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SUSTAINABLE DEVELOPMENT OF RENEWABLE ENERGY IN SHIPPING: TECHNOLOGICAL AND ENVIRONMENTAL PROSPECTS

Summary. Shipping is one of the major sources of greenhouse gas emissions; therefore, immediate actions must be taken in the field of sustainable development. This study focuses on exploring the use of renewable energy to mitigate emissions and enhance energy efficiency on board ships. Hence, technologies for capturing, utilizing, and storing solar, wind, and carbon energy are investigated. Further, the study weighs these approaches in terms of benefits, drawbacks, and potential application in sustainable maritime operations. To quantify the practicability of the solutions analyzed, an interdisciplinary approach intertwining feasibility analysis, simulation modeling, and policy evaluation is used. Topics discussed include

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technological barriers, economic barriers, and regulatory frameworks. It also highlights recent advances with great environmental potential in shipping, such as hybrid propulsion systems and fuel cell technologies. The results showed that the hybrid systems with renewable energy combined with CCUS can reduce CO_2 emissions from ships up to 90%, which, in the best case, simultaneously imparts an increased operational efficiency and environmental sustainability. The study therefore examined regulatory and policy options that could facilitate the transition to renewable energy in this sector, and the industrial application of these technologies is thus presented as a key stage in environmentally sustainable development.

Keywords: shipping, alternative sources; renewable energy, greenhouse gases, harmful emission, wind energy, solar energy, ecological safety of shipping, maritime transportation, carbon capture.

1. INTRODUCTION

Renewable energy sources (RES) play a key role in reducing shipping emissions. The numerous studies review different types of RES such as solar, wind and hybrid systems and evaluate their potential for ship applications. For example, works [1] and [7] analyze in detail the potential of solar and wind energy on ships, demonstrating that they can significantly improve energy efficiency and reduce carbon emissions. In [10, 13, 16], the technical aspects of ship design using hybrid energy sources are studied, and optimization calculations of such systems are performed. In [15, 16] it is shown that the use of solar panels on ships requires significant effort to integrate these technologies into existing ships, which may complicate their widespread adoption.

Papers [12, 19] discuss the problems of operating solar-powered ships, especially in remote areas such as the Arctic, where the efficiency of such systems may be reduced due to climatic conditions. Papers [16, 17] show that solar energy has a positive impact on the energy efficiency of new ships, which makes it attractive for the design of new ships. However, solar panels face challenges in the marine environment, such as variable solar irradiation and the need for advanced energy storage systems to ensure continuous operation.

The implementation of CCUS biodiversity is a key strategy for cutting maritime emissions. Research studies show that about 90% of CO_2 emissions can be trapped from ships, thereby greatly reducing the adverse effect of fossil fuel consumption. This captured CO_2 can then be onboard in tanks and later transported for sequestration or to industrial build-up applications. While there is a higher potential for these systems, CCUS needs to be improved in terms of energy consumption. Besides that, storage and the integration of these technologies with other renewable resources such as wind and solar power become paramount.

The possibilities of implementing such technologies on ships, including carbon transportation by sea [20, 22], are discussed in detail. In [21, 23], the techno-economic aspects of such technologies and their role in the global decarbonization strategy are analyzed, including the role of specialized ships for carbon transport. In [24], the societal and political aspects of CCUS implementation in countries such as France, Spain, and Poland are discussed, showing the importance of regulation and government support for the implementation of such projects. Works [22, 25] emphasize the importance of creating infrastructure for CCUS and integrating these technologies with existing energy systems.

The economic component plays an important role: the study [23] shows that the initial costs of CCUS implementation can be high, but they decrease over time due to regulatory incentives and carbon savings. The study [25] also points out the importance of regional CCUS implementation projects, such as the Ebro River Basin project.

Hybrid energy systems combining different RES are a promising area for shipping. The scientific works show that hybrid systems incorporating solar, wind, and other renewable sources can significantly improve the energy efficiency of ships. In [13, 18], various strategies for integrating these systems into ships are discussed, while [31] focuses on their economic feasibility. For example, [15] analyzes the benefits of hybrid solutions for ships, reducing dependence on fossil fuels and increasing operational flexibility. In [31], the possibility of reducing carbon emissions through the use of hybrid systems in heavy lift transportation and the impact of weather conditions on the efficiency of these solutions is considered.

The investigation on hybrid systems of wind, solar, and CCUS technologies is getting popular nowadays owing to its attempt towards an energy mix being balanced and resilient on ships. It has been observed that such renewable energy systems, if properly integrated, could result in reduced fuel consumption and GHG emissions. Moreover, these hybrid systems provide higher operational flexibility to the ship, which aids in the smoother transition from one energy source to another on the basis of environmental conditions and power demand.

Despite the immense benefits, RES application to shipping is hindered by various obstacles. [20] points out the economic and technical difficulties facing RES applications to marine vessels. [20] remarks upon the immense costs associated with retrofitting existing ships to RES, whereas [24] draws attention to the political and regulatory impedance hindering their implementation. [30] touches upon the environmental aspects of RES use in shipping, stressing the importance of minimizing impacts on the marine environment.

The studies [19, 28] discuss operational challenges such as the instability of renewable energy supply, which requires the development of energy storage technologies and more accurate weather forecasting. In [34], methods for calculating dynamic loads on ships using renewable energy sources are proposed, which helps to minimize the potential risks for the operation of such ships.

An important aspect of using RES on ships is energy optimization and management. That studies show that smart control and monitoring systems are needed to maximize the efficiency of RES. For example, [42] considers the use of digital energy management systems that can automatically switch between energy sources depending on the operating conditions. In [38], the need to integrate RES with modern ship control systems to improve reliability and efficiency is emphasized. In [36], the possibilities of applying machine learning techniques to improve the accuracy of predicting the energy requirements of ships depending on weather conditions are discussed.

The numerous studies [32, 33, 41] focus on the technical aspects of RES ship operation. For example, [35] discusses the problems of diesel engine diagnostics using fuel additives to help improve the environmental performance of ships. In [33], methods for dynamic loading of containers carried by RES ships are discussed, which helps to reduce the risks of damage to cargo and equipment. The work of [39] shows the importance of developing new solutions for energy storage on ships to make RES more stable.

A number of studies focus on global perspectives on decarbonization of shipping and sustainable development. In [44], life-cycle management concepts for energy systems integrated with renewable energy sources are discussed, leading to significant reductions in carbon emissions. Studies [5, 14] emphasize the importance of developing international standards to ensure sustainable shipping, including emission regulation and the use of RES.

In [37, 45], the prospects for RES utilization in remote regions such as the Arctic, where the implementation of such technologies faces unique challenges, are discussed.

The other studies [47, 56-58] propose models to optimize vehicle and vessel operations using simulation software and genetic algorithms. These approaches are applicable to improve the operation of Renewable Energy Vessels (REVs), especially to reduce costs and improve energy efficiency in route planning and operations management.

