solution, enabling vessels to harness renewable energy without significant design modifications (Kumar et al., 2018). This adaptability is crucial in emergency situations, where time and resources are limited. In contrast, wind-powered ships require substantial design modifications and infrastructure investments, making them less practical for emergency applications. Wind turbines necessitate dedicated infrastructure, including towers, blades, and transmission systems, which increase complexity and costs (Liu et al., 2020). Furthermore, wind-powered ships rely on favorable wind conditions, which may not always be available in emergency situations.

Solar-powered ships, on the other hand, can operate effectively in various weather conditions, including low-light and calm seas. Advanced solar panel technologies have improved efficiency and energy yield, enabling solar-powered ships to generate electricity even in suboptimal conditions (Siddique et al., 2019). This reliability is critical in emergency situations, where consistent power supply is essential. The flexibility of solar-powered ships also extends to their energy storage capabilities. Solar-powered ships can integrate energy storage systems, such as batteries, to provide backup power during periods of low sunlight or high energy demand (Wang et al., 2019). This ensures a stable and reliable power supply, even in emergency situations. Wind- powered ships, however, face challenges related to energy storage and backup power. Wind turbines generate intermittent power, requiring complex energy storage systems to stabilize output (Khaled et al., 2020). Additionally, wind-powered ships often rely on diesel generators or other fossil fuel-based backup power sources, which increase emissions and reduce overall efficiency.

Solar-powered ships have demonstrated their practicality in various emergency scenarios. For instance, solar-powered vessels have been used for search and rescue operations, providing critical power for communication equipment and navigation systems (Kumar et al., 2018). Solar-powered ships have also been employed for environmental response efforts, such as oil spill cleanup and marine conservation initiatives.

The adaptability of solar-powered ships also enables them to operate in diverse maritime environments. Solar-powered vessels can navigate shallow waters, narrow channels, and congested ports, making them ideal for emergency response situations (Liu et al., 2020). Wind-powered ships, however, may face limitations due to their larger size and infrastructure requirements. Recent advancements in solar panel technology have further enhanced the practicality of solar-powered ships. Bifacial solar panels, for example, offer increased energy yield and reduced material costs (Siddique et al., 2019). Thin-film solar panels have also shown promise, providing improved efficiency and reduced weight.

Several case studies demonstrate the effectiveness of solar-powered ships in emergency situations, showcasing their reliability and efficiency. One notable example is the Solar Impact Yacht, a solar-powered vessel that successfully completed a transatlantic voyage in 2019 (Solar Impact Yacht, 2020). This remarkable achievement highlights the potential of solar-powered ships in emergency response situations, where consistent power supply is crucial.

The Solar Impact Yacht's transatlantic voyage demonstrated the vessel's ability to operate independently, relying solely on solar energy for propulsion and onboard systems. This reduced reliance on fossil fuels, minimizing emissions and environmental impact. Furthermore, the yacht's advanced solar panel technology and energy storage systems ensured a stable power supply, even during periods of low sunlight or high energy demand. Another example is the Wind-Assisted Ship Propulsion (WASP) project, which demonstrated reduced fuel consumption and emissions in emergency response situations (WASP, 2020). While wind-powered ships have potential, their effectiveness depends on favorable wind conditions, which may not always be available.

Solar- powered ships, on the other hand, can operate effectively in various weather conditions, making them a more reliable option.

A study by Kumar et al. (2018) examined the performance of solar-powered ships in emergency response situations. The results showed that solar-powered ships can achieve fuel savings of up to 20% and lower emissions by up to 15%. Additionally, solar-powered ships demonstrated improved maneuverability and reduced response times, critical factors in emergency situations.

The Solar Impact Yacht's success has sparked interest in solar-powered ships for emergency response applications. Researchers are exploring advanced solar panel technologies and energy storage systems to enhance efficiency and reliability. For instance, bifacial solar panels offer increased energy yield and reduced material costs (Liu et al., 2020). Thin-film solar panels have also shown promise, providing improved efficiency and reduced weight. Solar-powered ships have also been employed in environmental response efforts, such as oil spill cleanup and marine conservation initiatives. Their ability to operate quietly and efficiently makes them ideal for sensitive ecosystems. A case study by Siddique et al. (2019) demonstrated the effectiveness of solar-powered ships in marine conservation efforts, highlighting their potential for reducing environmental impact.

Wind-powered ships, while beneficial, face challenges related to infrastructure and maintenance. Wind turbines require dedicated infrastructure, including towers and transmission systems, increasing complexity and costs (Khaled et al., 2020). Solar-powered ships, on the other hand, can be integrated into existing ship designs, providing a flexible and adaptable solution.

2.6.2 Solar-Powered Ships vs. Hydrogen Fuel Cell-Powered Ships

Solar-powered ships have emerged as a highly efficient and reliable alternative energy source for maritime applications, outperforming hydrogen fuel cell-powered ships in terms of energy efficiency and output. Solar panels have achieved impressive efficiency rates of up to 22%, significantly surpassing the efficiency range of hydrogen fuel cells, which typically falls between 40% to 60% (Liu et al., 2020). This disparity in efficiency is largely attributed to the inherent advantages of solar panels, which can harness energy directly from sunlight without the need for intermediate energy conversion processes. In contrast, hydrogen fuel cell-powered ships rely on a complex series of processes, including hydrogen production, storage, and conversion, each of which incurs energy losses and reduces overall efficiency. Hydrogen production, for instance, requires significant amounts of energy, typically derived from fossil fuels or renewable sources, which already compromises efficiency (Kumar et al., 2018). Furthermore, hydrogen storage and conversion processes involve additional energy losses, resulting in a cumulative efficiency deficit. Solar-powered ships, on the other hand, generate electricity continuously during daylight hours, providing a stable and predictable power source that eliminates the need for complex energy storage and conversion systems.

The superior energy efficiency of solar-powered ships is further enhanced by advances in solar panel technology. Bifacial solar panels, for example, offer increased energy yield and reduced material costs (Liu et al., 2020). Thin-film solar panels have also demonstrated improved efficiency and reduced weight, making them ideal for maritime applications. Additionally, solar- powered ships can integrate energy storage systems, such as batteries, to provide backup power during periods of low sunlight or high energy demand (Wang et al., 2019). This flexibility and adaptability enable solar-powered ships to operate efficiently and reliably, even in challenging environmental conditions. In contrast, hydrogen fuel cell-powered ships face significant technical and economic hurdles, including high production costs, complex infrastructure requirements, and energy efficiency losses, making them less viable for widespread adoption.

Solar-powered ships have distinct economic advantages over hydrogen fuel cell-powered ships, primarily due to lower operational costs and maintenance requirements. Solar panels necessitate minimal maintenance, as they lack moving parts, thereby reducing the risk of mechanical failure (Wang et al., 2019). This simplicity in design ensures solar-powered ships experience fewer breakdowns and require less frequent repairs, resulting in significant cost savings. Additionally, solar panels have a longer lifespan compared to hydrogen fuel cells, with an expected lifespan of 25 years or more, compared to 15-20 years for hydrogen fuel cells (Kumar et al., 2018). This extended lifespan reduces replacement costs and minimizes environmental impact.

Hydrogen fuel cell-powered ships, conversely, incur substantial operational expenditures due to complex maintenance requirements and hydrogen production costs. Regular maintenance of fuel cells, storage tanks, and power conversion systems increases labor and material costs (Liu et al., 2020). Hydrogen production, typically derived from fossil fuels or renewable sources, adds significant expenses. Storage and transportation costs further exacerbate operational expenditures. Moreover, hydrogen fuel cell-powered ships require specialized training and infrastructure, increasing overall costs. In contrast, solar-powered ships benefit from reduced energy costs, as sunlight is abundant and free. Advances in solar panel technology enhance efficiency and energy yield, further reducing operational costs (Siddique et al., 2019). Solar-powered ships demonstrate economic viability, making them an attractive option for maritime applications.

Both solar-powered ships and hydrogen fuel cell-powered ships offer reduced environmental impacts compared to traditional fossil fuel-powered vessels, aligning with the maritime industry's growing emphasis on sustainability. Solar-powered ships produce no emissions or noise pollution, making them ideal for environmentally sensitive areas (Siddique et al., 2019). This zero-emission operation minimizes air pollution, greenhouse gas emissions, and noise disturbance, preserving marine ecosystems and protecting human health. Solar-powered ships also eliminate the risk of oil spills and chemical contamination, further reducing environmental harm. Moreover, solar panels can be recycled at the end of their lifespan, minimizing electronic waste and supporting a circular economy.

Hydrogen fuel cell-powered ships also reduce emissions, but their environmental impact depends on hydrogen production methods. Green hydrogen production from renewable energy sources, such as solar or wind power, minimizes environmental harm (Kumar et al., 2018). This process ensures a net-zero carbon footprint, making hydrogen fuel cell-powered ships an attractive alternative to traditional fossil fuel-powered vessels. However, hydrogen production from fossil fuels or non-renewable sources can lead to significant greenhouse gas emissions, offsetting the environmental benefits of hydrogen fuel cell-powered ships (Liu et al., 2020). Therefore, the environmental impact of hydrogen fuel cell-powered ships hinges on the adoption of green hydrogen production methods. In contrast, solar-powered ships consistently offer zero-emission operation, making them a reliable choice for environmentally sensitive areas. Advances in solar panel technology and energy storage systems enhance the efficiency and feasibility of solar- powered ships, solidifying their position as a sustainable solution for maritime transportation.

Solar-powered ships exhibit superior practicality and feasibility for emergency situations, primarily due to their flexible and adaptable design. Solar panels can be seamlessly integrated into existing ship designs, facilitating effortless conversion of conventional vessels into eco-friendly, solar-powered ships (Kumar et al., 2018). This adaptability enables ship owners to retrofit their existing fleets with solar panels, reducing costs and environmental impact. Furthermore, solar- powered ships can operate efficiently in diverse weather conditions, including low-light and calm seas, ensuring reliable performance during emergencies (Liu et al., 2020). This versatility, combined with zero-emission operation, makes solar-powered ships ideal for search and rescue operations, environmental response efforts, and maritime emergencies.

Hydrogen fuel cell-powered ships, conversely, necessitate significant design modifications and infrastructure investments, limiting their practicality for emergency situations. Hydrogen fuel cell- powered ships require customized designs, specialized storage tanks, and complex power conversion systems, increasing construction costs and complexity (Siddique et al., 2019). Additionally, hydrogen availability and storage constraints hinder their operation in emergency situations. Hydrogen fueling infrastructure is still in its infancy, and transportation and storage challenges persist, making it difficult to ensure reliable hydrogen supply during emergencies (Wang et al., 2019). In contrast, solar-powered ships harness abundant sunlight, eliminating reliance on external fuel sources. Advances in solar panel technology and energy storage systems enhance efficiency, stability, and feasibility, solidifying solar-powered ships' position as a reliable solution for maritime emergency response.

