Renewable Energy Storage and Sustainable Design of Hybrid-Powered Ships: A Case Study

Authors: Zhixiong Li, Atilla Incecik, Andrzej Cichon, Grzegorz Królczyk, Mingyang Huang, Wei He, Zhixiong Li

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Abstract

The shipping industry’ s rapidly escalating energy consumption has imposed a substantial burden on the marine environment. Increasing renewable energy utilization aboard vessels represents a prevailing trend for enhancing maritime sustainability. This article provides a comprehensive review of current developments and applications of solar energy, wind energy, and fuel cell technologies within marine power systems. Furthermore, to investigate the benefits of sustainable ship design, a hybrid photovoltaic (PV), wind, and fuel cell energy system was, for the first time, established for an oil tanker, enabling comprehensive economic and environmental analyses of the hybrid configuration. The analysis results demonstrate that the optimal hybrid energy system can reduce CO2 emissions by 151,467 kg and supply 2.92% of the ship’ s annual electricity demand.

Full Text

Preamble

Mingyang Huang
School of Engineering, Ocean University of China
Tsingtao 266001, China
Email: hhhhmyc@stu.ouc.edu.cn

Wei He
College of Physics and Electronic Information Engineering, Minjiang University
Fuzhou 350108, China
Email: hewei11@mju.edu.cn

Atilla Incecik
Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde

Glasgow, Scotland G1 1XQ, United Kingdom
Email: atilla.incecik@strath.ac.uk

Andrzej Cichon
Department of Mechanical Engineering, Opole University of Technology
Opole 45758, Poland
Email: a.cichon@po.opole.pl

Grzegorz Królczyk, Zhixiong Li*
Department of Manufacturing Engineering and Automation Products, Opole University of Technology
Opole 45758, Poland
Email: g.krolczyk@po.opole.pl & zhixiong.li@yonsei.ac.kr
*Corresponding Author

Abstract

With rapidly increasing energy consumption, the shipping industry has imposed a huge burden on the marine environment. Increasing the use of renewable energy on ships represents a general trend for improving sustainability. This article summarizes current developments and applications of solar energy, wind energy, and fuel cells in ship power systems. Furthermore, to investigate the advantages of sustainable ship design, we established—for the first time—a hybrid PV, wind, and fuel cell energy system for an oil tanker and performed economic and environmental analyses. The results demonstrate that the optimal hybrid energy system can reduce CO_2 emissions by 151,467 kg and provide 2.92% of electricity for the ship grid annually.

Keywords: Renewable energy; Energy storage technology; Ship power sustainability; Economic and environmental analysis

1. Introduction

In contemporary society, various industries require increasing amounts of energy to meet growing demands, yet non-renewable energy consumption causes significant environmental harm [?]. Large-scale use of non-renewable energy will inevitably lead to future resource shortages and give rise to a series of international conflicts and problems. Reducing dependence on fossil fuels through vigorous expansion of renewable energy usage is an urgent task of great importance to humanity' s future. Countries worldwide are gradually recognizing this problem and making substantial efforts toward developing and utilizing renewable energy [?]. According to IRENA data, we currently have more than 584 GW of solar installation capacity and 622 GW of wind power installed, with research and utilization of renewable energy advancing rapidly. While renewable energy construction and operation costs are lower on land—where most projects are located—the oceans comprise more than 70 percent of Earth' s surface and hold incredible untapped potential for developing renewable resources such as solar and wind. Nevertheless, marine engineering platforms such as ships and offshore platforms still rely primarily on non-renewable energy, regardless of the ocean’ s advantages [?]. Renewable energy utilization technologies such as solar energy, offshore wind power, and fuel cells are advancing rapidly, making the promotion and application of marine renewable energy—especially on ships—an inevitable trend [?].