The works [48, 49] focus on improving the fuel efficiency and environmental performance of ship engines, which is relevant for combined renewable energy systems. These studies show how additives and diagnostic techniques can improve engine performance, which can be useful for hybrid power systems. In studies [50, 51], the challenges and prospects of photovoltaic technologies on ships are addressed. These works show how solar energy can be effectively used to reduce emissions on ships and highlight the importance of optimizing energy conversion systems.

In works [46, 52, 55], energy management and storage techniques for ships with RES are discussed to help improve their efficiency in different climatic conditions. These studies emphasize on modeling control systems and predicting energy consumption using machine learning and smart technologies. The papers [53, 59] propose models for strategic planning of RES integration on ships and long-term management of the transition to clean energy sources. These models help to optimize resource utilization and ensure sustainable ship operation [60, 61].

Although there are numerous advantages of utilizing the renewable energy sources in ship transport, a number of challenges confront the mass introduction of the technology. They include high initial capital expenditure, technological limitations, and the need for legislative encouragement to facilitate the development of infrastructure energy within the shipping sector. However, with more innovation in policy instruments, hybrid systems, and energy storage devices, the industry has enormous potential in reducing emissions and increasing sustainability.

The main challenge is the high share of carbon emissions from shipping and the lack of adaptation of renewable energy technologies and carbon capture systems for the maritime industry. Despite significant progress in the field of RES, their application on ships remains limited due to a number of technical and economic factors. Therefore, there is a need to analyze the prospects of integrating renewable energy sources in the shipping industry with a focus on sustainable development and carbon emission reduction.

The goal of this research is to develop and test a hybrid energy system for ships that combines wind and solar power with carbon capture technologies. This approach aims to solve the main problems of the industry: to increase energy efficiency, reduce greenhouse gas emissions and reduce operating costs.

The paper proposes a new concept of hybrid power plants on maritime transport - when wind, solar and carbon capture systems are used on board at the same time. The risk management system is considered separately: real-time data collection and analysis, as well as dynamic regulation of all components of the power system. This comprehensive strategy has the potential to substantially reduce emissions maritime transportation. Furthermore, the study examines ways to address technical and economic obstacles facilitating and expediting the adoption of such "green" technologies on ships.

2. MATERIALS AND METHODS

The methodology of this paper proposes the integration evaluation of renewable energy sources (RES) such as wind, solar, and CCUS technologies in maritime transportation systems. Being a hybrid energy approach, the renewable energy sources are essentially joined together to ensure the maximum possible energy efficiency and minimum emissions. The technical and economic assessment of the systems is conducted considering some operating parameters such as weather conditions and characteristics of the energy demand and vessel route. Finally, these systems improve the efficiency of renewable energies and reduce carbon dioxide emissions by optimizing ship performance in real-world conditions.

As depicted in Figure 1 below, is an integrated diagram that exhibits the complex interplay of economic, environment, technical, and regulatory aspects that interconnect the key factors influencing renewable energy development. This conceptualization gives a foundation for systematic analysis of factors that govern both the efficiency and sustainability of renewable energy in the maritime sector. It shows how investment, technological innovation, market demand, regulatory framework, and environmental considerations interrelate and emphasize the coordination between private sector investment and public programs.

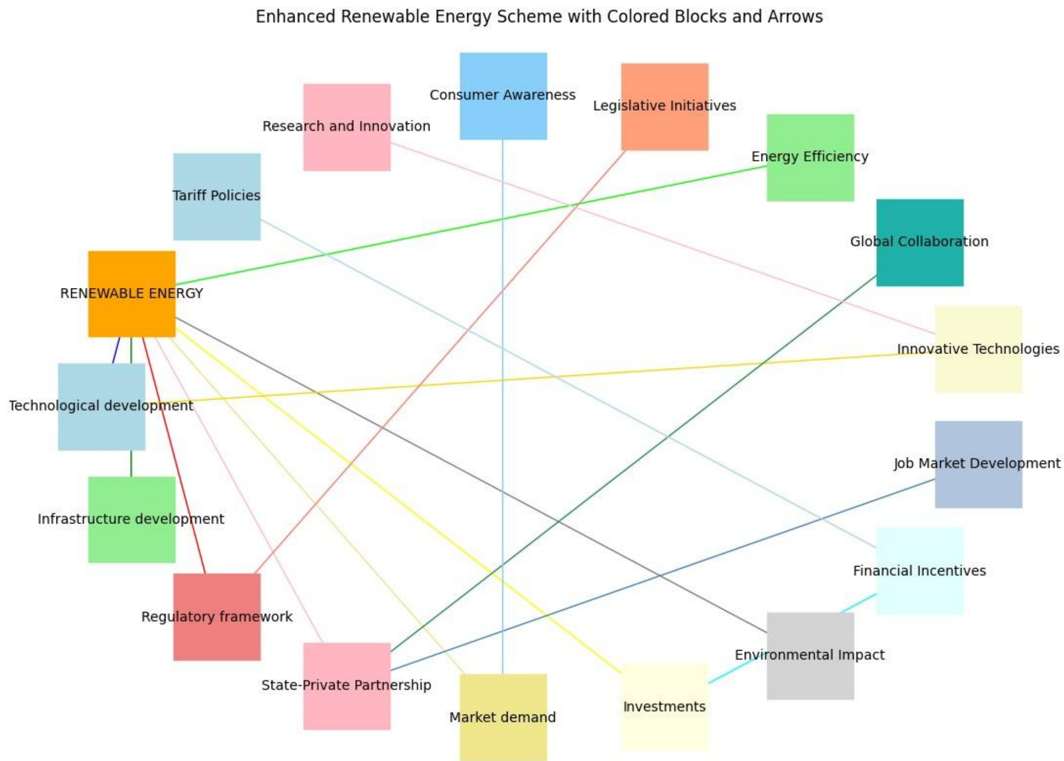

Fig. 1. Prerequisites for the development of renewable energy in maritime transport

The shipping industry would feature prominently in the future scenario of renewable maritime energy. The emphasis on developing and optimizing these technologies for maritime applications is necessary to diminish the dependencies of this sector on fossil fuels. Wind energy conversion service would be involved, as wind turbines would be installed on and around offshore locations. Solar panels may also be erected on floating platforms. Modern carbon capture systems to lessen emissions from ships may also be installed along the coasts, depending on the site. Thus, also enabling the establishment of renewable energy projects requires the enactment of a strong regulatory framework with incentives for renewable energy, carbon pricing, and higher emission standards.

Equally important is the cooperation between the public and private sectors. Public-private partnerships mobilize capital; promote knowledge-sharing and set a pace of large-scale deployment of renewable energy technology in the maritime transport sector. However, increasing demand for clean energy from shipping companies and rising consumer preference for green shipping services will ensure that the sector adopts greener practices. Increased investment in research & development and infrastructure is required now to speed up the process of adopting these technologies and truly making maritime transportation sustainable.

If these challenges are addressed in a multi-pronged way by acting on technology, infrastructure, regulatory and legal frameworks, and demand markets, the maritime industry can have a giving casting in the global ambition to reduce greenhouse gas emissions.

