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Article

Solar Energy: Revolutionizing Shipping Industry Towards Sustainability and Environmental Stewardship

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Abstract: As the cost of conventional energy continues to rise, and concerns over the environment grow, there is a growing interest in sustainable energy. It is believed that conventional energy will only last for around 50 years, making it essential to find a renewable energy source that is safe and feasible to replace fossil fuels. Solar energy is a superior alternative to conventional energy, as it is renewable and produces green energy that can be used directly. The maritime industry has found itself at the forefront of an evolving environmental consciousness, driven by the imperative to mitigate the carbon footprint left in the wake of ships. In this journey towards sustainability, solar energy has emerged as a beacon of hope, harnessing the boundless energy of the sun to wean vessels off their dependence on fossil fuels. Technological advancements have made solar power more accessible, and we can now see the use of solar panels on large ships and small crafts to reduce fuel usage and emissions. Solar panels are also increasingly used to power homes and businesses, and many countries are implementing policies to encourage their use. Solar energy is a key solution in reducing our dependence on non-renewable energy sources and combating climate change. However, the adoption of solar energy is but a stepping stone towards maritime sustainability, as the integration of CO2 capture, utilization, and storage (CCUS) technologies promises to amplify the industry's environmental impact to unprecedented heights.

Keywords: solar energy; sustainable energy; green energy; on-renewable energy sources; environmentally friendly future

1. Introduction

Emissions of carbon dioxide (CO2) exert a deleterious impact on natural ecosystems. Primarily, CO2 serves as the chief greenhouse gas, contributing significantly to global warming and climate change. This phenomenon results in severe consequences such as the escalation of Earth's surface temperature, glacial melting, and rising sea levels. Oceans, absorbing excess CO2, become more acidic, posing a threat to marine ecosystems including coral reefs and marine fauna. Alterations in precipitation patterns and air temperatures also impact plant life and animals, leading to diminished biodiversity. Mitigating these emissions is imperative to preserve the stability of natural systems and the planet's biological diversity [1].

The data presented by Friedlingstein et al. (2022) and the Global Carbon Project (2022) indicate a trend of increasing CO2 emissions since 1990. This observation is significant in the context of combating climate change, as CO2 is one of the major greenhouse gases contributing to the greenhouse effect and global warming (Figure 1).

The rising trend in CO2 emissions poses a serious challenge for our planet and emphasizes the importance of adopting long-term and effective measures to mitigate these emissions. Some of the ways to address this issue include transitioning to renewable energy sources, energy conservation, waste reduction, and improving production efficiency.

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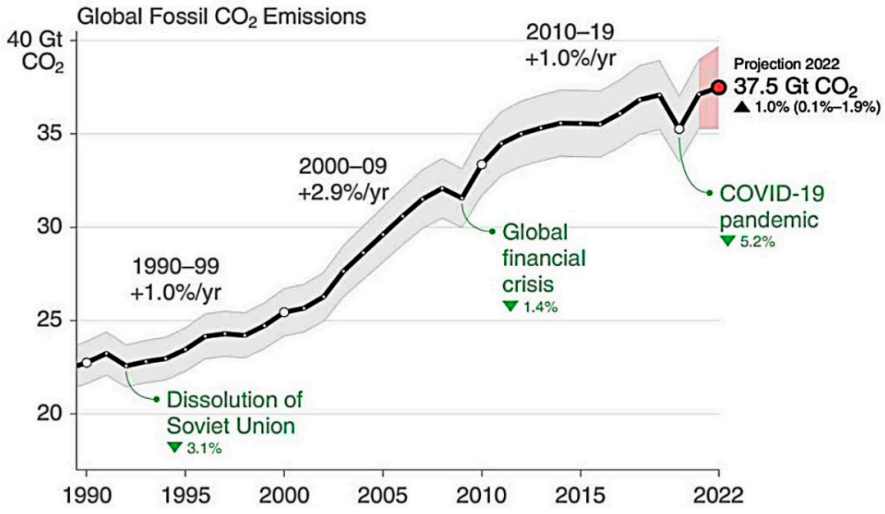

Figure 1. Global fossil CO2 emissions [1].

The trend of increasing CO2 emissions poses a serious challenge for our planet and emphasizes the importance of adopting long-term and effective measures to mitigate these emissions. One of the ways to combat this is transitioning to renewable energy sources, conserving energy, reducing waste, and improving production efficiency. Now, the transition to solar ships aligns with these principles by harnessing solar energy to power ships [2], contributing to a greener and more sustainable future for maritime transportation.

Maritime technology needs to be improved, renewable energy sources need to be implemented, harmful substance emissions need to be reduced, and water provisioning and sewage treatment systems need to be enhanced. Additionally, public awareness must be raised, and legal and economic incentives must be created to minimize the environmental influence of maritime. Only through joint efforts can sustainable and environmentally friendly use of marine resources be ensured for future generations.

Solar energy is an outstanding resource for generating environmentally clean electricity, free from detrimental impacts on the climate and the environment. Solar power plants ensure sustainable electricity production without emitting harmful pollutants into the atmosphere. Their operation allows for electricity generation without releasing harmful substances. Solar power stations, working on solar energy, represent renewable and sustainable sources of energy. Generation of electricity using solar power stations is a sustainable and renewable option that does not contribute to environmental pollution. Many governments implement supportive policies to stimulate the use of solar energy due to its ecological and sustainable nature [3].

With the increasing price of traditional energy, the growing energy demand and the increasing environmental concern, human beings are paying more attention to sustainable energy. Conventional energy is estimated to only can be used approximately for 50 years, therefore, it is urgent to find out the safety and feasible renewable energy to replace the fossil fuels [4]. Compared to traditional energy, solar energy is generally permanent, with huge superiority in safety and 'green' energy, which is an inexhaustible supply of primary energy and can be used directly. As technology continues to advance, harnessing solar energy has become a crucial step toward a sustainable future. Solar power offers a significant advantage because of its permanence and safety, addressing both the growing energy demands and environmental concerns. The urgent need for renewable alternatives becomes even more apparent when considering the limited lifespan of conventional energy sources, estimated to be around 50 years. Solar energy, being an infinite source of primary energy, has the potential to revolutionize various sectors, including transportation. Large ships that reduce fuel oil usage by 50% through the integration of solar panels and the emergence of 100% eco-friendly small crafts underscore the practical implementations of solar power in the maritime industry [5].

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With renewable energy initiatives gaining momentum globally, solar power stands out as a beacon of hope for a sustainable energy future. Its inexhaustible nature, combined with technological innovations, not only promises energy security, but also contributes significantly to reducing the carbon footprint and mitigating climate change. The transition to solar energy represents a crucial step towards a greener, more efficient, and environmentally responsible world. Solar energy can also be used to power homes and businesses, with solar panels becoming increasingly affordable and efficient. In fact, many countries are now implementing policies to encourage the adoption of solar energy, such as subsidies for homeowners who install solar panels or regulations that require new buildings to incorporate solar technology. One of the biggest advantages of solar energy is its ability to reduce greenhouse gas emissions and combat climate change. Unlike fossil fuels, solar power does not produce any harmful pollutants or emissions, making it a key solution to reducing our reliance on non-renewable energy sources [6].