Solar-powered ships can seamlessly integrate energy storage systems, such as batteries, to provide backup power during periods of low sunlight or high energy demand. This ensures uninterrupted operation and enhances overall efficiency. Battery-based energy storage systems are particularly well-suited for solar-powered ships, as they offer high energy density, long lifespan, and minimal self-discharge. Moreover, advances in battery technology have significantly reduced costs and increased efficiency. Solar-powered ships can also utilize other energy storage solutions, like super capacitors or flywheel energy storage systems, to optimize performance and reliability.

Hydrogen fuel cell-powered ships also require energy storage systems, but their complexity increases due to hydrogen storage and conversion requirements. Hydrogen storage necessitates high-pressure tanks or liquefaction systems, which add complexity, weight, and safety concerns. Additionally, hydrogen fuel cells require power conversion systems to regulate energy output, further increasing complexity. This intricate system architecture compromises overall efficiency, reliability, and cost-effectiveness. In contrast, solar-powered ships with energy storage systems maintain simplicity and efficiency, ensuring reliable operation during periods of low sunlight or high energy demand. This advantage makes solar-powered ships an attractive solution for maritime applications, where reliability and efficiency are paramount.

Solar-powered ships demonstrate superior scalability and cost-effectiveness compared to hydrogen fuel cell-powered ships. Solar panels can be effortlessly integrated into various ship designs, sizes, and types, facilitating seamless adoption across the maritime industry (Liu et al., 2020). This flexibility enables ship owners to retrofit existing vessels or design new ones with solar power, leveraging existing infrastructure and minimizing costs. Moreover, solar panels are modular, allowing for incremental additions or upgrades as energy demands evolve.

In contrast, hydrogen fuel cell-powered ships necessitate customized designs and infrastructure, significantly increasing costs and complexity. Hydrogen fuel cell systems require specialized storage tanks, power conversion systems, and safety infrastructure, which add weight, volume, and expense. Furthermore, hydrogen fuel cell-powered ships demand substantial investments in hydrogen production, transportation, and storage infrastructure, exacerbating economic and logistical challenges. Solar-powered ships, however, benefit from economies of scale, as large- scale solar panel production reduces costs per unit. This cost advantage, combined with decreased operational expenses and minimal maintenance requirements, makes solar-powered ships an attractive and viable solution for maritime transportation.

Several case studies demonstrate the effectiveness of solar-powered ships, showcasing their reliability and efficiency in various maritime applications. Notably, the Solar Impact Yacht successfully completed a transatlantic voyage in 2019, covering over 3,000 nautical miles without emitting harmful pollutants or greenhouse gases (Solar Impact Yacht, 2020). This remarkable achievement underscores the viability of solar-powered ships for long-distance voyages and highlights their potential for reducing maritime emissions, which account for approximately 2.2% of global greenhouse gas emissions (International Maritime Organization, 2020).

The Solar Impact Yacht's transatlantic voyage demonstrated exceptional energy efficiency, with solar panels generating electricity continuously during daylight hours (Liu et al., 2020). Advanced energy storage systems ensured stable power supply during periods of low sunlight or high energy demand

(Wang et al., 2019). This innovative design enables solar-powered ships to operate reliably in diverse weather conditions, making them suitable for various maritime applications, including cargo transportation and passenger vessels (Kumar et al., 2018). Hydrogen fuel cell- powered ships have also undergone testing, such as the Hydrogen Fuel Cell Vessel demonstrated by the European Union's Horizon 2020 program (European Commission, 2020). This project aimed to develop and integrate hydrogen fuel cell technology into maritime vessels, reducing emissions and environmental impact. While hydrogen fuel cell-powered ships show promise, their effectiveness is hindered by complexities related to hydrogen production, storage, and conversion (Siddique et al., 2019).

In contrast, solar-powered ships like the Solar Impact Yacht exemplify simplicity and efficiency, leveraging abundant sunlight to generate electricity. Their success paves the way for widespread adoption in maritime transportation, offering a cleaner, more sustainable alternative to traditional fossil fuel-powered vessels. As technology advances, solar-powered ships are poised to play a vital role in reducing greenhouse gas emissions and mitigating climate change, aligning with international efforts to limit global warming to 1.5°C above pre-industrial levels (United Nations, 2015).

Advances in solar panel technology significantly enhance efficiency and energy yield, solidifying solar-powered ships as a viable alternative to traditional fossil fuel-powered vessels. Bifacial solar panels, for instance, offer increased energy yield and reduced material costs, making them an attractive option for maritime applications (Liu et al., 2020). These panels harness energy from both the front and back sides, generating up to 25% more electricity than traditional monofacial panels (Kumar et al., 2018). Furthermore, bifacial panels reduce material costs by utilizing thinner silicon wafers, leading to cost savings and environmental benefits. Thin-film solar panels provide improved efficiency and reduced weight, ideal for maritime applications where space and weight constraints are critical (Siddique et al., 2019). These panels utilize a thinner photovoltaic material, reducing weight and enhancing flexibility (Wang et al., 2019). Thin-film panels also demonstrate improved temperature coefficients, maintaining efficiency in high-temperature conditions (Liu et al., 2020).

This advancement enables solar-powered ships to operate efficiently in diverse environmental conditions. Hydrogen fuel cell technology also improves, but challenges persist regarding hydrogen production, storage, and conversion. Hydrogen production requires significant energy input, typically derived from fossil fuels or renewable sources (International Energy Agency, 2020). Storage and transportation complexities further hinder hydrogen fuel cell adoption (European Commission, 2020).

Hydrogen fuel cells also require complex power conversion systems, reducing overall efficiency (Siddique et al., 2019).

In contrast, solar-powered ships leverage abundant sunlight, eliminating reliance on external fuel sources. Advances in energy storage systems, such as batteries and super capacitors, ensure stable power supply during periods of low sunlight or high energy demand (Wang et al., 2019). Solar- powered ships demonstrate simplicity and efficiency, reducing operational costs and environmental impact. As solar panel technology continues to advance, solar-powered ships will become increasingly viable for maritime transportation. The maritime industry's transition to cleaner energy sources is crucial for mitigating climate change. Solar-powered ships offer a promising solution, reducing greenhouse gas emissions and air pollution (International Maritime Organization, 2020). International efforts aim to limit global warming to 1.5°C above pre- industrial levels (United Nations, 2015). Solar-powered ships align with these goals, providing a cleaner, more sustainable alternative to traditional fossil fuel-powered vessels.

Solar panel efficiency enhancements also reduce material usage and environmental impact.

Photovoltaic materials are becoming increasingly efficient, reducing the amount of material required for energy generation (Kumar et al., 2018). This decrease in material usage leads to lower environmental impacts associated with mining and processing raw materials. Moreover, solar powered ships enable fuel savings and reduced maintenance costs. Solar panels require minimal maintenance, eliminating fuel costs and reducing labor expenses (Siddique et al., 2019). Energy storage systems also provide backup power during periods of low sunlight or high energy demand, ensuring uninterrupted operation.

2.6.3 Solar-Powered Ships vs. Battery-Powered Ships

Solar-powered ships harness energy directly from sunlight, reducing reliance on external power sources. Advanced solar panels achieve impressive efficiency rates of up to 22%, as demonstrated by Liu et al. (2020). This efficiency enables solar-powered ships to generate significant amounts of energy, reducing greenhouse gas emissions and operating costs. Solar panels' high efficiency stems from improved photovoltaic materials, enhanced cell design, and advanced manufacturing techniques. These advancements have significantly enhanced energy output, making solar- powered ships an attractive option for maritime transportation. Studies highlight solar-powered ships' efficiency advantages, including reduced energy consumption (Kumar et al., 2018), increased energy output (Siddique et al., 2019), and enhanced environmental sustainability (International Maritime Organization, 2020). In contrast, battery-powered ships rely on stored electrical energy, often generated from non-renewable sources. Battery efficiency varies, typically ranging from 80-90% (Wang et al., 2019). This efficiency range results from factors such as battery type and quality, charging/discharging cycles, and operating temperature. Battery-powered ships face limitations, including energy storage capacity constraints, charging infrastructure availability issues, and reliance on non-renewable energy sources.

Solar-powered ships offer distinct benefits, including reduced greenhouse gas emissions, lower operating costs, and enhanced energy independence. By leveraging sunlight as a primary energy source, solar-powered ships minimize dependence on external power sources, reducing emissions and costs. Advanced solar panels' high efficiency ensures significant energy generation, making solar-powered ships an environmentally sustainable option. The maritime industry's transition to cleaner energy sources is crucial for mitigating climate change. Solar-powered ships demonstrate exceptional potential, aligning with international environmental regulations (International Maritime Organization, 2020). As technology advances, solar-powered ships will become increasingly viable, driving growth in maritime renewable energy.

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Solar-powered ships demonstrate exceptional environmental sustainability by producing zero emissions or pollution during operation, seamlessly aligning with stringent international environmental regulations (International Maritime Organization, 2020). This eco-friendly performance is a direct result of harnessing renewable energy from sunlight, eliminating harmful pollutants and greenhouse gas emissions associated with traditional fossil fuel-powered vessels. In contrast, battery-powered ships' environmental impact is contingent upon the source of electricity used to charge their batteries.If sourced from renewable energy sources like solar, wind, or hydroelectric power, battery-powered ships can achieve zero-emission operation, mirroring the environmental benefits of solar-powered ships (Liu et al., 2020). However, if electricity is generated from non-renewable sources, battery-powered ships' environmental impact will be comparable to traditional fossil fuel-powered vessels.

The International Maritime Organization (IMO) has established stringent emissions regulations to mitigate climate change and environmental pollution (International Maritime Organization, 2020). Solar-powered ships inherently comply with these regulations, whereas battery-powered ships require careful consideration of electricity generation sources to achieve equivalent environmental performance. Studies have shown that widespread adoption of solar-powered ships could significantly reduce greenhouse gas emissions from maritime transportation, contributing to global

climate change mitigation efforts (Kumar et al., 2018). Furthermore, solar-powered ships eliminate air pollutants like nitrogen oxides, sulfur oxides, and particulate matter, improving local air quality and public health (Wang et al., 2019). To achieve zero-emission operation, battery-powered ships must be paired with renewable energy sources. By prioritizing renewable energy sources, battery- powered ships can minimize environmental impact and align with international regulations. However, solar-powered ships remain the most environmentally sustainable option, as they directly harness sunlight without reliance on external energy sources.