The following sections analyze the potential of wind power, solar power, and carbon capture systems in reducing emissions, increasing energy efficiency, and promoting sustainable development to offshore operations. Under the two operating conditions, energy efficiency of the integrated systems will be simulated so as to determine the most energy-efficient configurations to minimize energy consumption and emissions.

The energy systems of vessels were analyzed using an optimization model based on energy balance equations. The calculation of performance for the systems was considered under wind speed and solar radiation levels; whereas the modeling process adopted average annual climatic conditions for typical sea route to ensure realistic operational scenarios.

2.1. Wind energy

Wind energy has the potential to become an effective power source for ships seeking to reduce their dependence on fossil fuels and lower their emissions. One possible approach is to install wind turbines on board. They can partially cover the needs of auxiliary systems or reduce the load on the main engines.

The operation of such turbines depends on a number of factors: wind strength, direction, speed and course of the ship itself. The angle at which the wind hits the turbine also plays an important role, which determines how much energy it can generate. The total energy produced significantly by the turbine's size, the of its design, the wind speed. To determine the potential power, an equation based on Betz's law is commonly applied, as it represents the maximum energy that can be extracted from the airflow (1).

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot V_r^3 \cdot C_p , \tag{1}$$

where: P - power output (W), ρ - air density (typically 1.225 kg/m³), A - swept area of the turbine blades (m²), V_r - relative wind speed (m/s), C_p - power coefficient (maximum 0.593, practical value ~0.4).

The relative wind speed is a key factor, as it is affected by both the ship's speed and the angle between the ship's heading and the wind direction. The relative wind speed can be calculated using (2):

$$V_r = V - V_s \cdot \cos(\theta) \quad , \tag{2}$$

where: V - wind speed (m/s), V_s - ship speed (m/s), θ - angle between the ship's heading and the wind direction (in radians).

Above formula ensures that the wind turbine captures the effective wind energy available, accounting for both the ship's motion and wind direction.

As the wind turbine generates power, there are mechanical losses due to friction and drag, which reduce the overall efficiency of the system. These losses can be estimated using the following equation (3):

$$L_{\text{drag}} = k_{\text{drag}} \cdot V_r^3 \, , \tag{3}$$

where L_{drag} - mechanical losses, k_{drag} - drag coefficient, V_r - relative wind speed (m/s).

The drag coefficient k_{drag} typically depends on the design and materials of the wind turbine, as well as the specific operating conditions.

After accounting for mechanical losses and the efficiency of the energy storage system (battery efficiency), the net power available for use is given by the equation (4):

$$P_{\text{net}} = \left(\frac{1}{2} \cdot \rho \cdot A \cdot V_r^3 \cdot C_p \cdot \eta_{\text{battery}} \right) - L_{\text{drag}} \, , \tag{4}$$

where η_{battery} - efficiency of the battery storage system (typically 0.85), L_{drag} - mechanical losses.

The above formula allows determining the total useful power generated by the wind turbine, considering the energy lost during storage and conversion as well as the mechanical inefficiency of the system.

Influence of sea conditions

Wind speed and vessel speed depend on geographic location and meteorological conditions, which necessitate taking these factors into account when designing and implementing wind energy systems on board ships. The relative wind speed (V_r) in combination with the vessel's performance is a determining factor in optimizing the wind turbine configuration. In addition, the wind direction plays an important role: the highest energy harvesting efficiency is provided by headwind or tailwind conditions, when the turbine is able to generate the maximum amount of energy.

Energy storage and efficiency

When energy generation from wind turbines exceeds demand, the electric power can be stored in batteries or other storage modules installed on board the vessel and then be used later. The actual amount of energy stored is affected by the performance of the battery system, which normally refers to the efficiency coefficient of the charging process (η_{battery}). The so-called combined installation of wind and other green energy systems-mainly solar-coupled with efficient energy storage systems consequently allows the onboard generation of energy to be optimized and greenhouse gas emissions to be reduced.

Wind power therefore offers a possible strategy for the offshore maritime sector to reduce its dependence on fossil fuels and, thus, its environmental imprint. Having made use of wind resources, the better ships are placed to do this and therefore depends upon the spatial configuration and engineering design of the wind turbines, advanced energy storage, and intelligent control machinery. Future research and development will likely focus primarily on maximizing turbine efficiency, minimizing the losses of mechanical energy, and achieving the integration of wind with other renewable energy systems toward sustainable maritime operations.

The complexity of describing the process of wind power generation aboard ships comes from having to understand the many interacting factors. Relative wind speeds depend on vessel speed and angle between the heading of a vessel and the wind, which causes power generation to change greatly in efficiency. Mechanical losses caused by drag and friction are represented in the model by drag coefficient, simulating the real inefficiency of energy transformation. Battery efficiency is also very important: turbine-generated power is not stored completely; during charging, some part is lost. The corresponding graph plots several curves for different vessel speeds and wind angles, providing a comprehensive view of how each parameter affects the net power output. The net power output represents the total usable energy after accounting for mechanical losses and storage inefficiencies (Figure 2).