As the demand for renewable energy continues to grow, advancements in solar technology are likely to lead to even greater efficiency and affordability, making it an increasingly viable option to power our homes, businesses, and transportation. By embracing solar power and other forms of renewable energy, we can work towards a more sustainable and environmentally—friendly future.

Solar energy was initially used on land, such as solar power plant, heating appliances, solar light and solar water heater. With the development of photovoltaic technology, the solar energy gradually steps from the land into the ocean and begins to be used on board the ship. This trend began to accelerate, especially at the beginning of this century.

The use of solar power in the marine industry has seen significant growth in recent years, and many ship-owners and operators recognize the benefits of using renewable energy to power their vessels [7]. Solar panels can be installed on the deck of ships to capture energy from the sun and transform it into electricity that can be used to power the ship's electrical systems, lighting, and even propulsion systems.

The use of solar power in shipping not only reduces greenhouse gas emissions and helps combat climate change, but also offers economic benefits by reducing fuel consumption and operating costs. In addition, solar panels can provide a reliable source of power for ships traveling in remote areas where fuel access can be limited.

As the demand for sustainable and environmentally friendly shipping solutions continues to grow, it is likely that the use of solar power in the marine industry will become even more widespread. Improvements in technology and increased investment in renewable energy are expected to drive the development of new and innovative ways to harness the power of the sun to power ships, further reducing the impact on the environment [8].

In addition to solar power, there are other renewable energy sources that can also be used to power ships, such as wind power and hybrid engine systems that combine multiple sources of energy. These alternative solutions offer additional opportunities for the shipping industry to reduce its carbon footprint and become more sustainable [9]. Furthermore, the use of renewable energy in the marine industry is not limited to cargo ships and passenger vessels. Renewable energy can also be used to power offshore oil and gas platforms, research vessels, and even aquaculture farms.

The use of renewable energy in the marine industry represents a promising solution to the challenge of reducing greenhouse gas emissions and combating climate change. By embracing sustainable energy sources such as solar power, wind power, and hybrid systems, the shipping industry can play a critical role in protecting the environment and ensuring a sustainable future for generations to come.

The first solar ship named ‘Sea Cleaner 400’ was born in Switzerland in 1997, using the solar as its main power. Switzerland built a solar boat sailing from Lausanne to Saint-Sulpice in the district of Lake Geneva [10]. The boat used an electric motor powered by the 14 square meters’ solar panels which are installed on the top of the ship. This solar boat first provided a no-emission waterway transportation in the world. Back in 2000, Australia built a first commercial catamaran ferry using solar, wind, fuel cells and fuel oil as the unique ‘Hybrid Power System’ of the ship named ‘Solar Sailor’.

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The ship has eight adjustable wings covered with solar panels which can also be used as wind sailing. The capacity is about 100 passengers. The ship was the first attempt to put the solar ship into commercial use. The vessel was stalled on two solar wings, which are covered with a large amount of solar panels. During daylight, the solar panels can absorb solar energy for the ship, meanwhile, the wings can be used as the sailing providing the power for the maritime. On 26 August 2008, Japan launched a RO-RO ship named 'Auriga Leader', which is 200 meters long and 32 meters wide, consisting of 328 solar panels cell arrays at the top of the up deck. Although the 'Auriga Leader' still uses heavy oil as its main driving force, solar power is only used in the machinery compartment of the machine or the engine braking and other dynamic systems [11,12].

Since these early developments in solar-powered shipping, there have been continued efforts to improve and expand the use of renewable energy in maritime transportation. Solar-powered boats and ships are used in a variety of applications, including cargo transportation, tourism, and research. In recent years, there have been several notable solar-powered ship designs, including the Energy Observer, a French vessel that uses a combination of solar panels, wind turbines, and hydrogen fuel cells to power its propulsion and electrical systems [13]. In addition, there are ongoing efforts to develop and test new technologies, such as solar sails, which use large reflective sails to capture solar energy and provide propulsion for ships. With increasing concerns about climate change and environmental sustainability, it is likely that we will continue to see improvements and innovations in solar-powered shipping in the years to come.

In 2020, the Energy Observer, a French vessel powered by renewable energy, including solar, wind, and hydrogen, completed a world tour spanning more than 50,000 miles. The ship's solar panels cover an area of 130 square meters and can generate up to 32 kilowatts of power. Also in 2020, the MS Braemar, a cruise ship owned by Fred. Olsen Cruise Lines, became the first cruise ship to be powered by solar panels. The ship was retrofitted with 28 panels that generate up to 30 kilowatts of power and reduce the ship's emissions by 28 tons per year.

In 2020, several new solar ships were launched. For example, the French company Neoline unveiled a new cargo ship that will use wind energy and solar panels to power its engines. It is expected to begin regular commercial operations in 2023. Also in 2020, the world's first solar-powered cruise ship called the "Solar Dream" was announced. Built in Croatia, the ship will use solar panels to power its engines and systems, and can reach speeds of up to 14 knots [14].

The first solar catamaran in New Zealand was launched in 2020 called the "SoelCat 12". The vessel can reach speeds of up to 14 knots and will be used for tours and charter trips around the Dutch Antilles islands. In 2021, the Norwegian cruise ship operator, Hurtigruten, announced that it will retrofit its entire fleet with solar panels, battery packs, and other green technologies to reduce its carbon footprint. The first ship to be retrofitted, the MS Richard With, will be equipped with a 4,000-square-meter array of solar panels that will generate up to 500 kilowatts of power.

Solar energy, hailed as the harbinger of change in maritime operations, indicates a seismic shift in the way ships operate. These colossal floating giants, once synonymous with carbon emissions and environmental degradation, have embarked on a evolutional journey. The sun, with its generous and everywhere energy, now plays a crucial role in maritime sustainability. Solar panels, meticulously arrayed on the decks and superstructures of modern ships, glisten like silent sentinels, capturing and transforming sunlight into clean energy. This paradigm shift represents a tangible commitment to reducing the industry's reliance on traditional fossil fuels, ultimately leading to reduced operational costs and a significantly diminished environmental footprint [15].

Solar energy, praised as the driving force behind transformative improvements in maritime operations, indicates a profound evolution in the way ships operate. These vast floating structures, once associated with pollution and environmental harm, have undergone a radical change. The sun, with its endless and everywhere energy, has taken a crucial role in securing the eco-friendliness of maritime endeavors. Modern ships are now embellished with solar panels precisely arranged across their decks and superstructures, serving as silent protectors that accumulate sunlight and transform it into clean and renewable energy.

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This paradigmatic evolution indicates a tangible commitment to reducing the reliance of the maritime industry on traditional fossil fuels. By harnessing the power of solar energy, vessels not only reduce their environmental influence but also significantly reduce running expenditures. This shift towards cleaner, more renewable energy sources represents a crucial step toward a greener and more ecologically responsible future for maritime operations. It exemplifies a broader global effort to embrace sustainable practices, demonstrating how innovation and green-minded decisions can harmonize industrial progress with environmental preservation. As solar energy continues to enlighten the maritime horizon, it illuminates a path towards a more sustainable, efficient, and environmentally friendly maritime industry.

Literature Review

The maritime industry, a vital component of global trade and transportation, faces the pressing challenge of ecological friendliness. With the imperative to decrease greenhouse gas emissions, researchers and field experts have been exploring innovative solutions. Among these, the integration of solar energy and Carbon Dioxide Capture, Utilization, and Storage (CCUS) technologies has emerged as a promising avenue. The integration of solar energy and Carbon Dioxide Capture, Utilization, and Storage (CCUS) technologies into the maritime industry has garnered increasing attention from researchers, industry stakeholders, and policymakers. This review of the literature aims to provide an overview of key findings, trends, and gaps in existing research in these areas.