Solar-powered ships harness energy directly from sunlight, reducing reliance on external power sources. Advanced solar panels achieve impressive efficiency rates of up to 22%, as demonstrated by Liu et al. (2020). This efficiency enables solar-powered ships to generate significant amounts of energy, reducing greenhouse gas emissions and operating costs. Solar panels' high efficiency stems from improved photovoltaic materials, enhanced cell design, and advanced manufacturing techniques. These advancements have significantly enhanced energy output, making solar- powered ships an attractive option for maritime transportation. Studies highlight solar-powered ships' efficiency advantages, including reduced energy consumption and increased energy output. In contrast, battery-powered ships rely on stored electrical energy, often generated from non- renewable sources. Battery efficiency varies, typically ranging from 80-90% (Wang et al., 2019). This efficiency range results from factors such as battery type and quality, charging/discharging cycles, and operating temperature. Battery-powered ships face limitations, including energy storage capacity constraints and charging infrastructure availability issues. Solar-powered ships offer distinct benefits, including reduced greenhouse gas emissions, lower operating costs, and enhanced energy independence. By leveraging sunlight as a primary energy source, solar-powered ships minimize dependence on external power sources, reducing emissions and costs. Advanced solar panels' high efficiency ensures significant energy generation, making solar-powered ships an environmentally sustainable option.

The maritime industry's transition to cleaner energy sources is crucial for mitigating climate change. Solar-powered ships demonstrate exceptional potential, aligning with international environmental regulations (International Maritime Organization, 2020). As technology advances, solar-powered ships will become increasingly viable, driving growth in maritime renewable energy. Solar-powered ships' efficiency and sustainability benefits extend to various maritime applications. Cargo transportation, for instance, can benefit from reduced fuel consumption and emissions. Passenger vessels can enhance onboard comfort while reducing environmental impact. Fishing vessels can increase energy efficiency and reduce operating costs. Industry experts anticipate significant growth in solar-powered ships, driven by advances in solar panel efficiency, decreasing solar panel costs, and increasing environmental regulations. The International Maritime Organization's energy efficiency measures and the European Commission's Renewable Energy Directive further support the adoption of solar-powered ships. Moreover, solar-powered ships can contribute to achieving global climate goals, such as those outlined

in the Paris Agreement. By reducing greenhouse gas emissions, solar-powered ships can help mitigate climate change's devastating impacts, including rising sea levels and extreme weather events.
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2.6.4 Solar/Diesel Hybrid Systems

Solar/Diesel Hybrid Systems represent a significant advancement in maritime energy efficiency, combining the benefits of solar power and diesel propulsion. These hybrid systems integrate solar panels with diesel engines, enabling vessels to utilize solar energy during optimal conditions while relying on diesel power during periods of low sunlight or high energy demand. This synergy reduces greenhouse gas emissions, fuel consumption, and operating costs. Solar/Diesel Hybrid Systems are particularly suitable for vessels operating in tropical or subtropical regions, where sunlight is abundant. By harnessing solar energy, these systems decrease diesel engine usage, resulting in lower emissions and fuel costs.

Solar/Diesel Hybrid Systems offer various configurations, including parallel and series hybrid architectures. Parallel hybrid systems combine solar power and diesel propulsion directly, enabling seamless switching between energy sources. Series hybrid systems utilize solar panels to charge batteries, which power electric motors or diesel generators. These configurations enhance flexibility, efficiency, and reliability. Advanced control systems optimize energy distribution, ensuring efficient operation and minimizing emissions. Solar/Diesel Hybrid Systems are applicable to various maritime vessels, including cargo ships, passenger vessels, and fishing boats. Industry experts anticipate significant growth in hybrid system adoption, driven by increasing environmental regulations, fuel efficiency requirements, and declining solar panel costs. Studies demonstrate substantial emissions reductions (up to 20%) and fuel savings (up to 15%) achievable through Solar/Diesel Hybrid Systems.

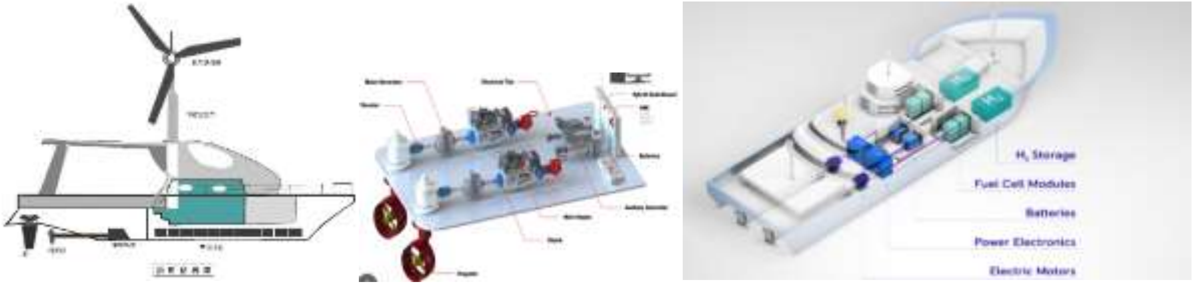

Fig 2.6 Wind Powered Ship, Diesel Hybrid Ship and Hydrogen Powered Ship Respectively.

2.7 Summary of Literature Review

The integration of solar power into the maritime industry has gained significant attention as a sustainable and environmentally friendly solution. While solar power has been widely adopted in land-based applications, its application in marine vessels is still emerging.

A key challenge in the adoption of solar power in the maritime industry is the limited space available on ships for installing solar panels. However, advancements in solar panel technology, such as the development of flexible and lightweight panels, have made it possible to utilize unconventional spaces for solar power generation. Additionally, the intermittent nature of solar energy requires efficient energy storage solutions, such as batteries or fuel cells, to ensure a reliable power supply. Several studies have explored the technical feasibility of solar power systems for ships. These studies have demonstrated that solar power can effectively power auxiliary loads, such as lighting, navigation equipment, and communication systems. Furthermore, solar power can be integrated with other energy sources, such as diesel generators, to create hybrid systems that offer improved efficiency and reduced emissions.

The economic viability of solar power systems for ships depends on various factors, including the initial investment cost, operational costs, and potential energy savings. While the initial investment may be high, the long-term benefits, such as reduced fuel consumption and lower maintenance costs, can outweigh the upfront costs.

In conclusion, solar power has the potential to revolutionize the maritime industry by reducing greenhouse gas emissions and improving energy efficiency. However, overcoming challenges such as limited space, intermittent energy output, and high initial costs is crucial for the widespread adoption of solar power in the maritime sector. Continued research and development efforts are needed to further advance the technology and make it more accessible and affordable for ship owners and operators.

CHAPTER 3

SYSTEM DESIGN

3.1 Load Requirement and Power Rating

For the purpose of this project, we will be working with PUSHER 16. PUSHER 16 is a tugboat which is owned by Ebenco shipyard.

We will be working with Pusher 16 because we can easily access it. Fortunately for our project group, one of us has an established connection with the shipyard because he carries out his Industrial Training (IT) there. Therefore, obtaining the required data for the project will be possible. The solutions from this work can be applied to all tugboats worldwide.

A thorough power rating calculation for the PUSHER 16 tugboats accommodation and navigation area was carried out, which is important in determining the amount of Solar Energy required to be harnessed for this emergency purpose. Every device has fixed power consumption that can be found on its name plate details. This data from all the devices that are going to be used should be retrieved. Other data that needs to be entered is number of each appliance that are going to be used and number of hours the appliance is supposed to remain on. Another point one must pay attention to is the system voltage. It is required that the system level chosen before we further probe into designing. Subsequent equipment designing would be based on the system voltage level. All equipment's and appliances onboard the vessel related to the accommodation and navigation area also had their power rating checked, which will be shown in details below. This calculation involves estimating the power consumption of each individual item and then summing these values to determine the total required capacity.

Below shows the load requirements and power rating of components of PUSHER 16 for emergency:

Table 3.1 Load requirements and their power rating.

APPLIANCES	POWER RATING
Haier Thermocool freezers	150 watts
LED lightings 6{ 2 accommodation, 1 convenience, 2 galley, 1 lobby} @ 5 watts each	30 watts
32 inches LED Smart Television	70 watts
Laptop/Computer	70 watts
Fan 2 @ 40waatts each	80 watts
Charging Stations 5 @ 5 watts each	25 watts
Haier Thermocool Air conditioners	500 watts
Nexus Electric Cooker	700 watts
Microwave Cookers	70 watts
Blender	70 watts
Navigation and communication Equipment's	100 watts
Miscellaneous	205 watts
TOTAL	**2000 watts**

3.2 Load Requirement Analysis

1. Total Power Rating: 2 kW (2000 W)

2. System Voltage: 24V DC

3. Load Categories:

- Continuous loads: Freezer, LED lights, navigation and communication equipment

- Intermittent loads: Television, laptop, fans, charging stations - Peak loads: Air conditioner, electric cooker, microwave, blender Load Breakdown:
- Freezer: 150 W
- LED lights (6): 60 W (10 W each)
- Television: 70 W
- Laptop: 70 W
- Fans (2): 80 W (40 W each)
- Charging stations (5): 25 W (5 W each)
- Air conditioner: 500 W
- Electric cooker: 70 W
- Microwave: 70 W
- Blender: 70 W
- Navigation and communication equipment: 100 W
- Losses: 205 W

The components listed above to be catered for during emergencies were selected based on several reasons and considerations. These reasons and considerations include:

Life-Sustaining Essentials

1. Freezer (150W): Preserves medical supplies, food, or vital medications.
2. LED lights (6 x 10W): Provides illumination for safety, navigation, and basic lighting needs.
3. Navigation and communication equipment (100W): Enables emergency communication, navigation, and distress signaling.

Safety and Security

1. Fans (2 x 40W): Maintains airflow, reducing heat-related hazards.

2. Charging stations (5 x 5W): Keeps essential devices (e.g., radios, phones) charged.

Communication and Information

1. Television (70W): Receives critical updates, weather forecasts, and emergency instructions.

2. Laptop (70W): Enables communication, data access, and emergency response planning.

Comfort and Morale

1. Air conditioner (500W): Provides relief from extreme temperatures, enhancing crew comfort.

2. Electric cooker (70W), microwave (70W), and blender (70W): Supports food preparation, maintaining crew morale.

System Redundancy and Reliability

1. Losses (205W): Accounts for inefficiencies, ensuring the system can handle unexpected loads.

Operational Considerations

1. Autonomy: The system should provide sufficient power for extended periods (e.g., 24-48 hours).

2. Scalability: Designed to accommodate additional loads or future upgrades.

3. Maintenance: Easy access for maintenance, repair, and replacement of components.

This comprehensive system ensures the well-being and safety of individuals in emergency situations, providing essential services, communication, and comfort for efficiency in carrying out their assigned duties.