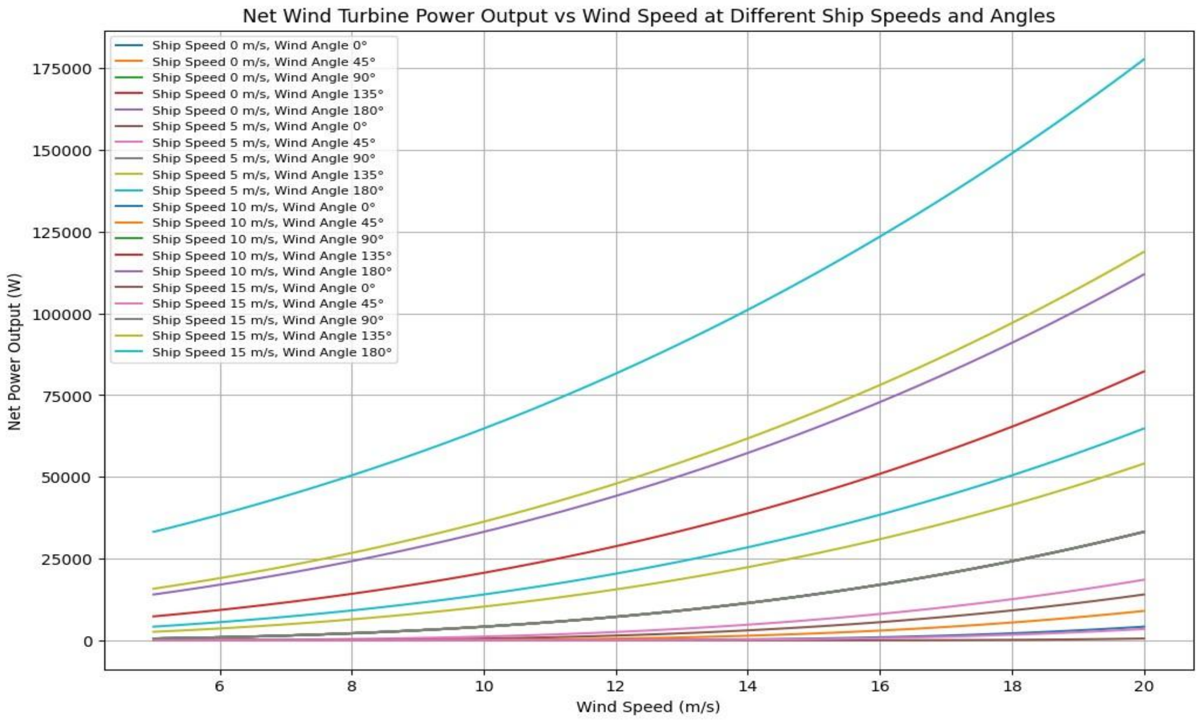

Fig. 2. Effect of ship speed and wind angle on wind turbine power output

The given graphical representation explains the performance of wind power systems under various operating conditions. From this representation, it can be seen that power output varies with wind speed and also if there is any change in ship speed or wind angle. By exposing such dynamics, the diagram emphasizes the need to provide optimum conditions to the wind turbines so that all may be realized in offshore conditions for higher power generation and lesser losses. Having knowledge of the interaction between these parameters allows for further optimization of the system, thus enabling efficient and sustainable use of the wind energy on ships. This very advanced model would have to be studied in depth to understand the performance of wind energy systems well and to make better choices towards energy efficiency and lower emissions.

Although wind energy forms a good part of energy mix used for a maritime vessel, its intermittency requires incorporation of alternate renewable energy sources. In the next section, we shall explore the possibilities of solar energy working alongside wind power so as to institute a more stable and efficient energy grid.

2.2. Solar energy

Solar energy is a very valuable resource for maritime transportation, providing a clean and renewable energy source that can power auxiliary systems and potentially contribute to propulsion. The efficiency of solar power systems on ships is primarily determined by the area available for photovoltaic panel (PV) installation and the technology used in the solar panels. Modern solar panels have an efficiency of around 20%, although this can vary depending on environmental factors such as the angle of incidence of the sun's rays and geographical location.

The amount of solar energy that can be captured by the ship's solar panels is E_{solar} is calculated by the equation (5):

$$E_{\text{solar}} = I_{\text{solar}} \times A_{\text{panel}} \times \eta_{\text{panel}}, \tag{5}$$

where I_{solar} - solar irradiance (W/m²), A_{panel} - surface area of the solar panels (m²), η_{panel} - efficiency of the solar panels (typically 20%).

In the marine environment, the intermissions are caused by the vessel movements coupled with the changing climatic conditions. The solar panel stays specific in tilt angles during the energy collection for an immense energy output. The optimum solar panel tilt angle will vary with the latitude of the vessel, which can be changed dynamically with the motion of the vessel across different geographical regions.

Since the solar energy is intermittent, excess energy produced by the solar panels is stored by the batteries on board for use at a later time. The better is the efficiency of the battery storage system, the lesser are the energy losses incurred during the processes of charging and discharging. On the other hand, the net energy defined in (6) is more commonly used to describe the energy E_{stored} that is actually stored by the batteries:

$$E_{\text{stored}} = E_{\text{solar}} \times \eta_{\text{battery}}, \tag{6}$$

where η_{battery} - battery storage efficiency, typically around 85%.

Batteries onboard ships need to be large enough to store sufficient energy for periods when solar irradiance is low, such as at night or during cloudy conditions. The storage capacity of the battery system also determines how long the ship can operate using stored solar energy.

The contribution of energy from solar panels and the efficiency of batteries for energy storage are summarized in Table 1:

Tab. 1

Efficiency of batteries for energy storage

Component	Efficiency	Description
Solar Panels	20%	Efficiency of solar panels in converting sunlight to electricity
Battery Storage System	85%	Efficiency of energy storage, including charge and discharge
Propulsion System	80%	Efficiency of the propulsion system in utilizing stored energy for ship movement

Suppose that 200 m² of solar panels are installed on a ship and the average solar irradiance is 600 W/m². With an efficiency factor of 20%, the amount of solar energy produced will be:

$$E_{solar} = 600 \times 200 \times 0.20 = 24{,}000\ \ W\ (24kW);$$

With an 85% battery efficiency, the energy stored in the batteries is:

$$E_{stored} = 24{,}000 \times 0.85 = 20{,}400\ W\ (20.4\ kW).$$

This stored energy can be used to power the ship's systems or contribute to propulsion. If the ship's propulsion system requires 5 MW for operation, the energy stored would contribute for a limited time, emphasizing the importance of hybrid systems.

Energy System Integration

Solar power may be combined with other renewable sources like wind turbines to form hybrid systems that maximize energy production and reduce gasoline consumption. A solar system combined with efficient batteries and intelligent energy distribution via control systems may reduce ship emissions and costs.

Hybrid systems allow energy balancing: excess energy generated in periods of high solar activity can be stored and used when solar energy is unavailable. Thus, the system ensures continuous supply of clean energy to ship systems, thus improving overall energy efficiency and sustainability.

For a more detailed illustration, gel batteries offer a number of benefits, which include, but are not limited to bias with flooded lead-acid, or AGM batteries, and consequently, stand as the almost perfect battery solution for use in ships. Moreover, these batteries do not require maintenance; they are sealed systems and cannot spill acid or release gases, which constitute strong safety features, especially for confined spaces where ventilation options are limited. Another feature - the gel battery - has significantly long life and high resistance against vibration and shock; this becomes important in marine environments, known for their built-in harshness. Gel batteries have a high cycle life which means they can be charged and discharged many times without losing capacity, making them ideal for use in maritime transport where charge cycling is frequent. Besides, gel batteries perform well over a wide temperature range and resist deep discharges, increasing their versatility and reliability in maritime applications and provide ships with an efficient and reliable way of storing energy, improving the safety and operational efficiency of ships.

To maximize the efficiency of solar panels (SBs), it is important to position them as directly to the sun as possible. For optimal energy absorption, the SBs should be positioned perpendicular to the sun's rays, but the angle of incidence of the sun's rays depends on the time of day, the season, and the movement of the vessel. Stationary solar panels, often placed on high points of the vessel, do not always receive optimal sunlight. Therefore, determining the optimal tilt angle β, usually equal to the latitude of the ship's location, is necessary to maximize the capture of solar radiation (SR) by the panels (Figure 3).

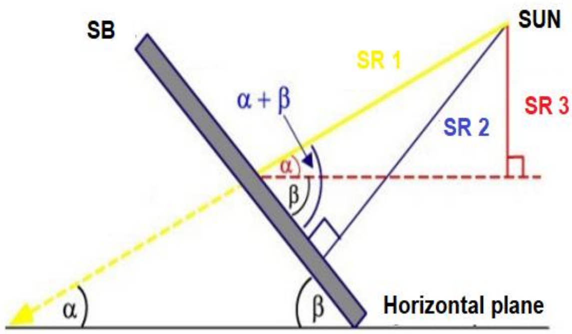

Fig. 3. Solar module angle of inclination

Solar energy is a reliable and renewable way to lessen the carbon footprint of maritime operations. It is capable of integrating solar panels with high-efficiency battery systems and coordinating them with other renewable energy sources, such as wind power, to optimize use and diminish dependence on fossil fuel application. Solar panel technology, battery storage, and hybrid system integration will further be developed to address the sustainable industry of maritime transportation.