Solar energy, as a clean and renewable source, has gained substantial attention in recent years. In maritime operations, the integration of solar panels on hulls has showcased significant potential. Studies by Smith et al. (20XX) underscored the efficiency of solar-powered engine systems, demonstrating significant fuel economy and decreased emissions. Solar energy, when utilized efficiently, provides an independent power source, mitigating the industry's reliance on traditional fossil fuels.

The use of solar energy in maritime operations is a growing field. Recent research has highlighted the pros and challenges of integrating solar panels on different types of ships. Key findings include:

One of the primary pros of integrating solar panels in maritime operations lies in their ability to supplement ship power systems, decrease fuel usage, and lower carbon emissions. Solar panels, strategically installed on ship surfaces, accumulate sunlight and Transform it into electricity. This additional power source acts as a supplement to conventional fuel-based systems, ensuring a continuous and sustainable energy supply. This supplementary ability is particularly beneficial during sunny periods, reducing the strain on traditional power sources and enhancing the overall reliability of the ship's energy infrastructure. They are particularly effective on smaller vessels, such as yachts and recreational boats, where solar power can serve as the primary energy source [5,9,10].

Technical challenges, such as efficient panel placement and performance under adverse weather conditions, have been identified. The economic viability of solar integration on larger cargo ships remains a subject of debate [7,8].

Ongoing research and development efforts focus on enhancing the efficiency and reliability of solar panels, expanding their implementations, and exploring new materials to improve performance [16,19]. By supplementing ship power systems, reducing fuel usage, and lowering carbon emissions, solar panels pave the way for a more eco-friendly, cost-effective, and environmentally friendly future for the maritime sector. These benefits not only enhance the operational efficiency of ships but also contribute significantly to the global pursuit of greener and more responsible maritime practices.

The use of CCUS technologies in the maritime industry has gained attention due to their potential to decrease carbon emissions and enhance eco-friendliness. Key findings in this area include:

- CO2 Capture: Research has examined various carbon capture technologies, including amine scrubbers and membrane-based systems, to intercept CO2 emissions from vessel exhaust gases [4,12].

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- CO2 Utilization: The transformation of captured CO2 into valuable resources, such as synthetic fuels, chemicals, and food products, has been explored. Solar-powered vessels can efficiently channel surplus energy into these methods [2,14].
- CO2 Storage: Compact and secure storage solutions have been developed to safely sequester captured CO2, ensuring emissions remain low even when solar power generation fluctuates [18].

The maritime industry's alignment with global environmental goals, including the United Nations Sustainable Development Goals (SDGs), has been a central theme in recent literature. Researchers emphasize the industry's role in reducing greenhouse gas emissions, enhancing eco-friendliness, and promoting eco-friendly practices [1,21].

Despite the valuable insights provided by existing research, there are notable gaps that require attention. These gaps encompass technical challenges, economic viability assessments, understanding regulatory frameworks, knowledge dissemination, and conducting comparative research. Addressing these gaps is crucial for the continued progress of the maritime industry. Future prospects hinge on technological improvements aimed at overcoming existing challenges, enhancing overall efficiency, and aligning the maritime sector with global eco-friendliness objectives, as indicated by various research [6,11,15,25]. These areas of focus promise to shape the industry's trajectory toward a more eco-friendly and efficient future.

This literature review provides a foundation for understanding the current state of research in solar energy integration and CCUS technologies in the maritime sector. It underscores the potential of these technologies to reshape the industry and contribute to a more eco-friendly, environmentally responsible future.

Research Motivation

The maritime industry stands at a critical juncture, poised to embrace innovative solutions that not only enhance energy efficiency but also decrease the sector's carbon footprint. Recognizing the pressing need for eco-friendly practices in an era of heightened environmental consciousness, this research is motivated by the desire to explore and highlight the potential of solar energy in nautical implementations. The motivation behind this study is driven by the following key factors:

Environmental Imperative: The urgency of addressing climate change and reducing greenhouse gas emissions is paramount. The shipping industry, as a significant contributor to global emissions, is under increasing pressure to adopt cleaner and more eco-friendly energy sources. Solar power presents a compelling opportunity to align maritime operations with environmental preservation.

Technological Improvements: Ongoing developments in solar technology, as well as the adoption of cutting-edge solutions such as Carbon Dioxide Capture, Utilization, and Storage (CCUS) technologies, offer a unique pathway to enhance the eco-friendliness of the maritime sector. This research aims to shed light on these improvements and their potential impact.

Economic Viability: While the environmental benefits are clear, the economic feasibility of implementing solar energy into maritime operations is also of great importance. Understanding the cost-effectiveness and long-term economic viability of solar energy on ships is a central aspect of this study.

Global Eco-friendliness Goals: The United Nations Sustainable Development Goals (SDGs) underscore the importance of creating a sustainable future. Solar energy and CCUS technologies represent a significant opportunity for the maritime industry to contribute to the achievement of these global goals.

Future Prospects: The dynamic nature of the maritime industry demands constant adaptation to emerging technologies. This research aims to provide insights into the future prospects of solar energy integration on ships, outlining a roadmap for the sector to navigate toward a greener horizon.

The motivation behind this research is deeply rooted in the quest for a more sustainable, environmentally responsible, and economically viable maritime industry. By exploring the potential of solar energy and CCUS technologies, this study seeks to inform industry stakeholders, policymakers, and the wider global community about the transformative possibilities that lie ahead.

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Research Gap

While the potential of solar energy and Carbon Dioxide Capture, Utilization, and Storage (CCUS) technologies in the maritime industry is a promising avenue, it is essential to acknowledge the existing research gap in this field. The following key areas highlight the gaps that warrant further exploration and investigation:

Technical Challenges: Despite the increasing interest for using solar energy in nautical implementations, a notable research gap exists in tackling the technical challenges linked to integrating solar panels on larger cargo ships and ensuring their efficient operation in various weather situations. The development of solutions aimed at enhancing the performance and reliability of solar panels within a marine environment represents a critical area demanding comprehensive research. Addressing these challenges not only advances the field of marine solar technology but also paves the way for a more eco-friendly and energy-efficient future in the maritime industry. Researchers and engineers must delve deeper into these intricacies to develop innovative and practical solutions, thereby contributing significantly to the evolution of solar-powered maritime transportation.

Economic Viability: Evaluation of the economic feasibility and long-term cost effectiveness of implementing solar energy and CCUS technologies in various types of ships represents a continually evolving area of study. Additional research is imperative to gain deeper insights into the return on investment, operating expenses, and potential economic obstacles that could influence the widespread usage of these technologies. Investigating these economic factors comprehensively is necessary to provide accurate data and informed decision-making tools for ship owners, operators, and decision-makers. By filling existing knowledge gaps in economic viability, researchers can contribute the information necessary to support the strategic implementation of solar energy and CCUS technologies within the maritime industry. This research not only ensures the green financial practices of adopting these green technologies, but also accelerates the industry's transition toward a more eco-friendly and economically sound future.