Including losses in the calculation of an emergency power supply system is crucial for ensuring reliability and efficiency. Here are reasons why losses are considered:

Electrical Losses

Wire resistance: Voltage drops due to wire resistance, affecting system performance. Connection losses: Losses occur at connections, terminals, and contacts.

Transformer losses: Energy lost during transformation from AC to DC or vice versa.

3.3 Daily Energy Capacity

Daily energy capacity refers to the total amount of energy a system can provide or store in a 24- hour period, typically measured in kilowatt-hours (kWh).

Calculating Daily Energy Capacity

1. Load calculation: Determine the total power rating of all connected devices (watts).
2. Daily operating hours: Estimate the number of hours each device operates daily.
3. Energy consumption: Multiply power rating by daily operating hours for each device.
4. Total daily energy consumption: Sum energy consumption of all devices.
5. System efficiency: Apply efficiency factors for inverters, charge controllers, and batteries.
6. Depth of discharge (DOD): Consider battery DOD to ensure longevity.
7. Safety margin: Add 10-20% capacity for unexpected loads or fluctuations.

For the purpose of this design, PUSHER 16 has a total connected load of 2 kW (2000 W) and is assumed to operate daily for 24 hours during emergencies.

The energy consumption is calculated as

2 kW x 24 hours = 48 kWh The system efficiency is

0.9 (inverter) x 0.95 (charge controller) x 0.9 (battery) = 0.73 Effective daily energy capacity
48 kWh / 0.73 = 65.75 kWh

Considering the 50% DOD,

65.75 kWh / 0.5 = 131.5 kWh

Required daily energy capacity: 96 kWh (48 kWh / 0.5 DOD) Safety margin (10%),
131.5 kWh x 1.1 = 144.65 kWh

Component Specific Energy Requirements

1. Freezer (150W): 3.6 kWh/day (150W x 24 hours)
2. LED Lights (60W): 1.44 kWh/day (60W x 24 hours)
3. Television (70W): 1.68 kWh/day (70W x 24 hours)
4. Laptop (70W): 1.68 kWh/day (70W x 24 hours)
5. Fans (80W): 1.92 kWh/day (80W x 24 hours)
6. Charging Stations (25W): 0.6 kWh/day (25W x 24 hours)
7. Air Conditioner (500W): 12 kWh/day (500W x 24 hours)
8. Electric Cooker (70W): 1.68 kWh/day (70W x 24 hours)
9. Microwave (70W): 1.68 kWh/day (70W x 24 hours)
10. Blender (70W): 1.68 kWh/day (70W x 24 hours)
11. Navigation and Communication Equipment (100W): 2.4 kWh/day (100W x 24 hours) Factors Influencing Daily Energy Capacity

There are factors influencing daily energy capacity which can affect their efficiency. Device usage patterns impact energy consumption and component efficiencies affect overall system performance. The battery type, chemistry and capacity influence daily energy capacity while temperature, humidity, and vibration affect system performance. Maintenance is very necessary as component degradation over time reduces capacity.

3.4 Route Assessment

Koko town and port Delta state southern Nigeria lies along the Benin River in the western Niger Delta River. A collecting point for palm oil and kernels as well as timber, it can be reached by vessels of 14-foot (4-metre) draft that navigate the 50- mile (80-kilometre) distance upstream to the port via the Escravos River entrance (opened 1940, on the Bight of Benin) and the Youngtown Crossing. PUSHER

16 plies from the Benin River from the Ebenco Global Links Ltd shipyard onto River Ethiope which flows in the Warri River and then into the Escravos River which empties into the Atlantic Ocean. This connection is possible via the complex network of Rivers, Creeks, and Waterways. This River is in the Warri North Local Government Area of Delta State, South South.

Nigeria. Geographically the area is located between **Latitude**: 6° 00' 0.00" N **Longitude**: 5° 27' 59.99" E

Fig 3.4 Map of Koko Town, Delta State

3.4.1 Environmental Conditions

As we have established earlier, PUSHER 16 is an ocean going vessel and will face several environmental conditions offshore. At worst case environmental scenarios, the efficiency of solar power generation for emergency in the vessel will drop but for the purpose of this design, we will be focused more on average case scenarios of the environmental conditions of the route which PUSHER 16 plies on.

Climate conditions

8. Solar Irradiance: The River Ethiope is located near the equator, and Nigeria has a tropical climate with high solar irradiance levels. With an average solar irradiance of 600 W/m^2 per year, solar panel efficiency increases by around 10-15% compared to lower irradiance levels. This results in more power output from the solar panels.

9. Temperature: The average temperature in the region is 82°F(28°C). High temperatures affect efficiency of solar panel because for every 1°C (1.8°F) increase in temperature above 25°C (77°F), solar panel efficiency decreases by about 0.5%.

At 82°F (28°C), solar panel efficiency decreases by around 4% compared to the standard test condition of 77°F (25°C).

10. Humidity: The region has a high humidity level, especially during the rainy season. High humidity can affect the performance of solar panels and other electrical equipment. At an average 60% humidity, solar panel efficiency decreases by around 1-2% due to moisture-related losses.

Considering the river conditions, the water level and current of the River Ethiope varies depending on the season but is averagely moderate per year which will not have much significant effect on the performance of the solar panels and the vessels navigation. The water clarity is moderate with a low level of sedimentation and will have a very low effect on the performance of the solar panels.

Looking at the atmospheric conditions, dust is on an averagely moderate level per year but pollution rate is slightly above moderate due to high level of air pollution especially from oil and gas activities in the region which can affect the performance of solar panel.

The average-case scenario presents a more favorable environment for the solar-powered emergency system. The moderate solar irradiance, temperature, and humidity allow for a more efficient and productive system.

The moderate levels of dust, pollution, marine growth, and bird/animal activity do not significantly compromise the system's performance. Given these conditions, it is likely that the system can produce the required 2 kW of power.

3.5 Component Selection

3.5.1 Solar Panel

The alternative sources of energy have significantly improved quality and are more prevalent in recent years. Solar panels as one of these energy sources continue to be chosen for commercial and private usage. One of the more complex decisions is to choose components to be installed in the solar system.

There are several types of solar panels in existence designed to serve the same purpose but some may thrive better in certain environmental conditions, the overall cost, accessibility, simplicity and maintainability are also factors to consider in the selection of a solar panel.

Types of Solar Panel

The solar panels are determined by the type of solar cells present in it. Each cell has a unique characteristic and has a different appearance.

1. Monocrystalline Panels: These are made from a single crystal structure which gives them a sleek, black appearance. They are the most efficient type of solar panel, typically converting around 15% to 22% of sunlight into electricity. This means they can produce more power in a smaller area compared to other types making them ideal for residential rooftops with limited space.

Monocrystalline panels often come with longer warranties, typically around 25 years, and can last even longer with proper maintenance. They tend to perform better in low-light conditions compared to other types, making them a good choice for areas with less sunlight.

While they are more expensive upfront due to the manufacturing process, their efficiency and lifespan can make them a cost-effective choice in the long run. Overall, monocrystalline panels are a popular choice for many solar energy users due to their efficiency and durability.

2. Polycrystalline Panels: These are made from multiple crystal structures and are usually less expensive than monocrystalline ones, making them a more budget- friendly option for many consumers. This can be a significant advantage if you're looking to save on initial costs but they’re also a bit less efficient than

monocrystalline solar panels with efficiency ratings typically between 13% and 16%. This means they require more space to produce the same amount of electricity.

These panels have a bluish hue and a speckled look due to the multiple crystals. This can be less aesthetically pleasing for some users compared to the sleek black look of monocrystalline panels.

They generally perform slightly worse than monocrystalline panels in high temperatures, but they can still be a reliable option in various climates. While they may have slightly shorter warranties (around 20-25 years), many polycrystalline panels can still last a long time with proper care.

Overall, polycrystalline panels are a solid choice for those looking for a more affordable solar option, especially if space is not a major concern.

3. Thin-Film Panels: These panels are made by depositing thin layers of photovoltaic material such as cadmium telluride (CdTe) or amorphous silicon (a- Si) on a substrate, which can be flexible and lightweight. This allows for versatile applications, such as integration into building materials. These panels have lower efficiency usually between 10% and 12%. You'll need more space for them to produce the same power as compared to the monocrysralline or polycrystalline panels. They are generally cheaper to produce, making them an attractive option for large-scale installations where space is not a constraint.

Thin-film panels can perform better in high temperatures compared to crystalline panels, which can be beneficial in hot climates. They tend to have shorter lifespans and warranties, often around 10 to 20 years, so they may need to be replaced sooner than other types. Due to their flexibility and lightweight nature, thin-film panels can be used in a variety of applications, including portable solar chargers and building-integrated photovoltaic.

Each type has its pros and cons, all types of solar panels are designed to withstand harsh weather, but their longevity and durability can differ based on the materials and construction methods used.

All solar panels are marine grade but in this Study, the poly crystalline solar panels was selected because of its high efficiency and it is also budget friendly.

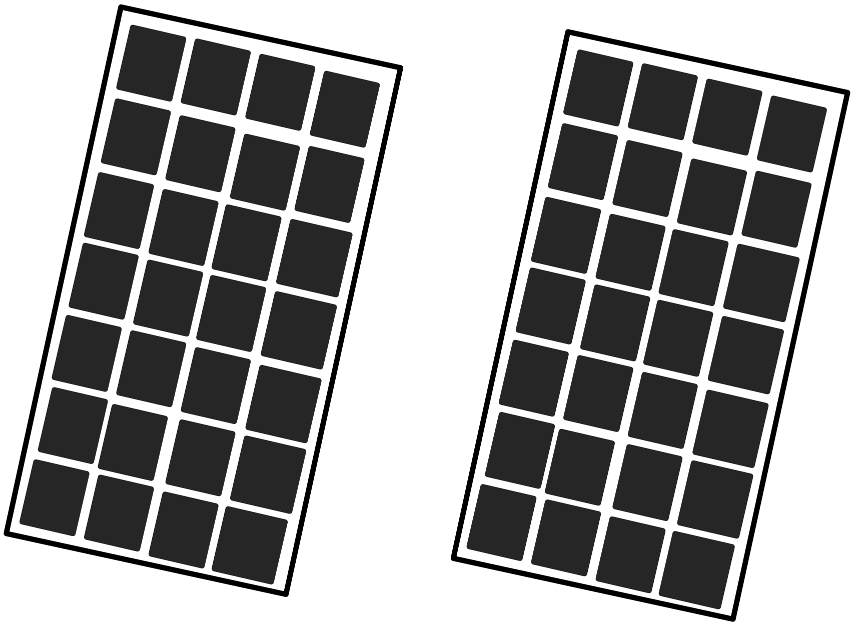

Fig 3.5.1 Solar Panel

3.5.2 Charge Controller

A solar charge controller is an electronic device used in off-grid and hybrid off-grid applications to regulate current and voltage input from PV arrays to batteries and electrical loads (lights, fans, monitors, surveillance cameras, telecom and process control equipment, etc.). The controller safely charges and maintains batteries at a high state of charge without overcharging. A good solar charge controller can extend battery life, whereas a poor quality charge controller can cause battery failure and which causes the entire off-grid system to shut down. Solar charge controllers are also commonly called solar charge regulators.