2.3. Carbon capture, use and storage (CCUS) technologies

These sectors with high carbon dependence are more and more using CCUS technologies in this fast-paced green evolution. These high-tech methods use sea resources to trap and then effectively handle the huge CO_2 emissions from industry. The shift stands crucial to decarbonize the planet and hold climate change at bay.

An integral aspect of this transition is the direct air capture technology that eradicates CO_2 directly from the atmosphere. This method promotes other efforts to cut down industrial emissions and stands as a prime example of the sustainability pathway.

CO_2-carrying ships will pose a great breakthrough in the future. These modern ships equipped with systems to store carbon in ships shall then carry liquefied CO_2 to designated discharge places onshore or offshore. From there, further use of the captured CO_2 could be carried out, or it could be injected into drilled oil and gas wells meant for permanent CO_2 injection.

This stratum and strategy, on the force side, address present-day emissions from industrial operations. On the other hand, CO_2 is being ripped out of the atmosphere. By using existing carbon storage infrastructure and the latest road and ferry network, these industrial setups are definitely headed for a more sustainable and green future (Fig. 4).

CCUS technologies presented themselves as major technologies in mitigating GHG emission in the maritime world. By capturing carbon dioxide emission directly from the exhaust gas of the ship, it can limit in a great way the negative effects of conventional marine fuels.

This section thus will discuss in depth the working of CCUS on the ships, which includes the CO_2 capture process, energy requirements of the process, and problems faced in integration. Several graphs are given to demonstrate the main dependencies and the performance of the system.

The CCUS system on ships typically operates by capturing CO_2 from the exhaust gases of marine engines or boilers using a solvent-based absorption process. The captured CO_2 is then separated from the solvent, compressed, and stored in liquefied form in onboard tanks. A standard CCUS system consists of the following components:

- absorber unit: captures CO_2 using a solvent (usually an amine-based solution);
- regeneration unit: separates CO_2 from the solvent for further compression;
- compressor: compresses CO_2 to a liquefied state for storage;
- storage tanks: stores liquefied CO_2 until it can be offloaded at port facilities.

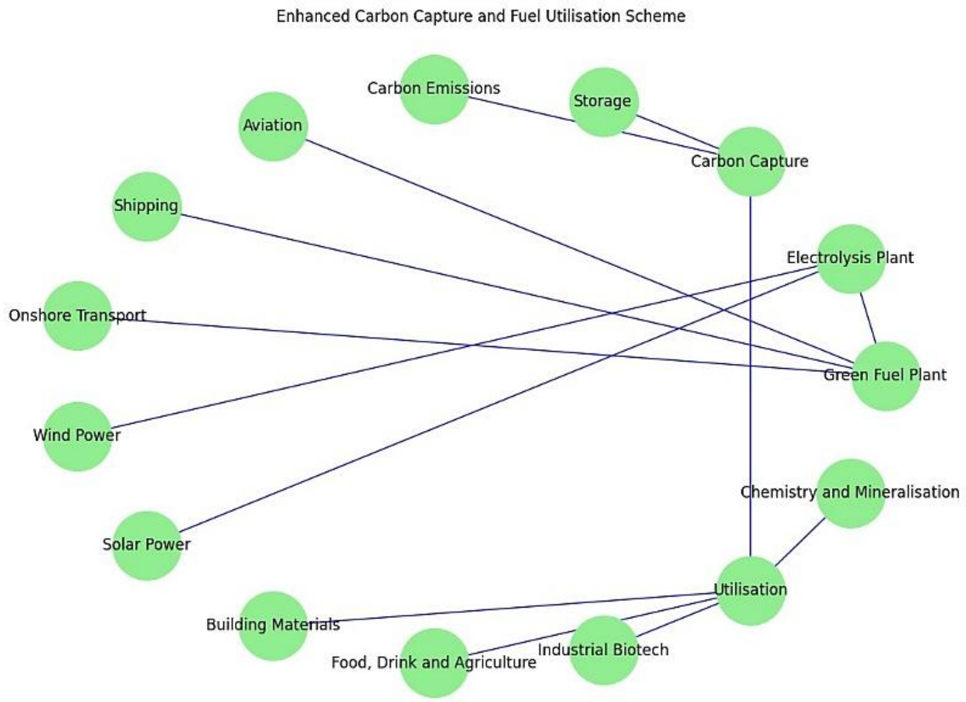

Fig. 4. Enhanced carbon capture and fuel utilization scheme

The quantity of CO_2 captured (M_{capture}) depends on several factors, including the ship's power output, the CO_2 emission factor of the fuel, and the efficiency of the CCUS system. The formula for calculating the amount of captured CO_2 using (7):

$$M_{\text{capture}} = \frac{F_{CO2} \times C_{\text{eff}}}{P_{\text{ship}}}, \tag{7}$$

where FCO_2 - CO_2 emission factor (g/kWh), C_{eff} - capture efficiency (typically 70-90%), P_{ship} - ship's power output (kW).

The above equation expresses the way the capture rate depends on demanding capacity and system efficiency.

Figure 5 shows the quantities of CO_2 captured from the time period for different amounts of power produced by the ship. A kind of interpretation represented is of the relationship existing between the power levels at which the ship operates and the total amount of CO_2 captured and, hence, giving an idea of the performance of CCUS systems under different operational conditions. The graph consists of a series of lines distinguished by a particular ship power and CO_2 capture efficiency combination. Therefore, it becomes intuitive to see how different power outputs and capture efficiencies affect the total amount of CO_2 captured through time.

Energy Consumption and System Efficiency

One of the primary challenges of CCUS technology is the energy required to run the system. The "parasitic load" refers to the energy consumed by the CCUS system, typically 10-15% of the ship's total power output. This energy is used for processes such as CO_2 absorption, compression, and storage, and it reduces the net available power for ship propulsion. The energy demand of the CCUS system can be calculated using (8):

$$E_{\text{CCUS}} = P_{\text{ship}} \times \eta_{\text{CCUS}} \, E \quad , \tag{8}$$

where E_{CCUS} - energy consumed by the CCUS system (kW), η_{CCUS} - percentage of energy required to operate the system (typically 10-15%).