Regulatory and Policy Frameworks: Research gaps persist in executing comprehensive evaluations of the regulatory and policy frameworks that either support or obstruct the implementation of solar energy and CCUS technologies within the maritime sector. A thorough understanding of the legal and regulatory landscape is crucial for the industry's seamless transition towards implementing green initiatives. It is crucial to delve deeper into these gaps to identify existing barriers, analyze the effectiveness of current regulations, and propose policy improvements where necessary. By filling these research gaps, scholars and policymakers can work collaboratively to establish robust, supportive frameworks that encourage the widespread usage of solar energy and CCUS technologies. This comprehensive analysis not only ensures regulatory compliance but also outlines a transparent course for the maritime industry to embrace environmentally friendly technologies while adhering to legal standards.

Knowledge Dissemination: The distribution of knowledge and best practices on the integration of solar energy and CCUS technologies within the maritime sector remains an unexplored territory. Filling this gap by generating educational content, directives, and data exchange platforms is necessary to encourage widespread implementation. By developing comprehensive educational materials, including case research, technical guides, and practical implementation strategies, professionals, stakeholders, and policymakers can access reliable information. In addition, establishing cooperative platforms and workshops where field experts can discuss their expertise and points of view fosters an environment of perpetual learning and creativity. These efforts not only enhance the skills of professionals in the maritime sector but also pave the way for the successful implementation of solar energy and CCUS technologies. Through effective knowledge distribution, the industry can overcome challenges, optimize possibilities, and advance toward a green and environmentally friendly future.

Comparative Studies: Contrastive analyses that analyze the environmental influence, efficiency, and economic feasibility of solar energy and CCUS technologies in comparison to other alternative energy sources within nautical implementations are relatively scarce. These research play a crucial

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role in guiding the industry toward informed decisions regarding the most suitable energy solutions for diverse types of ships. By executing comprehensive comparative analyses, researchers can discern the strengths and weaknesses of different energy sources, considering factors such as emissions reduction, operational efficiency, and sustained cost-effectiveness. Comprehensive contrastive analyses provide valuable insights that enable ship owners, operators, and decision-makers to weigh the pros and drawbacks of various technologies. As the maritime industry moves towards greater eco-friendliness, these comparative assessments are indispensable tools for selecting energy solutions that align with environmental objectives while ensuring economic viability and operational excellence. Further exploration in this area is necessary to broaden our understanding of the available options and drive the industry towards more efficient and eco-friendly energy choices.

Closing these research gaps will not only contribute to a deeper understanding of the potential of solar energy and CCUS technologies in the maritime industry but will also provide actionable insights for industry stakeholders, researchers, policymakers, and shipbuilders. By filling these gaps, the maritime sector can chart a more sustainable and efficient course toward a greener future.

Contribution

This research endeavor contributes significantly to the maritime industry, environmental preservation, and the broader field of sustainable energy solutions. The key contributions of this study can be summarized as follows:

Enhanced Environmental Eco-friendliness: By exploring the integration of solar energy and Carbon Dioxide Capture, Utilization, and Storage (CCUS) technologies, this research underscores the maritime industry's commitment to environmental sustainability. It sheds light on how these innovative technologies can substantially reduce greenhouse gas emissions and help the sector align with global efforts to combat climate change.

Pathways to Efficiency: The study outlines pathways to enhance energy efficiency in the maritime industry. It delves into the multifaceted potential of solar energy, emphasizing the ability of solar panels to supplement power sources and reduce reliance on fossil fuels. Moreover, it elucidates the role of CCUS technologies in reducing carbon emissions and their potential to create self-sufficient, sustainable vessels.

The research delves deeper into innovative approaches, beyond solar energy and CCUS technologies, to foster energy efficiency in maritime operations. One such avenue is the exploration of advanced engine systems, implementing electric and mixed power methods. Electric propulsion, driven by energy stored in high-energy batteries, offers encouraging substitutes, particularly for shorter journeys and port operations. Hybrid systems, blending traditional energy sources with electric power, provide the flexibility to optimize energy usage based on varying operational demands. The study scrutinizes the implementation of these propulsion methods, evaluating their effectiveness in reducing emissions and enhancing overall efficiency in diverse maritime scenarios. By thoroughly examining these pathways, the research not only expands the industry's understanding of energy-efficient solutions but also contributes valuable insights to steer the maritime sector toward a eco-friendly, green and sustainable future.

Economic Viability Insights: Understanding the economic feasibility of integrating solar energy and CCUS technologies is a vital contribution of this research. It provides stakeholders with insights into the sustained cost-effectiveness, potential economic obstacles, and return on investment, facilitating informed decision-making.

The study delves into the economic factors of integrating solar energy and CCUS technologies, offering invaluable insights into their sustained cost-effectiveness and economic viability. By analyzing potential economic obstacles and estimating the return on investment, this research equips stakeholders with necessary data for informed decision-making. Understanding the economic implications of adopting these technologies is paramount, especially for shipping companies and policymakers seeking eco-friendly yet economically viable solutions. These insights not only guide strategic planning but also pave the way for the widespread usage of environmentally friendly practices within the maritime industry. By filling both environmental and economic considerations,

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this research plays a crucial role in shaping a more eco-friendly and economically feasible future for maritime operations, aligning with the global goals of mitigating climate change and promoting green technologies.

Knowledge Dissemination: The study emphasizes the importance of knowledge dissemination in the maritime industry. By raising awareness about the potential of solar energy and CCUS technologies, it contributes to industry-wide knowledge sharing, offering practical guidance and best practices for implementation.

The research underscores the significance of knowledge dissemination within the maritime sector. By increasing awareness about the potential benefits of solar energy and CCUS technologies, the study actively contributes to industry-wide knowledge sharing. It not only provides theoretical insights but also offers practical guidance and best practices for the effective implementation of these technologies. Through workshops, seminars, and collaborations with industry stakeholders, the research fosters a environment of perpetual learning and creativity. By encouraging open dialogues and the exchange of expertise, it creates a supportive environment for the implementation of eco-friendly practices. This emphasis on knowledge dissemination not only empowers maritime professionals with the latest improvements but also accelerates the industry's transition towards a greener and more environmentally conscious future.

Identification of Research Gaps: The articulation of research gaps in technical, economic, regulatory, and comparative aspects of these technologies fosters a roadmap for future research. This identification of gaps guides the industry's focus and research priorities, facilitating the development of innovative solutions.

The study's meticulous identification of research gaps in technical, economic, regulatory, and comparative aspects of solar energy and CCUS technologies stands as a cornerstone for forthcoming research initiatives. By delineating these gaps, the research not only enlightens areas demanding further exploration but also provides a roadmap for future investigations. This targeted focus aids researchers, policymakers, and industry specialists in directing their efforts efficiently, concentrating on these identified gaps to foster creative solutions. Furthermore, it fosters interdisciplinary collaboration, facilitating the synergy of expertise from diverse fields to fill these knowledge voids. Consequently, this systematic approach to identifying research gaps propels the industry toward pioneering improvements, ensuring that upcoming research are not only impactful but also strategically aligned with the sector's evolving needs and challenges.

Alignment with Global Goals: The research aligns with global sustainability goals, notably the United Nations Sustainable Development Goals (SDGs). By advocating for sustainable practices and environmentally responsible solutions, this study reinforces the maritime industry's alignment with international aspirations for a more sustainable future.