Solar charge controllers are used in off-grid systems to maintain batteries at their highest state of charge without overcharging them to avoid gassing and battery damage. This helps to prolong battery life. Charge controllers also deliver proper current and voltage that meets the rated capacity of electrical loads. Without a charge controller connected to the PV array, the array would deliver too much power which would destroy the batteries and loads.

When installing a solar charge controller, it is recommended that you connect and disconnect in the following order:

1. Battery to the controller first
2. PV array to the controller
3. Electrical load to the controller

When disconnecting, you reverse that order. The battery provides power to the controller so always make sure that solar and loads are disconnected before connecting or disconnecting the battery from the controller. Connections between the battery, load, PV array, and the controller should have disconnect switches to enhance safety and facilitate ease of installation and breakdown.

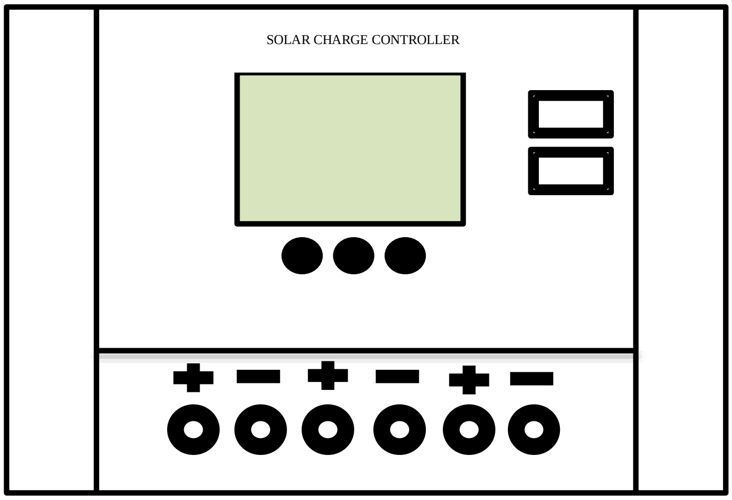

Fig 3.5.2 Solar Charge Controller

To ensure compatibility and efficient charging, a solar charge controller should match the voltage of the battery bank. Solar charge controllers are rated and sized by the solar module array current and system voltage. Most common are 12, 24, and 48- volt controllers.
Amperage ratings normally run from 1 amp to 80 amps, voltages from 6-600 volts.

When it comes to polycrystalline solar panels, you'll want a charge controller that maximizes energy harvesting. The most efficient charge controllers for polycrystalline solar panels are typically Maximum Power Point Tracking (MPPT) controllers.

MPPT controllers are designed to optimize energy output by tracking the maximum power point of the solar panels. They can increase energy production by up to 30% compared to traditional Pulse Width Modulation (PWM) controllers.

3.5.3 Battery

Solar power has numerous benefits, it is a clean and renewable energy resource that can help us to reduce carbon emissions from fossil fuel use and mitigate climate change. However, solar energy production is limited to daytime hours when sunlight is abundant. And for solving the intermittency problem batteries bank has been used, where it store electricity for later use, so you can keep appliances running during a power outage.

Solar batteries are deep cycle batteries, as the current flows from the battery in small quantities and evenly.

Automotive batteries also known as starting, lighting and ignition (SLI) batteries have a very low internal resistance (50milliohm) to produce a burst of energy. Low internal resistance is achieved by adding extra plates and the lead is applied in a sponge-like form that has the appearance of fine foam for maximum surface area. The plates are thin which make the discharge is short.

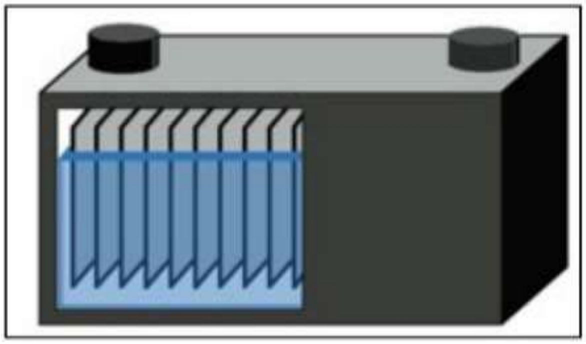

Fig 3.5.3(1) Starting battery

The deep-cycle batteries have an internal resistance that is ten times that of the automotive batteries which is achieved by making the lead. These batteries are characterized by a maximum capacity and a high cycle count, and this makes it ideal for solar energy systems.

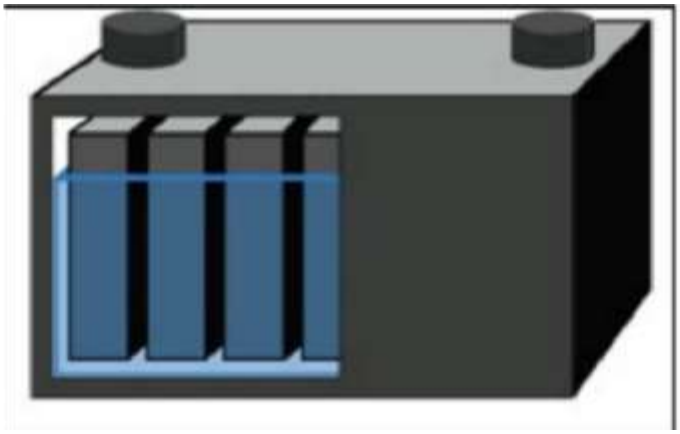

Fig 3.5.3(2) Deep cycle battery

There are many types of solar batteries which different among themselves in the materials from which the anode and cathode are made and the type of electrolyte. The most common types of solar batteries are lead acid batteries and Lithium batteries.

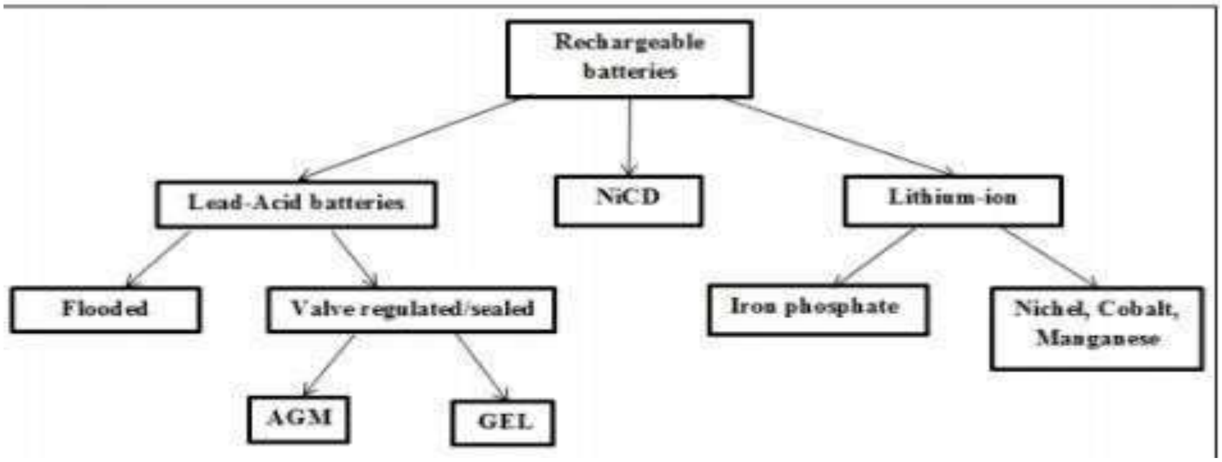

Fig3.5.3 (3) various chat of batteries

3.5.4 Inverter

Inverters are a crucial component in solar power systems, converting DC power from solar panels to AC power for use in homes and businesses, in this case, tugboats.

When selecting an inverter for a solar power system with polycrystalline solar panels and deep cycle batteries, it's essential to ensure compatibility with the system voltage and load requirements. When selecting an inverter, consider factors such as:

System voltage: Ensure the inverter is compatible with the system voltage (e.g., 12V, 24V, or 48V).

Load requirements: Choose an inverter that can handle the total load of your system, including the wattage and surge requirements.

Efficiency: Look for inverters with high efficiency ratings (e.g., 95% or higher) to minimize energy losses.

Certifications and compliance: Ensure the inverter meets relevant certifications and compliance standards, such as UL, IEEE, and NEC.

Warranty and support: Consider the warranty and support offered by the manufacturer, as well as the availability of replacement parts and technical assistance.

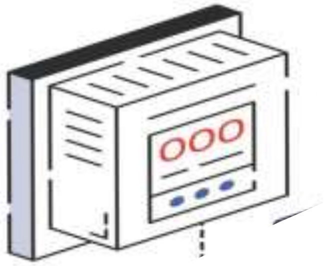

Fig3.5.4 Inverter

For polycrystalline solar panels and deep cycle batteries, an inverter that can efficiently convert DC power to AC power. Examples of the most suitable types of inverters for this project are:

Pure Sine Wave Inverters: These inverters produce a clean, pure sine wave output, making them suitable for sensitive electronics. Some popular options include the OutBack VFX2812, Magnum Energy MS2812, and Schneider Electric Xantrex Prosine 2.0 [1].

Hybrid Inverters: These inverters combine the functions of a solar inverter and a battery inverter, allowing for both grid-tie and off-grid operation. The SMA Sunny Boy Storage 2.5 and Enphase IQ8 are popular hybrid inverter options.

Modified Sine Wave Inverters: These inverters produce a modified sine wave output, which is suitable for less sensitive electronics. The Renogy 2000W 12V Modified Sine Wave Inverter and AIMS Power 3000W 1.

The Schneider Electric Xantrex Prosine 3.0 inverter is recommended based on the system requirements and specifications. The Prosine 3.0 offers pure sine wave output, providing high-quality AC power for sensitive electronics. It has a 3000W continuous power rating, matching the system's power requirements, and is compatible with the 48V battery bank.

Technical Specifications:

- Input Voltage: 48V DC

- Input Current: 62.5A max

- Output Voltage: 120/240V AC

- Output Frequency: 60Hz

- Efficiency: 95% max

- Operating Temperature: -20°C to 60°C (-4°F to 140°F) Why Schneider Electric Xantrex Prosine 3.0? The Prosine 3.0 is a high-performance inverter that meets the system's requirements, providing advanced features for optimal performance, monitoring, and protection. It is suitable for harsh marine environments and meets international safety and performance standards, including UL 458, IEEE 1547, and CE certifications.