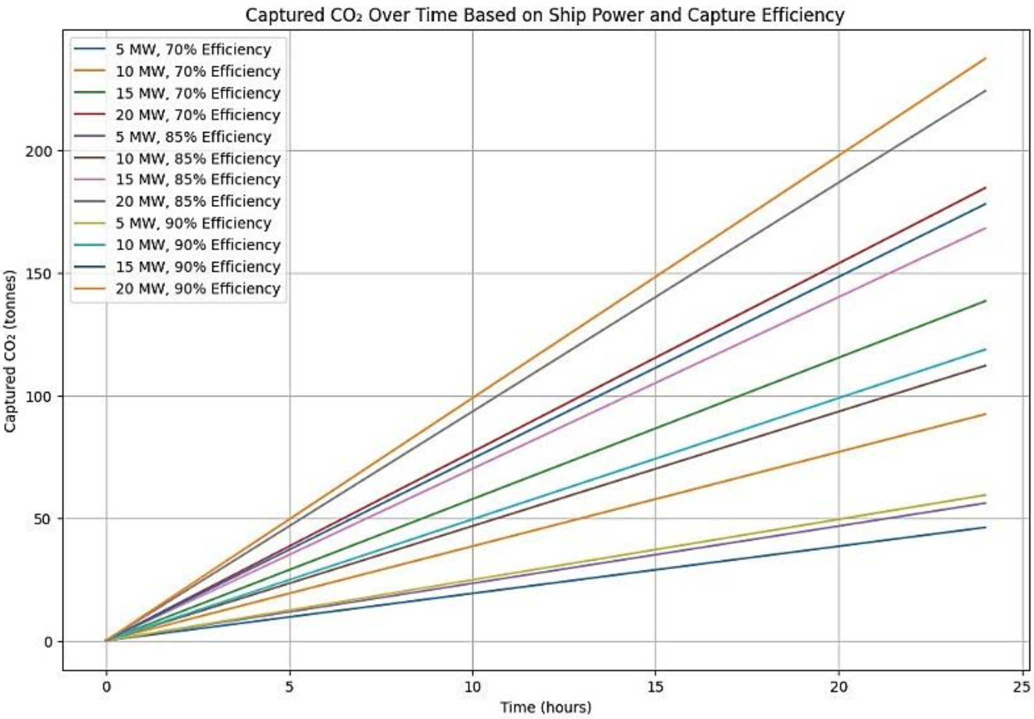

Fig. 5. CO_2 captured over time at different ship power outputs

The graph on Figure 6 shows how varying energy consumption percentages for CCUS (10%, 12%, and 15%) affect the total ship power and demonstrates how much power is diverted from propulsion to the CCUS system, illustrating the balance between emission reduction and operational efficiency.

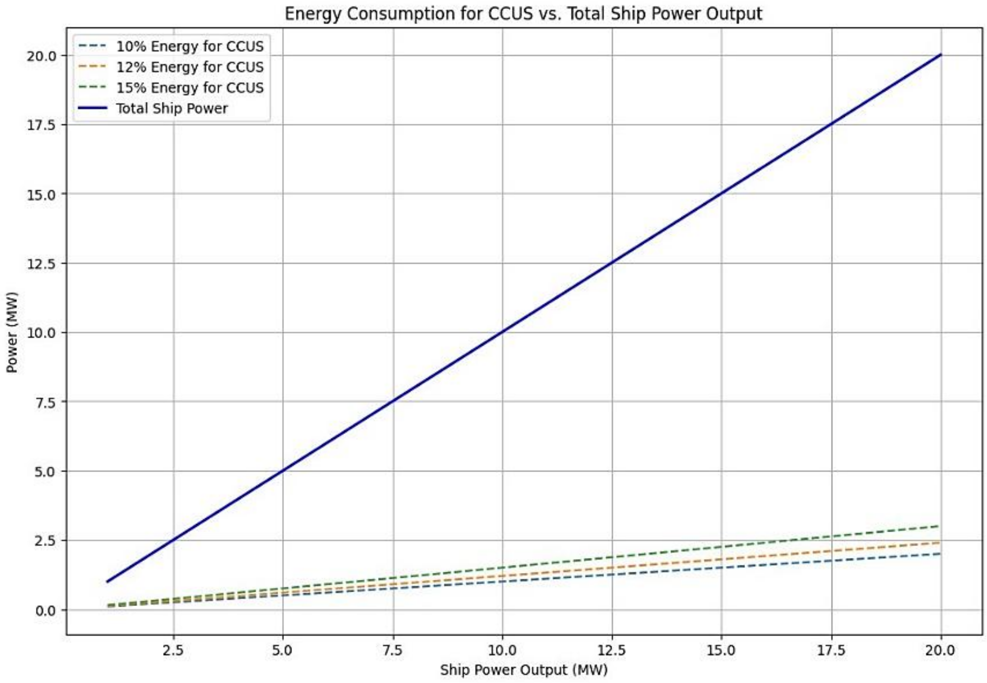

Fig. 6. Energy consumption for CCUS compared to ship power.

System Optimization and Integration

For CCUS to be successfully implemented on ships, it must be integrated into the overall energy management system of the vessel. Energy storage and distribution systems need to account for the additional energy demands of the CCUS system. Additionally, the capacity and design of CO_2 storage tanks onboard the ship must be optimized to minimize the impact on cargo capacity. The integration of CCUS with renewable energy sources, such as wind and solar power, could also improve overall system efficiency, allowing the ship to capture and store CO_2 while utilizing green energy for propulsion.

Figure 7 provides a flowchart of the CCUS process on a ship, detailing each stage from CO_2 capture to storage and eventual offloading at port facilities. This diagram demonstrates the key components and processes involved in capturing and storing CO_2 onboard ships.

The scheme above presents a sequence scheme explaining the capture of carbon dioxide (generation), purification, liquefaction, and storage of CO_2 on-board a ship. Flue gases are treated (conditioning: cooling and dehumidification) before entering the absorber, in which CO_2 reacts with a special solvent. Afterwards the solvent is treated thermally in a regeneration step under the solvent to obtain purified dry CO_2 at reduced pressure and temperature conditions. Subsequently, the gas is compressed and liquefied in the Monstag module for storage in cryogenic tanks. From there, the liquefied CO_2 can be transported to land-based treatment installations or specialized shuttle ships for utilization or storage.

Implementing CCUS technologies onto ships opens enormous possibilities for the reduction of maritime carbon footprints. These systems can capture almost (about 90% of) the CO_2 emissions, thus drastically limiting the environmental destruction converted by fossil fuel consumption. Further improvements in CO_2 capture and storage systems and their integration with energy could open gates for shipping becoming greener by means of CCUS.

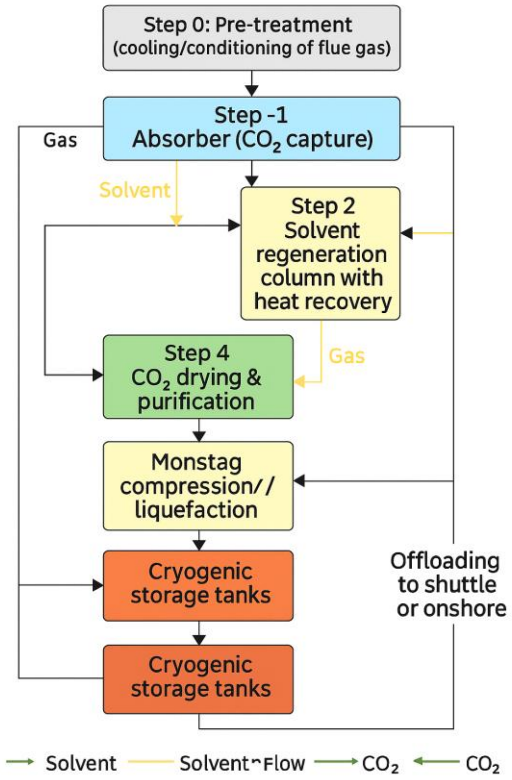

Fig. 7. Flowchart of the CCUS system onboard

Hybrid options combining CCUS with other renewable energy sources will make maritime transportation even more sustainable. As shown in Figure 5, producing carbon from a capture process and using it along with wind and solar energy would improve overall system performance, hence leading to lower emissions and greater energy savings.