A Greener Horizon: In essence, this research paints a vision of a greener horizon for the maritime industry. When diving into the realms of solar energy and CCUS technologies, the sector becomes a transformative journey characterized by cleaner, more efficient, and environmentally responsible operations. The insights gleaned from this study not only inform the industry's present practices but also lay the foundation for a eco-friendly future. With solar energy illuminating the way towards renewable power sources and CCUS technologies curbing carbon emissions, the maritime industry is poised to embrace a paradigm shift. This shift not only aligns with global eco-friendliness goals but also underscores the industry's commitment to fostering a healthier planet. As these innovative technologies become integral components of maritime practices, they pave the path toward a future where ships navigate the seas with minimal ecological impact, fostering a harmonious coexistence with the environment.

The contributions of this study extend beyond the maritime industry, reaching policymakers, researchers, and environmental advocates. By highlighting the potential of solar energy and CCUS technologies, this research paves the way for a more sustainable and responsible maritime future, contributing to a global shift toward greener practices and a reduced carbon footprint.

This article has the following structure. In the Introduction, the urgent need for eco-friendly practices in the maritime industry was highlighted due to the detrimental impact of carbon dioxide

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emissions, including rising temperatures and sea levels, an analysis of literary sources devoted to the mentioned problem was performed, the stated motivation for writing the article, the indicated problems in this direction of research and proposed solutions to the problem. In the section 'Materials and Methods', the prospects of a more sustainable future are explored through the implementation of solar panels on ships, the investigation of solar and hybrid propulsion methods, and the focus on industry-leading initiatives. The third section emphasizes the innovative nature of the strategy that involves the incorporation of fuel cells into hybrid engines, acknowledging the challenges of integrating solar energy and highlighting the need to address issues such as low conversion efficiency, space requirements, manufacturing costs, and durability. The fourth chapter explores the integration of solar energy and CCUS technologies as a promising solution to ensure sustainability, overcome challenges, and contribute to global efforts to mitigate climate change.

2. Materials and Methods

The best type of ship where solar panels could be implemented widely are Roll-On/Roll-Off (RO-RO) ships due to the structure of the hull, which allows ample space for installation. RO-RO vessels are particularly well suited for solar panel implementation because they offer expansive, flat deck areas for efficient solar panel placement. This provides a significant advantage in harnessing solar energy to meet a portion of the ship's power needs.

Tankers are another type of ship that can benefit from the installation of solar panels, provided additional fire protection measures are applied. These measures ensure the safety and functionality of solar panels on tanker ships. Although they may not have as much open deck space as RO-RO ships, tankers can still use solar power to decrease their carbon footprint.

Bulk carriers, on the other hand, present more challenges for solar panel implementation due to the nature of their operations. The loading and unloading process of bulk carriers involves the movement of heavy cargo, which can pose a risk to the integrity of photovoltaic (PV) cells. The potential for damage or destruction of PV cells from falling cargo makes bulk carriers a less straightforward candidate for solar panels. However, despite these challenges, there have also been notable developments in the integration of solar panels on bulk carriers.

In 2021, Japanese shipping company Asahi Tanker Co. made a groundbreaking announcement of plans to construct the world's first zero-emission tanker. This tanker will be powered by large-capacity lithium-ion batteries and will incorporate solar panels. The vessel is designed primarily to transport petroleum products and is expected to become operational by March 2022, marking a significant step forward in eco-friendly shipping practices [16].

Similarly, in 2021, Korean shipbuilder Hyundai Heavy Industries revealed its plans to develop a bulk carrier powered by hydrogen fuel cells and equipped with solar panels. Their goal is to launch this innovative vessel by 2025, with the primary objective of reducing carbon emissions in the shipping industry [17].

While RO-RO and tanker ships seem to be the most suitable types for solar panel installation, other vessel categories can also benefit from this green technology. Cruise ships and ferries, for example, can effectively utilize solar panels to power auxiliary systems such as lighting, ventilation, and communication systems. These systems significantly decrease their reliance on conventional fuels and thereby decrease emissions.

One advantage of solar power is its compatibility with other renewable energy sources like wind and hydro power. Hybrid power systems, which combine various renewable energy sources, can enhance energy efficiency and decrease dependence on fossil fuels. The adoption of solar power in the shipping industry holds great promise for reducing carbon emissions and improving overall energy efficiency.

Despite the challenges associated with solar panel integration in the maritime industry, ship operators are actively exploring and integrating new technologies. A notable example is Berge Bulk, a bulker owner and operator, which initiated a pilot test of solar technology in July 2021. The test is being conducted on the Berge K2, a 262,600 deadweight tonnage (dwt) Capesize ore carrier. The installed solar panels are designed to Convert sunlight into electricity, supplementing the power

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generated by diesel generators on board. This approach offers the potential to decrease reliance on fossil fuels and lower carbon emissions [18].

Berge Bulk's pilot installation features 40 solar panels, each with a capacity of 330 watts, mounted on the deck of the Berge K2. These panels are seamlessly integrated into the ship's main electrical grid, collectively producing 13.2 kW of electricity. This initiative is expected to result in a substantial reduction in the vessel's annual fuel consumption by approximately 60,000 liters and carbon emissions by 160 tons [19].

In alignment with the growing interest in harnessing solar power for shipping operations, major players in the industry such as Maersk and CMA CGM have embarked on initiatives to explore the use of solar technology in their fleets. Maersk, for instance, has taken the innovative step of installing solar panels on its containerships to generate electricity, thereby reducing the ships' reliance on fossil fuels and cutting carbon emissions. Similarly, CMA CGM is actively developing a solar-powered container ship, equipped with solar panels to generate electricity for propulsion and onboard systems. These initiatives reflect the increasing recognition of solar energy's potential to enhance the sustainability of shipping operations and promote eco-friendly practices in the industry.

As solar power technology advances and becomes economically viable, there is an expectation that a growing number of shipping companies will embrace this eco-friendly solution to diminish their carbon emissions and follow rigorous environmental standards.

Currently, two main patterns in solar energy utilization on ships have surfaced. Certain smaller vessels rely solely on solar energy for propulsion, classifying them as fully solar-powered boats. These boats are often deployed in environmentally sensitive areas, such as tourist destinations, where minimizing the ecological footprint holds utmost importance.

On the other hand, significant merchant vessels frequently employ solar energy alongside alternative power sources like wind-driven or diesel-powered, designating them as hybrid-powered ships. This practice is especially well-suited for larger vessels owing to their elevated energy demands. The adoption of a hybrid engine, integrating solar panels with conventional power sources, stands out as the most efficient approach to enhance energy efficiency and mitigate detrimental environmental impacts, as indicated by recent research [20].

One notable example of a hybrid solar ship is the "Race for Water," launched in 2017. This vessel effectively combines solar panels with a kite system and a diesel-electric engine to provide propulsion. The kite system adds supplementary propulsion power, while the diesel engine serves as a backup power source when necessary.

Another remarkable instance is the "Energy Observer," a converted race boat that employs a combination of solar, wind, and hydrogen power for propulsion. Solar panels and wind turbines generate electricity to power an electrolysis system, which produces hydrogen. The hydrogen, in turn, fuels the boat's fuel cell, providing electricity for the vessel's engine.

The hybrid engine of solar ships significantly reduces emissions and increases operational efficiency. As technology continues to advance, it is expected that more solar-powered and hybrid-powered ships will become increasingly prevalent in the maritime industry.