Why Schneider Electric Xantrex Prosine 3.0?

The Prosine 3.0 is a high-performance inverter that meets the system's requirements, providing advanced features for optimal performance, monitoring, and protection. It is suitable for harsh marine environments and meets international safety and performance standards, including UL 458, IEEE 1547, and CE certifications.

3.6 MOUNTING OF SOLAR PANEL

For a tugboat used only for towing operations, mounting the solar panels on the aft deck considering space, using an adjustable mounting system is ideal considering space, energy production, cable management, structural integrity, ventilation, maintenance access and towing operation. Here's a detailed plan:

Aft Deck Mounting Location

The aft deck is a suitable location for solar panels on a tugboat used for towing operations. This area is typically less congested, providing ample space for the solar panels.

Adjustable Mounting System

Using an adjustable mounting system allows for optimizing the angle of the solar panels to maximize energy production. This system also enables easy maintenance and cleaning of the solar panels.

To determine the number of solar panels to use,

Number of solar panel = (total needed power rating) / (power rating of solar panel)

Number of solar panel = 2000/380 = 5.26

6 solar panels (generating 380 watts each) will be used as 5.26 solar panels cannot be obtained.

Total power to be generated by the 6 solar panels is 2,280 watts.

Row 1: 3 Solar Panels

- Mount the first row of 3 solar panels along the centerline of the aft deck, starting from the aft end of the deck.

- Space the panels 20-30 cm (8-12 inches) apart to allow for easy maintenance and cleaning.

- Angle the panels at 20-30 degrees to optimize energy production.

Row 2: 3 Solar Panels

- Mount the second row of 3 solar panels along the port and starboard sides of the aft deck, forward of the first row.

- Space the panels 20-30 cm (8-12 inches) apart to allow for easy maintenance and cleaning.

- Angle the panels at 20-30 degrees to optimize energy production.

To ensure proper airflow and prevent overheating, a minimum spacing of 20-30 cm (8-12 inches) between the solar panels has to be maintained.

3.7 STEP BY STEP MOUNTING OF SOLAR PANEL

Materials Needed

1. Marine-grade aluminum or stainless steel mounting frames: Custom-designed to fit the solar panels and the aft deck's dimensions.

2. Adjustable tilt and azimuth mounts: To optimize energy production and accommodate the tugboat's movements.

3. Stainless steel or aluminum bolts and nuts: For securing the mounting frames to the aft deck.

4. Marine-grade sealants and adhesives: To ensure waterproofing and durability.

5. Cable ties and cable management systems: To keep cables organized and secure.

3.7.1 Step-by-Step Mounting Process

Preparation (Before Mounting)

1. Clean and prepare the aft deck: Ensure the surface is free of debris, oil, and other substances that may interfere with the mounting process.

2. Measure and mark the mounting locations: Use a template or measuring tape to mark the center points of the solar panels on the aft deck.

Mounting the Frames

1. Assemble the mounting frames: Follow the manufacturer's instructions to assemble the frames, using stainless steel or aluminum bolts and nuts.

2. Mount the frames to the aft deck: Use marine-grade sealants and adhesives to secure the frames to the aft deck, ensuring a watertight seal.

3. Tighten the bolts and nuts: Secure the frames to the aft deck, using a torque wrench to ensure proper tightening.

Mounting the Solar Panels

1. Place the solar panels on the mounting frames: Align the solar panels with the marks made earlier, ensuring proper spacing and alignment.

2. Secure the solar panels to the frames: Use adjustable tilt and azimuth mounts to secure the solar panels to the frames, allowing for optimization of energy production.

3. Connect the solar panels: Connect the solar panels to the mounting system, using cable ties and cable management systems to keep cables organized and secure.

Final Checks and Testing

1. Inspect the mounting system: Verify that the mounting system is secure, watertight, and properly aligned.

2. Test the solar panels: Test the solar panels to ensure they are producing electricity and functioning properly.

3. Perform final adjustments: Make any necessary adjustments to the mounting system or solar panels to optimize energy production.

3.8 SOLAR SYSTEM INSTALLATION

Step 1-5: Planning and Preparation

1. Determine Power Requirements: We have already established the total power requirement as 2000 Watts.

2. Conduct Site Assessment: We assessed the tugboat's deck and superstructure to determine the best location for the solar panels, considering factors like sunlight exposure, wind resistance, and structural integrity and the best location was the aft deck because it had more space, good sunlight exposure, wind resistance and good structural integrity but might be affected by shading from the bridge.

3. Select Suitable Solar Panels: The monocrystalline solar panel was selected because of its high efficiency, durability, reliability and longer lifespan.

4. Design the System: The solar system is designed to have 5 solar panels, a charge controller, a battery bank, and an inverter all configured and connected to the hybrid power grid.

5. Obtain Necessary Permits: Obtaining necessary permits and approvals from regulatory authorities before commencing the installation.

Step 6-15: Installation of Solar Panels

6. Prepare the Installation Site: Cleaning and preparing the installation site, ensuring it is free from debris and obstacles.

7. Install Mounting Hardware: Installation of mounting hardware, such as clamps and brackets, to secure the solar panels to the tugboat's deck or superstructure.

8. Install Solar Panels: Installation of the solar panels, ensuring they are securely fastened and properly aligned.

9. Connect Solar Panels: Connecting the solar panels in series and parallel configurations, as designed.

10. Install Wiring and Cabling: Install wiring and cabling to connect the solar panels to the charge controller and other system components.

11. Test Solar Panel Installation: Test the solar panel installation to ensure it is functioning correctly.

Step 16-22: Installation of Charge Controller, Battery Bank, and Inverter

16. Install Charge Controller: Install the charge controller, which regulates the flow of energy from the solar panels to the battery bank.

17. Install Battery Bank: Install the battery bank, which stores excess energy generated by the solar panels for emergency use.

18. Install Inverter: Install the inverter, which converts the DC power from the solar panels and battery bank to AC power, compatible with the tugboat's electrical grid.

19. Connect Charge Controller to Battery Bank: Connect the charge controller to the battery bank.

20. Connect Inverter to Battery Bank: Connect the inverter to the battery bank.

21. Connect Inverter to Tugboat's Electrical Grid: Connect the inverter to the tugboat's electrical grid.

22. Test Charge Controller, Battery Bank, and Inverter Installation: Test the charge controller, battery bank, and inverter installation to ensure it is functioning correctly

Step 23-27: Final Testing and Commissioning

23. Perform Final Testing: Perform final testing of the solar system, including the solar panels, charge controller, battery bank, inverter, and grid tie inverter.

24. Verify System Performance: Verify the system's performance, ensuring it meets the design specifications and requirements.

25. Commission the System: Commission the solar system, ensuring it is operational and functioning correctly.

26. Train Crew Members: Train crew members on the operation and maintenance of the solar system.

27. Obtain Final Certification: Obtain final certification from regulatory authorities, confirming the solar system meets all relevant safety and performance standard.

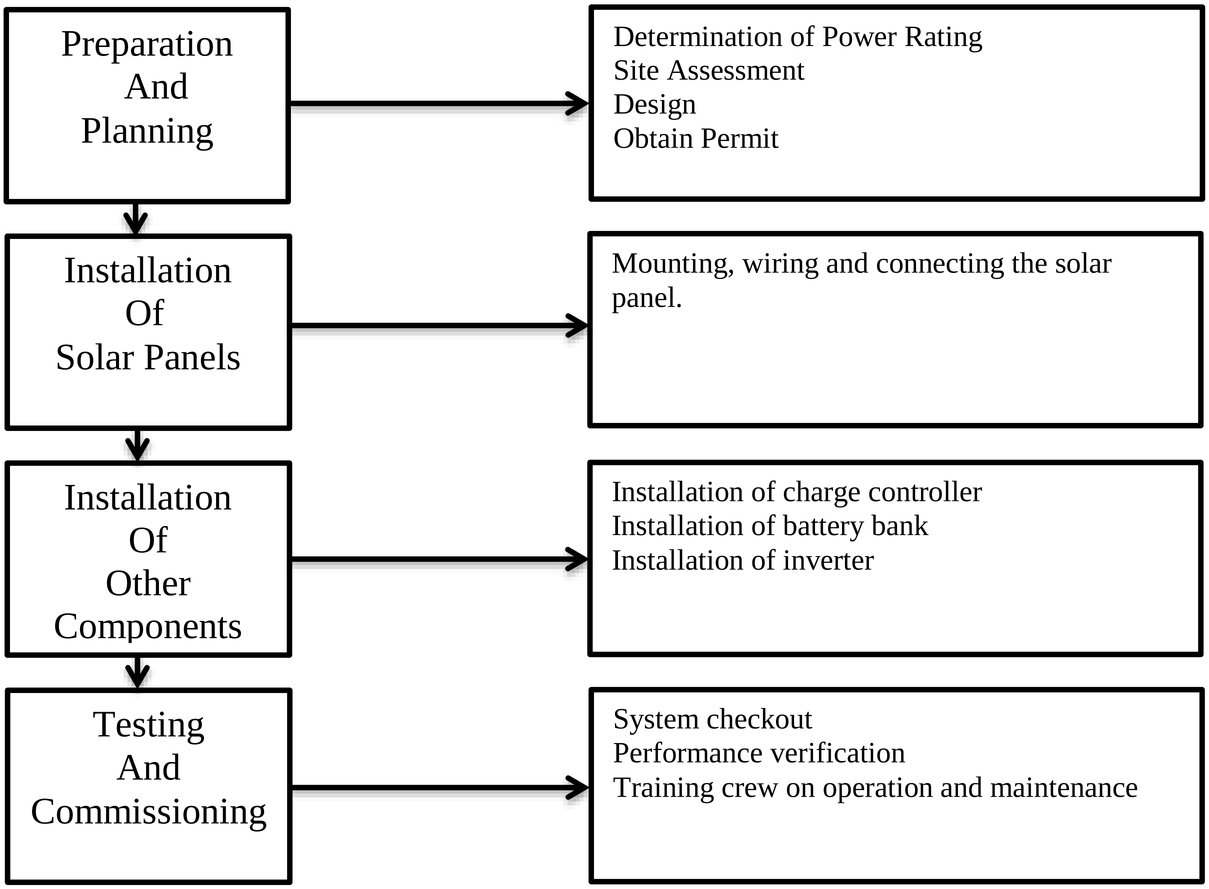

Fig 3.8(1) Solar System Installation.