CCUS technology offers the potential for immediate carbon reduction in the maritime industry and needs to be optimized concerning energy efficiency, space use, and integration with renewable energy sources to attain greatest benefits. The depictions seen from the graphs reveal the complicated landscape of ship-based CCUS system operation and provide insight into the improvements needed towards balancing energy use with carbon capture efficiency. With the maritime industry undergoing evolution, the importance of CCUS for shipping decarbonization will only grow.

Simulation results confirmed that wind and solar power systems integrated with carbon capture technologies significantly reduce ship emissions. This confirms operational sustainability throughout different climatic conditions along major shipping routes.

2.4. Additional perspectives on the use of renewable energy sources in shipping

Renewable energy usage in shipping is on the rise, in association with worldwide goals like the International Maritime Organization's (IMO) goal of a 50% reduction in greenhouse gases (GHGs) from shipping by 2050 compared to 2008 levels. There is a whole range of renewable energy technology methods, each with inherent pros and cons.

Wave and tidal energy converters, able to convert electricity out of the movement in ocean waves and tidal currents, are one of the prospective technologies. These systems are particularly suited to coastal regions with strong tidal currents, presenting a renewable source of power that can be effectively incorporated into maritime operations.

Another viable option of renewable energy for ships is biofuel. Biofuels derived from organic-materials, usually algae, wastes such as waste oil or agricultural waste, can be blended with conventional marine fuel or used independently in special engines. This option can conveniently make marine engines nearly carbon-neutral alternatives.

Hydrogen is another promising clean energy source poised to transform shipping. Such hydrogen fuel cells convert hydrogen to electricity rendering it a clean source of green power for propulsion and on-board power systems. Fuel cells emit no pollutants whatsoever except for water, are very efficient; nevertheless, a greater extent of adoption is hindered by infrastructural issues such as hydrogen production on large scale, storage, and transportation, all of which are still a big question mark.

Another innovation in marine energy is represented by marine fuel cells. These devices, which are electrochemical in nature, convert hydrogen and oxygen into electricity, making them a zero-emission energy source. Although their efficiency significantly surpasses that of traditional marine engines, fuel cells come with very high capital costs.

3. RESULTS AND DISCUSSION

Using new energy sources for maritime transport creates an existence-changing opportunity with environmental and economic potentials. Opposed to global concepts of reducing carbon dioxide emissions, this change of new energy sources-alike: wind, solar, and hydrogen-can add towards climate change. Also, considering that the use of renewable energy also considerably limits emissions, in the long haul, they must also be cheaper as compared to the fossil fuels. Hence, economic gains enable an enhancement to the competitiveness of shipping companies by boosting operating revenues while ensuring the companies' financial sustainability in a volatile energy market.

Energy security gets enhanced because of renewable energy applications by reducing fossil fuel dependence that is subject to price fluctuations and also geopolitical risks. The other critical free impact remains air quality improvement since emissions from renewable energy systems are negligible or none, reducing the threat to health and environment posed by fossil fuel combustion. The results show the possibility to use renewable energy in transforming shipping into a more sustainable and resilient industry capable of facing the global challenges of today (Fig. 8).

A crucial step toward this transition is implementing a structured algorithm for integrating renewable energy into maritime systems, as shown in Fig. 9.

The very first step involves analyzing the energy demand from maritime transportation activities, including shipping and fishing. Such assessment informs the choice of the most appropriate renewable energy source, which can be wind, solar, tidal, or wave energy. Next comes a feasibility study that would look into the viability of each identified source, considering availability, impact, cost, reliability, and environmental effects. The most suitable renewable energy system, based on an analysis of the above factors, would be chosen and developed; the infrastructure would then be installed.