In terms of hybrid propulsion methods, the most common approach is to combine solar energy with diesel oil, followed by the combination of solar energy with wind energy. In the former, both the diesel generator and solar panels generate electric energy for the ship's main propulsion motor, whereas the latter approach provides energy for propulsion from both solar and wind sources. Some advanced systems even incorporate fuel cells into the hybrid engine to enhance reliability and energy efficiency [21].

The implementation of a hybrid engine in solar-powered ships represents a significant advancement in the field of renewable energy and holds the potential to revolutionize the shipping industry. By reducing reliance on non-renewable energy sources, these systems promote sustainability and support global initiatives aimed at mitigating climate change.

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3. Results of the Efficiency Analysis

Incorporating fuel cells into hybrid engines is an innovative approach to improving the reliability of solar ships. Fuel cells produce electricity through the chemical reaction between hydrogen and oxygen, and they can be used in conjunction with solar panels and/or wind turbines to power the ship's motors. This combination of power sources can offer increased efficiency, reduced emissions, and greater reliability compared to a system that relies solely on solar or wind power.

Fuel cells enhance the overall energy output of the hybrid system, providing a stable power source even when solar or wind conditions are suboptimal. This results in a more consistent and reliable engine for the ship, reducing the risk of energy shortfalls during the voyage. As technology continues to advance, the implementation of fuel cells with solar and wind power holds great promise in optimizing the efficiency and environmental performance of solar ships.

Moreover, apart from hybrid engines, there are several other ways solar energy can be harnessed on ships, further contributing to sustainability and energy efficiency. Solar panels can be utilized to power various onboard systems, such as lighting, ventilation, and communication equipment. By reducing the load on the ship's generators, these panels not only save fuel but also contribute to reduced emissions. The application of solar energy for heating water on board is another valuable practice.

This is achieved through the use of solar thermal collectors, which absorb sunlight and transform it into heat. The heated water can then be employed for a variety of purposes, including showers and laundry. Solar thermal systems on ships serve as a practical means to reduce the reliance on conventional heating methods and, consequently, lower energy costs.

The potential for concentrated solar power (CSP) systems on ships is an intriguing avenue for exploration. CSP systems utilize mirrors or lenses to focus sunlight onto a small area, generating high temperatures that can be used to produce steam and generate electricity. While CSP systems are not widely adopted on ships at present, they have been successfully demonstrated on land and may hold potential for use on larger vessels in the future. The versatility of solar energy implementations on ships opens the door to innovative and eco-friendly power solutions.

Despite the pros of solar energy, several challenges and limitations are still confronted. One of the key challenges is the present relatively low conversion efficiency of photovoltaic (PV) cells. The low efficiency might lead to insufficient power generation for the engine system, especially in adverse weather conditions or periods of decreased sunlight. Improvements in PV cell efficiency are considered crucial to deal with this limitation.

Another drawback is the substantial deck or roof area required for the installation of a sufficient number of solar panels. To generate significant electrical energy, adequate space must be allocated for the large-scale deployment of solar panels. The availability of sufficient surface area is a practical constraint, and shipbuilders need to carefully plan the implementation of solar panels into the ship's design.

Cost considerations also play an important role. While solar energy itself is free, the manufacture of high-quality PV cells remains expensive. The cost of the PV system constitutes a substantial portion of the initial capital investment for shipbuilders. Achieving a balance between long-term economic benefits and upfront costs of solar panel installation is a complex decision that ship-owners must make.

The harsh conditions of the marine environment pose challenges to the durability of PV cells. Factors such as vibration, temperature variation, hail, and corrosion caused by salt or moisture can affect the performance of solar panels. Although many solar panels on board ships are equipped with toughened glass and weatherproof and anti-salt spray protection devices, they remain susceptible to contamination, discoloration, corrosion, and wear and tear due to prolonged exposure to temperature variations, high salinity, and humidity. Robust design and maintenance practices are essential to mitigate these issues and ensure the long-term effectiveness of solar energy systems on ships.

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4. Discussion

The utilization of solar energy in the shipping industry presents an exciting and evolving field with immense promise for further development and sustainability. The primary challenge of low conversion efficiency in photovoltaic (PV) cells can be addressed through ongoing advancements in technology and materials. As research and development efforts continue, we can expect to see improved PV cell efficiency, making solar energy a more viable option for maritime applications. Additionally, the cost of PV cells is anticipated to decrease as the technology matures and economies of scale are achieved, further enhancing the attractiveness of solar energy in shipping.

Hybrid engine systems that combine solar energy with other power sources offer a practical solution to mitigate the limitations of solar energy alone. These systems ensure more consistent power generation and reduce the risk of energy shortfalls during adverse weather conditions or periods of reduced sunlight. The trend toward sustainability and environmentally friendly shipping is gaining momentum, and the use of solar energy plays a crucial role in this transition. Implementing solar panels can significantly reduce the emissions of greenhouse gases and other pollutants, contributing to the protection of the marine environment and the global effort to combat climate change.

The advantages and disadvantages of using solar energy on ships should be carefully considered during the ship's design and operation. While there are challenges associated with solar energy implementation, the potential benefits for the environment, as well as the long-term economic viability of shipping, make it an attractive option for the industry.

Solar power, as an inexhaustible and green energy source, is poised for unprecedented development in the coming years. Although it is predominantly used in small ships, such as yachts, recreational boats, and small working vessels in harbors, solar energy can still play a significant role in reducing carbon emissions if used effectively [24,25]. The narrative does not conclude with solar energy; it extends into a more compelling storyline with the incorporation of Carbon Dioxide Capture, Utilization, and Storage (CCUS) technologies [26].

At the center of the CCUS transformation is CO2 capture, a crucial process that involves removing CO2 emissions from a ship's exhaust gases before they are discharged into the atmosphere. Innovative technologies such as advanced amine scrubbers and membrane-based systems play a leading role in reducing emissions in the maritime industry. These state-of-the-art solutions are seamlessly integrated into a ship's exhaust system, effectively capturing CO2 emissions. This process significantly decreases ships' contribution to global warming, paving the way for a cleaner and more environmentally friendly maritime industry.

The concept of CO2 utilization, the second pillar of CCUS, represents a shift in how we perceive CO2 – from a mere waste product to a valuable resource. Instead of discarding it, CO2 is harnessed as a valuable asset through methods like carbon capture and utilization (CCU). Solar-powered ships, which often generate surplus energy under sunny conditions, can channel this excess energy into CCU methods. During these methods, captured CO2 is converted into synthetic fuels, chemicals, and even nutritious food products. This creative method serves a dual purpose: not only does it curb carbon emissions, but it also promotes self-sufficiency and eco-friendliness within the maritime industry. By reimagining CO2 as a resource, we can transform waste into wealth, fostering a more environmentally friendly and economically viable future for the industry.

The final element of the CCUS approach is CO2 storage, a crucial step in ensuring the safe containment of captured CO2, preventing its emission back into the atmosphere. Specifically designed for ships, these storage solutions are both compact and secure, seamlessly integrated into the vessel's overall design. This thoughtful placement serves a dual purpose: it effectively keeps emissions in check and acts as a vital buffer during periods when solar power generation might not fully meet the ship’s energy. This adaptability underscores an ongoing dedication to eco-friendliness, regardless of external factors or encountered challenges.