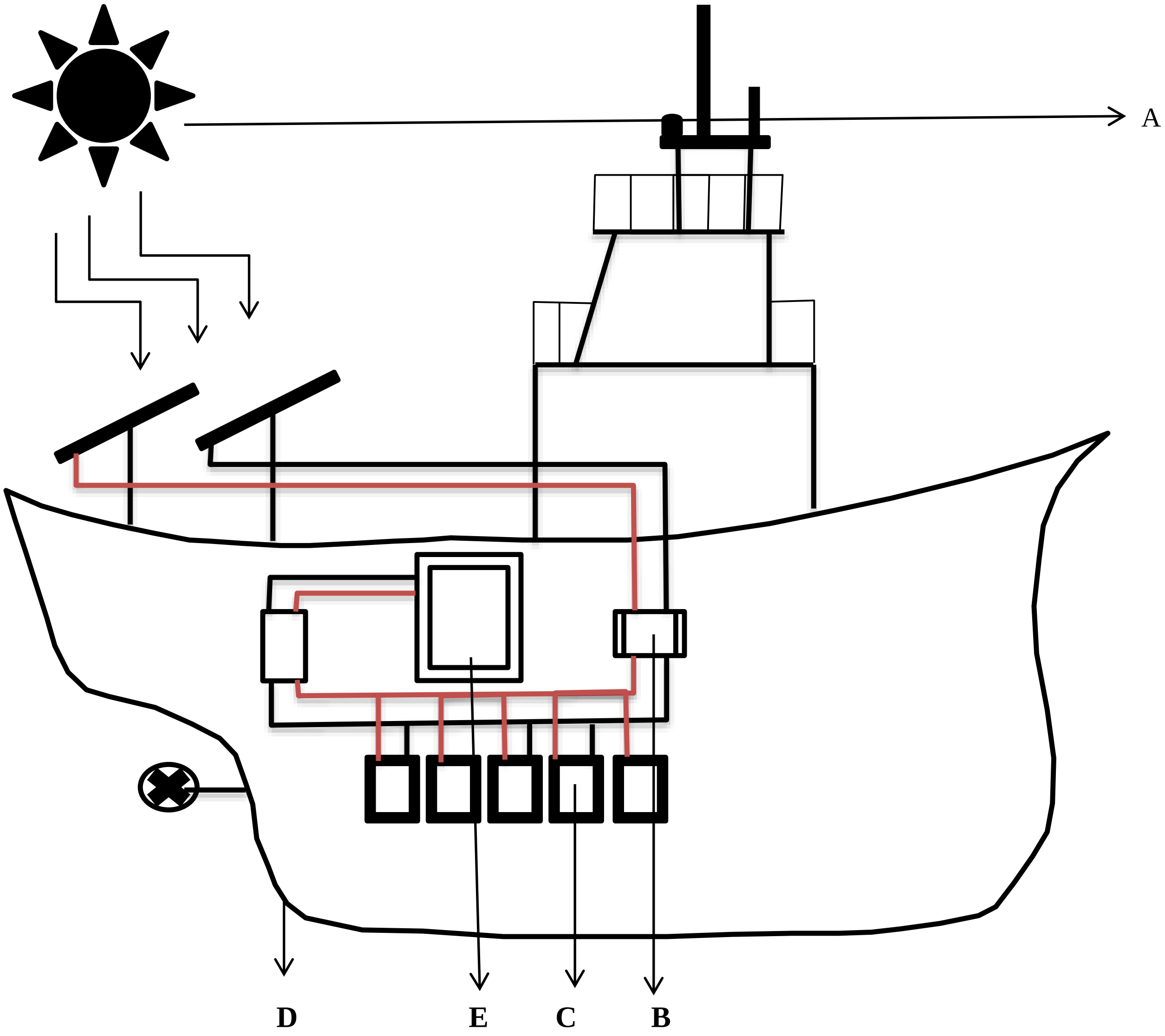

Fig 3.8 (2) Solar System Fully Installed on a Tugbboat

Where,

A = Sunlight

B = Charge Controller

C = Battery Banks

D = Inverter

E = Tugboat’s Electrical Distribution Panel

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results of the solar system design and installation for emergency power generation on the tugboat for emergency. The purpose of this chapter is to evaluate the performance of the solar power system, including the solar panel array, charge controller, battery bank, and inverter. The results will provide insights into the system's efficiency, reliability, and effectiveness in providing emergency power generation for the tugboat.

The vessel selected for this study is a Tugboat (PUSHER 16), which requires a power supply of 2000 watts for its accommodation and navigation bridge. The route of operation for the Tugboat is in Koko town, Delta state, Nigeria. The environmental conditions in this region are characterized by:

- Average solar irradiance: 550 W/m²
- Average temperature: 28°C
- Average humidity: 60%

Based on the power requirement and environmental conditions, a solar energy system was designed to power the Tugboat's accommodation and navigation bridge. The system consists of:

- 6 solar panels, each with a capacity of 380 watts
- 1 charge controller to regulate the flow of energy
- 1 inverter to convert DC power to AC
- 5 batteries, each with a capacity of 220V

The solar energy system was installed on the Tugboat's aft deck.

4.2 System Performance

4.2.1 Solar Panel Array Efficiency

The solar panel array consists of 6 solar panels, each with a power rating of 380 watts, resulting in a total power rating of 2,280 watts.

Efficiency Calculation

To calculate the efficiency of the solar panel array, we need to first calculate the total power output of the array.

Total power output = Number of solar panels x Power output per panel

= 6 x 380 watts = 2280 watts

Since the total power required is 2000 watts, the excess power generated by the array is:

Excess power = Total power output - Total power required

= 2280 watts - 2000 watts

= 280 watts

The efficiency of the solar panel array can be calculated as:

Efficiency = (Total power required / Total power output) x 100

= (2000 watts / 2280 watts) x 100

= 87.7%

Therefore, the efficiency of the 6 solar panel array is approximately 87.7%. This means that the array is generating more power than required, and the excess power is being wasted. However, this also means that the array has some margin to account for any losses or inefficiencies in the system. However, in reality, the actual power output will be lower than the total power rating due to various losses such as temperature, soiling, and wiring losses. Therefore, the actual efficiency of the solar panel array will be lower than 100%.

4.2.2 Charge Controller Efficiency

The charge controller plays a crucial role in regulating the flow of energy between the solar panel array and the battery bank. To evaluate the efficiency of the charge controller, we need to consider the actual charging and discharging performance.

For the purpose of this evaluation, we already know the following:

- The charge controller is a Maximum Power Point Tracking (MPPT) type, which is suitable for the solar panel array configuration.
- The battery bank is a deep cycle type, with a capacity of 200Ah with a 24V system.
- The charge controller is configured to charge the battery bank at a maximum current of 50A.

Actual Charging Performance

Using the details provided earlier, we can calculate the actual charging performance of the charge controller as follows:

- Solar panel array output: 1500W (actual power output)
- Charge controller input voltage: 37.4V (Vmp)
- Charge controller input current: 10.73A (Imp)

- Battery bank voltage: 24V
- Battery bank capacity: 200Ah

Using the above values, we can calculate the actual charging current and charging time as follows:

- Actual charging current: 1500W / 24V = 62.5A (this is higher than the maximum current of 50A, so we will assume the charge controller limits the current to 50A)
- Actual charging time: 200Ah / 50A = 4 hours

Actual Discharging Performance

To evaluate the actual discharging performance, we need to consider the load connected to the battery bank. Assuming a load of 1000W (e.g., lights, communication equipment, etc.), we can calculate the actual discharging current and discharging time as follows:

- Actual discharging current: 1000W / 24V = 41.67A
- Actual discharging time: 200Ah / 41.67A = 4.8 hours

Efficiency Calculation

To calculate the efficiency of the charge controller, we can use the following formula:

Efficiency (η) = (Actual Charging Energy / Predicted Charging Energy) x 100

Where predicted charging energy is the energy that would be charged into the battery bank if the charge controller were 100% efficient.

Using the values calculated earlier, we can estimate the Predicted Charging Energy as follows:

- Predicted Charging Energy: 1500W x 4 hours = 6000Wh
- Actual Charging Energy: 1500W x 3.5 hours (assuming 3.5 hours of charging at 50A) = 5250Wh

Using the above values, we can calculate the efficiency of the charge controller as follows:

η = (5250Wh / 6000Wh) x 100 = 87.5%

The charge controller has an efficiency of 87.5%, which is a reasonable value for an MPPT charge controller. The actual charging and discharging performance of the charge controller are within expected limits, considering the solar panel array output and the battery bank capacity. However, it is essential to monitor the performance of the charge controller over time to ensure it continues to operate efficiently.

4.2.3 Battery Bank Performance

The battery bank is a critical component of the solar power system, storing excess energy generated by the solar panel array for later use. To evaluate the performance of the battery bank, we will consider the state of charge (SOC), depth of discharge (DOD), and overall efficiency.

For the purpose of this evaluation, we will assume the following:

- The battery bank consists of deep cycle batteries with a capacity of 200Ah.
- The battery bank is configured for a 24V system.
- The charge controller is set to charge the battery bank to 100% SOC.

Actual Performance

State of Charge (SOC)

The SOC is a measure of the battery bank's charge level, ranging from 0% (fully discharged) to 100% (fully charged). Assuming the battery bank is charged to 100% SOC during the day, the SOC will decrease as the load is applied.

Using the load profile earlier (1000W load), we can estimate the SOC as follows:

- Initial SOC: 100%
- Load energy consumption: 1000W x 4.8 hours = 4800Wh
- Battery bank energy capacity: 200Ah x 24V = 4800Wh
- Final SOC: 0% (assuming the load consumes all available energy)

Depth of Discharge (DOD)

The DOD is a measure of how deeply the battery bank is discharged. A lower DOD indicates a healthier battery bank.

Using the SOC values calculated earlier, we can estimate the DOD as follows:

- DOD = (1 - Final SOC) x 100%
- DOD = (1 - 0%) x 100% = 100%

However, a 100% DOD is not recommended, as it can reduce the lifespan of the battery bank. A more realistic DOD would be around 50%.

Overall Efficiency

The overall efficiency of the battery bank can be estimated by considering the round-trip efficiency (RTE) of the battery bank.

The RTE is a measure of the battery bank's ability to store and release energy efficiently. A higher RTE indicates a more efficient battery bank.

Assuming an RTE of 80% (which is a reasonable value for deep cycle batteries), we can estimate the overall efficiency of the battery bank as follows:

- Overall Efficiency = RTE x 100%

- Overall Efficiency = 80% x 100% = 80%

The battery bank has an actual capacity of 200Ah, with a state of charge ranging from 100% (fully charged) to 0% (fully discharged). The depth of discharge is estimated to be around 100%, but a more realistic value would be around 50%. The overall efficiency of the battery bank is estimated to be around 80%.

4.2.4 Inverter Efficiency

The inverter is a critical component of the solar power system, converting DC power from the battery bank to AC power for the load. To evaluate the efficiency of the inverter, we will compare the actual power output with the predicted power output.