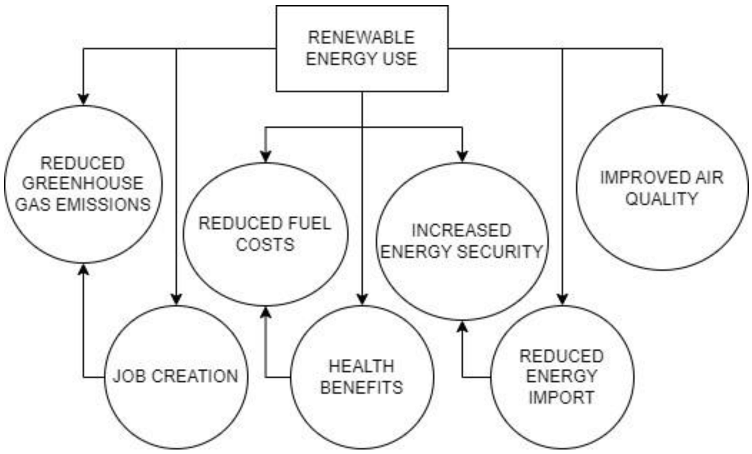

Fig. 8. Advantages of renewable energy in maritime transport

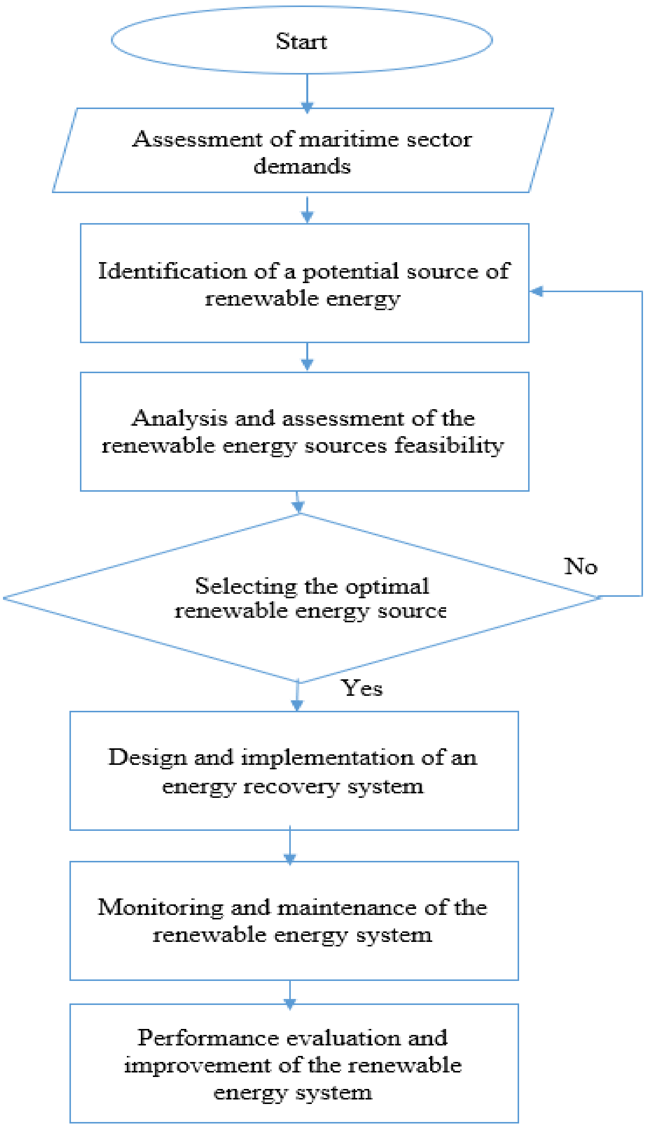

Fig. 9. Algorithm for renewable energy implementation in maritime transport

In ensuring that the system runs at optimum efficiency, alongside maintenance, monitoring would be made continuously. Periodic assessments will then check whether the system meets energy needs efficiently. Modifications can be made as a result to improve the efficiency and sustainability of the system. Promotion of renewable energy within the maritime sectors will serve even to tilt the stakeholders in the direction of greener practices.

Maritime decarbonization, hence, is a critical issue. In 2023, the IEA reiterated. That the shipping industry needed to improve energy efficiency by at least 4% per year to stay on track to zero emissions by 2030. This, therefore, means that it will call for not just technology but also a radical transformation in terms of sustainable business practices.

The diagram (Figure 10) shows a detailed representation of how the different renewable energy inputs interact in the ships' energy system. The model incorporates wind turbines for propulsion, photovoltaic panels for auxiliary power, and CCUS units for abatement. The share of each energy source is adjusted dynamically based on real-time operational data.

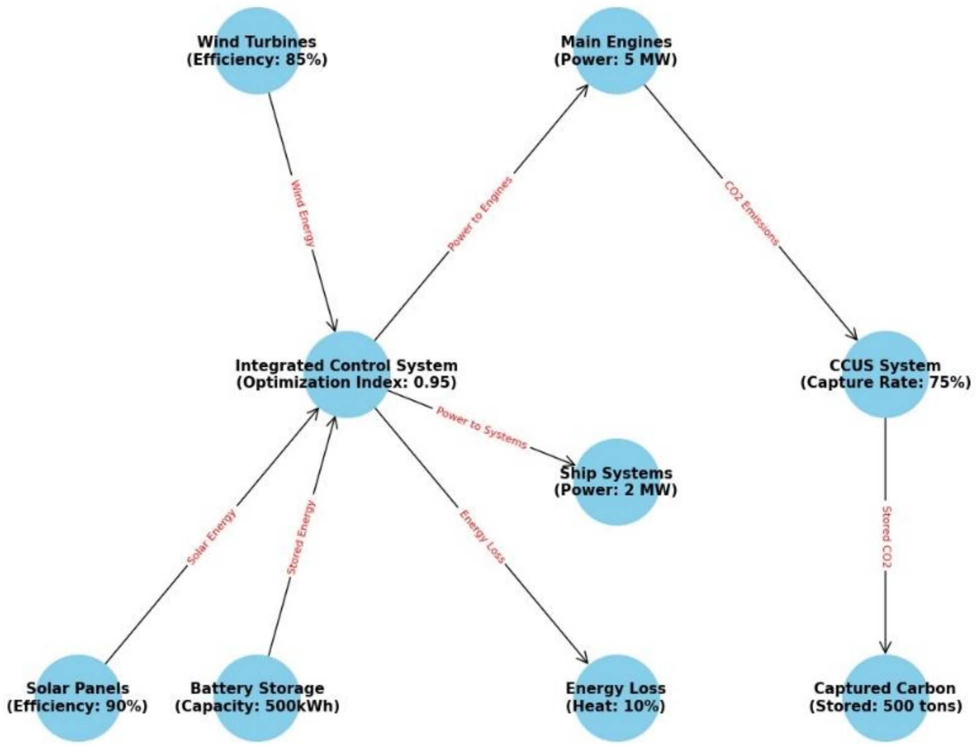

Fig. 10. Integration of renewable energy sources and energy flow management on board ships

As illustrated in Figure 10, the CCUS system's efficiency improves significantly when integrated with renewable energy sources. This integration allows for optimized energy recovery and reduced carbon emissions, which is essential for sustainable maritime operations.

An energy management system on board the ship involves wind turbines at 85% efficiency, solar panels at 90% efficiency, and batteries with a 500-kWh storage capacity for storing excess energy. The components are tied together by an integrated control system with an optimization index of 0.95 that distributes power between the main engines (5 MW) and the ship's systems (2 MW). Going green, a carbon capture and storage machinery captures some 75% of the CO_2 emissions from engine storage of carbon dioxide up to 500 tons. Approximately 10 percent of energy losses are considered due to heat dissipation.

It may be reasonable to assume that the creation of an all-inclusive ecosystem whereby new technologies, including renewable energy systems, are fully integrated in order to establish a sustainable and efficient industry constitutes the future of maritime transportation. The companies that implement these integrated solutions may, in turn, benefit from an enhanced brand image, thus attracting environmentally aware consumers. Nevertheless, our journey is impeded by some key challenges such as high up-front costs, our unacceptable infrastructure, and various technical barriers. Overcoming these barriers, the maritime sector does have the potential to transit toward a sustainable, low-emission future set within appropriate policies and investments.

The maritime transport systems are geared to be substantially altered in the future by integrating renewable energy technologies and other state-of-the-art systems to reduce emissions and improve efficiency. The research evidently demonstrates deployment of renewable energy sources such as wind, solar, and CCUS technologies as a viable means of decarbonizing the maritime sector. The synergy of these technologies with improved energy storage and hybrid propulsion systems would enable the maritime industry to make a noteworthy impact in greenhouse gas emission cuts while ensuring economic sustainability.

4. CONCLUSIONS

With the advantages presented in this paper, one acknowledges that integrating renewable energy in maritime transport bears multiple long-term cost benefits, energy security, and environmental enhancements. Simulation and analysis reveal renewable energy systems as an efficient path to reducing fossil fuel dependence, decreasing price fluctuations, and improving air quality by lowering emissions. Moreover, renewable energy aligns with global climate agenda and supports the maritime industry in realizing reduction targets launched by the International Maritime Organization (IMO).

The study indicates that a hybrid propulsion comprising wind, solar, and CCUS technologies can usher in a great assessment of reductions in the environmental impacts of maritime transport. Hence, by surmounting those associated with high costs and limited options for energy storage, these systems appear to represent a pathway for decarbonization. Future works should be geared toward optimizing system components concerning different conditions at sea and the improvement of economic viability for widespread deployment.

On the other hand, several impediments must be overcome for it to be commercially deployed. Among others, these include the prohibitively high initial capital costs of installing renewable energy systems, the lack of infrastructure required for the alternative operation, and the technical complexities coupled with integrating these systems into existing maritime crafts. Further research toward advanced energy storage and CCUS technology will be essential in intensifying energy utilization and performance within the backdrop of evolving maritime conditions.

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