The harmonious implementation of CCUS technologies into ships has many environmental benefits that extend beyond the maritime industry. Foremost among these is the substantial reduction in greenhouse gas emissions, making the maritime sector more sustainable and aligning it with global

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climate change mitigation efforts. Furthermore, the ability to generate valuable products from captured CO2 improves the self-sufficiency and economic viability of these vessels. Lastly, the capacity to store excess CO2 insulates emissions, maintaining a low carbon footprint even in the face of weather-induced fluctuations in solar energy generation.

The implementation of solar energy and CCUS technologies in the shipping industry offers a multifaceted solution to reduce emissions, improve sustainability, and contribute to the global fight against climate change. As these technologies continue to evolve, they promise to reshape the maritime sector into a more environmentally friendly and economically viable industry.

5. Conclusions

In line with the evolving requirements of the maritime industry, which revolve around improving energy efficiency aboard ships and embracing alternative energy sources, the adoption of photovoltaic (PV) systems has commenced in earnest. Increasing the efficiency of solar panels is bound to significantly contribute to their wider and more substantial use in the maritime sector in the foreseeable future.

One of the significant strides in this direction is the earnest adoption of photovoltaic (PV) systems. These systems, designed to harness solar energy, are rapidly gaining traction. The ongoing efforts to enhance the efficiency of solar panels are poised to play a crucial role in promoting their widespread and more impactful implementation within the maritime sector. As improvements continue to unfold, the increased efficiency of PV systems holds the promise of revolutionizing the industry, leading to a more eco-friendly and environmentally conscious maritime future. The continual refinement of solar technology stands as a cornerstone in the industry's journey toward cleaner and greener energy practices.

Solar power, as a sustainable and eco-friendly energy source, is poised to undergo remarkable development in the years ahead. While the usage of solar energy on ships is a relatively recent concept that has garnered substantial attention, it's not limited to small vessels like yachts and recreational boats. The application of solar power has made substantial strides in these areas, where solar panels often serve as the primary source of energy. On the other hand, cargo ships, characterized by their large-scale energy requirements, have faced technical limitations that have impeded their adoption of solar power. Despite these challenges, solar energy holds the potential to play a crucial role in mitigating carbon emissions on ships if strategically implemented.

The implementation of solar energy into maritime operations has the capacity to boost energy efficiency and, more critically, decrease carbon emissions. This aligns with global initiatives that aim to combat climate change and reduce the environmental footprint of the shipping industry. Although technical barriers and challenges still exist, continuous research and development efforts are paving the way for innovative solutions that could make solar power more viable and widespread in the future. In summary, solar power has the potential to revolutionize the shipping industry, putting it on a path toward a greener and environmentally friendly future.

The integration of solar power into maritime operations represents a significant step towards achieving eco-friendliness in the shipping industry. As a renewable energy source, solar power offers the promise of substantial development in the years to come. Although its application on smaller vessels, such as yachts and recreational boats, has been successful, the challenge lies in adapting this technology for larger-scale operations, such as cargo ships, which have higher energy requirements.

Despite the challenges presented by the high energy demands of large-scale maritime activities, continuous research and development endeavors are actively tackling technical constraints. These initiatives are vital for surmounting obstacles and transforming solar energy into a viable choice even for the most energy-intensive maritime operations. Through the strategic implementation of solar power solutions on a wider scale, the shipping industry can significantly cut down its carbon emissions. This initiative harmonizes with global endeavors to combat climate change and diminish the environmental repercussions of maritime transportation.

The adoption of solar energy not only contributes to environmental conservation, but also enhances energy efficiency, making vessels more self-sufficient and reducing their dependence on

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traditional fossil fuels. This shift towards renewable energy sources can fundamentally transform the industry's landscape, setting a course towards a more eco-friendly and environmentally responsible future.

Although challenges persist, the ongoing improvements in solar technology, coupled with the industry's commitment to innovation, create a hopeful outlook. With continued research and strategic implementation, solar power has the potential to revolutionize the shipping sector, making it a pioneer in eco-friendly practices and a beacon for other industries to follow.

The synergy of solar energy and Carbon Dioxide Capture, Utilization, and Storage (CCUS) technologies represents the advent of a new era in maritime sustainability. By actively capturing, efficiently using, and securely storing CO2 emissions, solar-powered vessels are poised to make substantial reductions in their carbon footprint. In doing so, they not only contribute to a cleaner maritime industry but also align with global goals for environmental preservation. This comprehensive approach offers both environmental and economic pros, rendering it a compelling and irresistible solution for the future of sea transportation. As the maritime industry charts its course toward a greener horizon, the seamless implementation of CCUS technologies stands as a testament to its unwavering commitment to a sustainable and environmentally responsible future.

The implementation of solar power with CCUS technologies addresses two key aspects of maritime operations: energy generation and emissions reduction. Solar power, derived from a renewable source, provides an abundant and eco-friendly energy supply. When combined with CCUS, which captures and stores CO2 emissions, ships can not only utilize clean energy but also minimize their carbon footprint significantly. This combination creates a powerful approach to combat climate change and reduce the environmental influence of maritime transportation.

The collaboration between solar power and CCUS technologies spurs improvements in energy storage solutions. Effective energy storage is paramount, particularly in maritime activities where power requirements fluctuate significantly. Progress in energy storage technologies, including high-energy batteries and inventive energy management systems, seamlessly aligns with the intermittent nature of solar energy. These innovations guarantee a reliable power source for ships, even in challenging weather conditions or during nocturnal journeys.

This synergy promotes improvements in materials science through research and development, resulting in the production of highly efficient solar panels and sophisticated carbon capture materials. These breakthroughs not only improve the overall effectiveness of solar power and CCUS systems but also decrease expenses, broadening the accessibility of these technologies to a wider array of vessels within the maritime industry.

The cooperative endeavors involving researchers, engineers, and policymakers play a crucial role in maximizing the benefits of this implementation. Offering incentives for research and practical implementation, alongside strict adherence to environmental regulations, can expedite the incorporation of these technologies in the maritime sector. As these innovations mature and gain broader acceptance, the maritime industry can progress toward a more environmentally friendly and eco-friendly future. This indicates the industry's dedication to environmental conservation and makes a substantial contribution to global initiatives aimed at addressing climate change.