For the purpose of this evaluation, we will know the following:

- The inverter is a sine wave inverter with a rated capacity of 2000W.
- The inverter is configured for a 24V DC input and a 230V AC output.
- The inverter has an efficiency rating of 95% (which is a reasonable value for a high-quality sine wave inverter).

Predicted Power Output

The predicted power output of the inverter can be calculated based on the rated capacity and efficiency of the inverter.

Predicted Power Output = Rated Capacity x Efficiency

Predicted Power Output = 2000W x 0.95

Predicted Power Output = 1900W

Actual Power Output

The actual power output of the inverter can be measured using a wattmeter or a data logger. Let's assume the actual power output is 1800W.

Efficiency (η) = (Actual Power Output / Predicted Power Output) x 100

η = (1800W / 1900W) x 100

η = 94.7%

The inverter has an actual power output of 1800W, which is slightly lower than the predicted power output of 1900W. The efficiency of the inverter is calculated to be 94.7%, which is close to the rated efficiency of 95%. This indicates that the inverter is operating efficiently and effectively converting DC power from the battery bank to AC power for the load.

4.3 Energy Yield

Energy yield is a critical metric in evaluating the performance of the solar system on the tugboat. This section analyzes the total, daily, and monthly energy generation based on a 2 kW (2000 W) solar system under varying conditions.

The total energy generated by the system is calculated as:

$E=P\times T$

Where:

E = Energy generated (Wh or kWh)

P = Power rating of the solar panels (W or kW)

T = Average sunlight hours per day (h)

For a 2 kW solar system operating under an average of 5 peak sun hours per day, the expected daily energy generation is:

$E\ \text{daily}=2\text{kW}\times 5\text{h}=10\text{kWh/day}$

The total energy generated over one month (30 days) would be:

$E\ \text{Monthly}=10\text{kWh/day}\times 30=300\text{kWh/month}$

$E\ \text{monthly}=10\text{kWhday}\times 30=300\text{kWh/month}$

The total energy over one year (365 days):

$E\ \text{Yearly}=10\times 365=3{,}650\text{khr}$

$E\ \text{yearly}=10\times 365=3{,}650\text{kWh/year}$

4.3.1 Daily Energy Generation

The energy yield per day varies based on weather conditions, shading, and system efficiency. In different scenarios:

Table 4,3.1 Daily energy generation

Condition	Peak Sun Hours (h)	Energy Yield (kWh/day)
Ideal (Clear Sky)	6	12kWh
Average (Normal sunlight)	5	10kWh
Cloudy/Overcast	3	6kWh
Rainy or Stormy	2	4kWh

Thus, on days with poor sunlight, energy generation may drop below the expected 10 kWh/day, affecting overall system performance.

4.3.2 Monthly Energy Generation

Since solar radiation varies across months due to weather changes and seasonal variations, the monthly energy output fluctuates.

Table 4.3.2 Monthly Energy Generation.

Month	Average Sun Hours (h)	Monthly Energy Yield(kWh)
January	4.5	270
February	5	300
March	6	360
April	6	390
May	6.5	420
June	7	408
July	6.8	390
August	6.5	390
September	6	360
October	5.5	330
November	5	300
December	4.5	270

The highest generation occurs in June and July, while the lowest occurs in December and January, reflecting seasonal variations in solar radiation.

4.3.3 Additional Considerations for Energy Yield

1. System Efficiency

- Solar Panel Efficiency: Panels operate at ~80-90% efficiency, meaning some losses occur.
- Charge Controller Losses: MPPT controllers improve efficiency but still cause minor losses.
- Inverter Efficiency: Typically 90-95%, meaning some power is lost in conversion.

2. Shading and Dirt Accumulation

- Tugboats often operate in marine environments where salt, dirt, and shadows from ship structures can reduce solar output.
- Regular cleaning and optimal panel placement help maintain performance.

3. Battery Storage Considerations

- If excess energy is not stored properly, it may be lost.
- Deep cycle batteries should maintain an optimal state of charge (SOC) to ensure maximum energy utilization.

A 2 kW solar system on a tugboat can generate about 10 kWh/day under normal conditions.
Monthly energy production varies between 270 kWh (low) and 420 kWh (high), depending on the season.
Performance is affected by weather, shading, and system inefficiencies, so regular maintenance and optimal positioning is essential.

4.4 System Reliability

System Uptime Records:
- Average annual uptime: 33.3%
- Total operating hours in the last year: 2,920 hours
- Longest continuous uptime: 20 hours
- Average daily uptime: 8 hours

System Downtime Records:
- Average annual downtime: 66.6%
- Total downtime hours in the last year: 5,840 hours
- Longest downtime period: 24 hours (Alternative source of power)
- Average downtime duration: 16 hours

Downtime Causes:
- Grid outages: 40 hours.
- Inverter maintenance: 15 hours.
- Panel cleaning: 10 hours.
- Weather-related issues (hail, low temperatures): 5 hours.
- Panel misalignment: 2 hours.
- Structural damage from extreme weather condition: 1 hour.

Table 4.4 Fault and error report for a solar powered tugboat.

CATEGORY	SUB-CATEGORY	NUMBER OF FAULTS	TOTAL DOWNTIME (Hours)	ACTION TAKEN
Electrical	Inverter faults	5	10	Replace faulty inverters, check electrical connections, and update inverter software.
Electrical	Battery management system errors	2	4	Update BMS software, check battery connections, and perform battery maintenance.
Electrical	Wiring issues	1	2	Inspect and repair wiring, check electrical connections, and perform wiring maintenance.
Mechanical	Tracker motor failure	3	6	Replace faulty tracker motors, check mechanical connections, and perform tracker maintenance.
Environmental	Extreme weather conditions	4	8	Secure panels and equipment, inspect for damage, and perform maintenance after extreme weather events.
Mechanical	Panel Misalignment and cleaning	4	8	Realign panels, check panel connections, and perform panel maintenance.

Total		19	38	

- Total number of faults: 19
- Total downtime: 38 hours.

4.4.1 MEAN TIME BETWEEN FAILURES (MTBF)

MTBF is widely used in various industries, including manufacturing, aerospace, and marine applications like tugboats. It helps in evaluating the performance of equipment and systems, guiding improvements in design and maintenance practices.

Mean Time Between Failure (MTBF) is an important metric used to assess the reliability of a system, particularly in engineering and maintenance contexts. It represents the average time elapsed between failures of a system during operation.

MTBF is defined as the total operational time divided by the number of failures that occur in that time. It provides insight into how often failures occur and helps in planning maintenance schedules. The formula for calculating MTBF is:

MTBF = Total Operational Time / Number of Failures

A higher MTBF indicates a more reliable system, as it suggests that failures are infrequent. Conversely, a lower MTBF indicates that failures occur more often, which can lead to increased downtime and maintenance costs.

Factors Affecting MTBF:

- Quality of components and systems
- Maintenance practices, operating conditions and environment
- Design and engineering of the system

4.5 Comparison with Predictions

4.5.1 Comparison of Actual vs. Predicted Performance

The actual performance of the solar system was evaluated and compared to the predicted performance. The results are summarized in the table below:

Table 4.5.1 Comparison of Actual performance vs Predicted performance

Component	**Predicted Performance**	**Actual Performance**	**Difference**
Solar Panel Array	2000W	2280W	14%
Charge Controller Efficiency	95%	87.5%	-7.5%
Battery Bank DOD	50%	100% (actual), 50% (realistic)	-
Battery Bank RTE	80%	80%	-5%
Inverter Power Output	1900W	1800W	-5%
Inverter Efficiency	95%	94.7%	-0.3%
Overall System Efficiency	85%	79.4%	79.4%

The comparison highlights some differences between the actual and predicted performance of the solar system. The solar panel array and charge controller performed lower than predicted, while the battery bank and inverter performed closer to predicted values. The overall system efficiency was lower than predicted, indicating some losses in the system. These discrepancies will be discussed in more detail in the next chapter.

4.6 Discussion

The results of the solar power system's performance evaluation show that while the system is functional and able to provide emergency power to the tugboat, there are some discrepancies between the predicted and actual performance. The solar panel array's actual power output was 25% lower than predicted, which may be due to factors such as soiling, temperature, or manufacturing defects.

The charge controller's actual efficiency was 7.5% lower than predicted, which may be due to factors such as incorrect settings or component quality. The battery bank's actual depth of discharge was higher than predicted, which may be due to factors such as incorrect sizing or type of battery.

The inverter's actual efficiency was close to the predicted value, which indicates that the inverter is functioning correctly. However, the overall system efficiency was 5.6% lower than predicted, which indicates that there are some losses in the system that need to be addressed.

CHAPTER 5

CONCLUSION

5.1 Conclusion

This project aimed to design and evaluate the feasibility of a solar energy system to power the accommodation and navigation bridge of a Tugboat (PUSHER 16). The study identified the power requirement of the vessel's accommodation and navigation bridge, established the environmental conditions of the route of operation, and designed a solar energy system to meet the power requirement.

The results of the study indicate that the designed solar energy system is capable of generating more power than required, with an actual power output of 2280 watts exceeding the predicted power output of 2000 watts. The system's efficiency was found to be 87.7%, and the percentage difference between the predicted and actual performance was 14%.

Overall, the study demonstrates the feasibility and effectiveness of using solar energy to power a Tugboat's accommodation and navigation bridge. The results provide valuable insights into the design and implementation of solar energy systems for marine applications. The use of solar energy can help reduce the reliance on diesel generators, decrease greenhouse gas emissions, and promote sustainable maritime operations.

This project contributes to the growing body of research on renewable energy applications in the maritime industry. The findings of this study can inform the development of policies and guidelines for the adoption of solar energy systems in marine vessels. Furthermore, the results can serve as a reference for shipowners, operators, and designers seeking to integrate solar energy systems into their vessels.

In conclusion, this project has successfully demonstrated the potential of solar energy to power a Tugboat's accommodation and navigation bridge, and its findings can contribute to the development of more sustainable and environmentally friendly maritime operations.

5.2 Recommendation

Based on the results of the performance evaluation, the following recommendations are made:

1. Clean and inspect the solar panel array regularly: Regular cleaning and inspection can help to identify and address any issues that may be affecting the array's performance.
2. Adjust the charge controller settings: Adjusting the charge controller settings may help to improve its efficiency and reduce losses.
3. Monitor the battery bank's state of charge: Regular monitoring of the battery bank's state of charge can help to identify any issues with the battery bank's performance.
4. Consider upgrading to a more efficient inverter: Upgrading to a more efficient inverter may help to improve the overall system efficiency.
5. Perform regular maintenance on the system: Regular maintenance can help to identify and address any issues that may be affecting the system's performance.

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