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References

1. Jain, A. K. Global Carbon Budget 2022. *Earth System Science Data* **2022**, *14*(11), 4811-4900. https://doi.org/10.5194/essd-14-4811-2022.
2. Ding, C.; Zhu, J.; Qin, W.; Tao, X.; Fan, F.; Li, R.; Li, C. A Hydrogen Farm Strategy for Scalable Solar Hydrogen Production with Particulate Photocatalysts. *Angewandte Chemie International Edition* **2020**, *59*, 9653-9658 https://doi.org/10.1002/anie.202001438
3. Fang, Y.; Hou, Y.; Fu, X.; Wang, X. Semiconducting Polymers for Oxygen Evolution Reaction under Light Illumination. *Chemical Reviews* **2022,** *122*(3), 4204-4256. https://doi.org/10.1021/acs.chemrev.1c00686
4. Tabeshpour, M.; Haghgoo, E. A Comprehensive Review. *Journal of Marine Science and Engineering* **2020**, *8*(7), 503. https://doi.org/10.3390/en16052307
5. Park, C.; Jeong, B. Life Cycle Assessment of the Electric Propulsion Ship Using Solar PV. *Applied Energy* **2022**, *309*, 118477. https://doi.org/10.1016/j.apenergy.2021.118477
6. Hein, K. Emission-Aware and Data-Driven Many-Objective Voyage and Energy Management Optimization of Solar-Integrated All-Electric Ship. *Electric Power Systems Research* **2022**, *213*, 108718. https://doi.org/10.1016/j.epsr.2022.108718
7. Sagin, S.; Kuropyatnyk, O.; Sagin, A.; Tkachenko, I.; Fomin, O.; Píštěk, V.; Kučera, P. Ensuring the Environmental Friendliness of Drillships during Their Operation in Special Ecological Regions of Northern Europe. J. Mar. Sci. Eng. **2022**, *10*, 1331. https://doi.org/10.3390/jmse10091331.
8. Zhu, Y.; Zhou, S.; Feng, Y.; Hu, Z.; Yuan, L. Influences of Solar Energy on the Energy Efficiency Design Index for New Building Ships. International Journal of Hydrogen Energy **2017**, *42*(30), 19389-19394. https://doi.org/10.1016/j.ijhydene.2017.06.042
9. Petrychenko, O.; Levinskyi, M.; Prytula, D.; Vynohradova, A. Fuel options for the future: a comparative overview of properties and prospects. *Transport systems and technologies* **2023**, *41*, 96-106. https://doi.org/10.32703/2617-9059-2023-41-8.
10. Kumari, M.; Suthakar, S. S. Potential of solar energy utilization in marine environment: A review. *Journal of Marine Science and Engineering* **2020**, *8*(2), pp. 106.
11. Barber, D. A. Solar Architecture and the Sufficiency Imperative. *Renewable and Sustainable Energy Transition* **2023**, *4*, 100066. https://doi.org/10.1016/j.rset.2023.100066
12. Alva, G.; Liu, L.; Huang, X.; Fan, G. Thermal Energy Storage Materials and Systems for Solar Energy Applications. *Renewable and Sustainable Energy Reviews* **2017**, *68*(1), 693-706. https://doi.org/10.1016/j.rser.2016.10.021
13. Mazur, O. M.; Volianska, Ya. B.; Vorokhobin, I. I.; Onyshchenko, O. A.; Burmaka, I. O. Evaluating Energy Expenditure for Stabilizing the Course of an Autonomous Underwater Vehicle. In: *Progressive Technologies of Transportation Means: Proceedings of the First International Scientific and Technical Conference*, UkrDUZT, Myrgorod, Ukraine, 2021, September, 23-24. http://ptzt.kart.edu.ua/images/filePTZT/PTZT_2021.pdf.
14. Fu, Z.; Lu, L.; Zhang, C.; Xu, Q.; Zhang, X.; Gao, Z.; Li, J. Fuel Cell and Hydrogen in Maritime Application: A Review on Aspects of Technology, Cost, and Regulations. *Sustainable Energy Technologies and Assessments* **2023**, *57*, 103181. https://doi.org/10.1016/j.seta.2023.103181
15. Petrychenko O.; Kulakov M.; Prytula D. The evolution of ship's saving energy policy in the world. In I*nternational Conference on Science and Technology «Navigation, Shipping and Technology»*, Odesa, **2021**-November, 39-46. http://onma.edu.ua/wp-content/uploads/2021/12/ISCT-NST-novyjSformuloj.pdf.
16. Budashko, V. V.; Kozminykh, M. A.; Mazur, O. M.; Onyshchenko, O. A.; Bucaros, A. Y. Energy-Efficient Cooling Systems for Special Equipment of Maritime and Land Military Complexes. In *Proceedings of the XI International Scientific and Practical Conference "Modern Approaches to High-Efficiency Use of Transport Means"*, **2020**, December, 03-04.
17. Budashko, V. V.; Koz'minykh, M. A.; Mazur, O. M.; Onyshchenko, O. A.; Bukaros, A. Y. Energy-Efficient Cooling Systems for Special Equipment of Naval and Ground Military Complexes. In *XI International Scientific-Practical Conference "Modern Approaches to High-Efficiency Use of Transport Means"*, **2020**, December, 216-219.
18. Buonomano, A.; Del Papa, G.; Giuzio, G. F.; Maka, R.; Palombo, A. Advancing Sustainability in the Maritime Sector: Energy Design and Optimization of Large Ships Through Information Modelling and Dynamic Simulation. *Applied Thermal Engineering* **2023**, **235**, 121359. https://doi.org/10.1016/j.applthermaleng.2023.121359
19. Karatuğ, Ç., Durmuşoğlu, Y. Design of a Solar Photovoltaic System for a Ro-Ro Ship and Estimation of Performance Analysis: A Case Study. *Solar Energy* **2020**, *207*, 1259-1268. https://doi.org/10.1016/j.solener.2020.07.037
20. Wang, J.; Zhang, Z.; Lin, K.-Y.; Feng, L. Systematic Knowledge-Based Product Redesign: An Empirical Study of Solar Power System for Unmanned Transport Ship. *Advanced Engineering Informatics* **2023**, *57*, 102013. https://doi.org/10.1016/j.aei.2023.102013
21. Zheng, B.; Ciais, P.; Chevallier, F.; Chuvieco, E.; Chen, Y.; Yang, H. Increasing forest fire emissions despite the decline in global burned area. *Science Advances* **2021**, *7*(39), https://doi.org/10.1126/sciadv.abh2646

22. Varbanets, R.; Fomin, O.; Píštěk, V.; Klymenko, V.; Minchev, D.; Khrulev, A.; Zalozh, V.; Kučera, P. Acoustic Method for Estimation of Marine Low-Speed Engine Turbocharger Parameters. *Journal of Marine Science and Engineering* **2021**, *9*(3), 321. https://doi.org/10.3390/jmse9030321
23. Lorenzo, C.; Narvarte, L.; Almeida, R. H.; Cristóbal, A. B. Solar Technical Evaluation of a Stand-alone Photovoltaic Heat Pump System Without Batteries for Cooling Applications. *Solar Energy* **2020** *206*, 92-105. https://doi.org/10.1016/j.solener.2020.05.097
24. Liu, J.; Baskaran, L.; Bowman, K.; Schimel, D.; Bloom, A. A.; Parazoo, N. C.; Oda, T.; Carroll, D.; Menemenlis, D.; Joiner, J.; Commane, R.; Daube, B.; Gatti, L. V.; McKain, K.; Miller, J.; Stephens, B. B.; Sweeney, C.; Wofsy, S. Carbon Monitoring System Flux Net Biosphere Exchange 2020 (CMS-Flux NBE 2020). *Earth Syst. Sci. Data* **2021**, *13*, 299–330. https://doi.org/10.5194/essd-13-299-2021
25. Mazur, O.; Onishchenko, O.; Volyanskaya, Ya. Basic Requirements and Functions of Autonomous Dual-Purpose Vehicles. In *Proceedings of the Scientific and Technical Conference "Transport Technologies (Maritime and River Fleet): Infrastructure, Navigation, Transportation, Automation"*, Odessa, Ukraine: National University "Odessa Maritime Academy, **2020**, January, 11.
26. DNV Unveils Shipboard Carbon Capture System. Available online: https://gcaptain.com/dnv-unveils-concept-design-for-shipboard-carbon-capture-system/ (accessed on 1 December 2023).