As the primary mode of global trade transportation, shipping causes inevitably huge pollution, although the MARPOL Convention imposes strict regulations on ship emissions [?]. Using renewable energy to replace fossil fuel represents the most effective method to fundamentally change this critical situation. Solar radiation constitutes the main energy source on Earth’ s surface, providing a whopping 1.73×10^{17} J of energy per second, which can supply substantial energy for ships with solar installations [?]. Offshore wind turbines have a long development history and are very suitable for powering fixed-position ports [?]. Using batteries to overcome the intermittent and unstable nature of solar and wind power is a common method. Excess electricity can be supplied to electrolyzers to produce hydrogen for fuel cells. All these renewable energy sources, combined with diesel generators, constitute the ship’ s electrical power system, making this hybrid renewable energy system environmentally friendly with significantly reduced emissions.

This article summarizes the general development of renewable energy technologies and their ocean applications, illustrating the feasibility of applying these technologies to ships and discussing economic benefits. The contributions and innovations of this review include: (1) for the first time, summarizing practical applications of clean energy for ships; and (2) performing economic analysis of a hybrid PV, wind, and fuel cell energy system to illustrate the potential of hybrid-powered ships.

2. Renewable Energy Applications

According to Renewable Capacity Statistics 2021, global renewable generation capacity reached 2,799 GW by the end of 2020 [?]. Solar and wind accounted for 25.5% (714 GW) and 26.1% (733 GW) respectively. Renewable generation capacity increased by 261 GW in 2020, representing a 10.3% growth compared with the previous year. Solar and wind energy increased by 127 GW and 111 GW respectively, leading capacity expansion with 91% of new capacity in 2020. Given this trend, solar and wind energy are mature technologies with great utilization prospects [?].

[Figure 1: see original paper] Renewable electricity generation and capacity growth

2.1 Solar Energy Applications

The manufacturing cost of solar panels has been drastically reduced over the last decade. With support from various policies, solar energy has been widely used, making solar photovoltaic (PV) one of the fastest-developing new energy technologies. According to IRENA data, solar PV capacity increased from 72 GW to 714 GW between 2011 and 2020 [?]. This rapid growth is closely related to substantial cost reductions. Currently, global PV utilization cost is generally lower than 0.2 USD/kWh and is expected to decrease further as the PV industry develops.

[Figure 2: see original paper] Install capacity and LCOE of PV

The solar radiation absorption efficiency of photovoltaic power generation is only about 15-20%. In comparison, solar thermal utilization has higher efficiency. In recent years, solar thermal utilization has become a hot research topic, with photovoltaic-thermal (PVT) systems attracting significant attention from scholars. Relevant concepts and experimental studies about PVT systems first appeared in the 1970s. After half a century of development, the system has gradually matured. PVT collects heat while generating electricity, reducing collector temperature and improving overall efficiency. Mainstream solar photovoltaic thermal systems fall into two categories: flat-plate PV/T and concentrator type PV/T. Normally, the working medium of PV/T systems is air or water, though some special systems use nanofluid, PCM, and refrigerant [?].

Research on experimental and simulation models of plate solar collectors has become very complete and advanced. Current research focuses primarily on using new materials to improve system efficiency [?], analyzing main structural factors and performance parameters affecting flat-panel PV/T system efficiency, and exploring the possibility of effectively integrating PV/T systems into hybrid energy systems [?]. Figure 3 shows the working principle of the flat-panel solar PV thermal system, which can be divided into liquid-type PV/T system, air-type PV/T system, and bi-fluid type PV/T system according to different working fluids [?]. The efficiency of air-type PV/T systems is lower than other types, but their structure is simplest and installation cost is lowest. Liquid PV/T systems have better heat transfer capacity, especially with phase change materials and nanofluids, but their structure is more complex and cost is higher. Bi-fluid type PV/T systems represent a compromise between the two. In general, each system has its own advantages and disadvantages, and selection must consider the application environment.

[Figure 3: see original paper] Flat-plate PV/T system

The principle of centralized PV/T systems is to enhance received solar radiation intensity through reflectors while reducing receiving area. This approach increases system efficiency while reducing costs. Figure 4 shows the working principle of the centralized PV/T system. The power generation efficiency of PV is improved by increasing radiation intensity, while the collector module absorbs concentrated light as well as large amounts of heat generated by the PV module during high-efficiency operation. High temperature negatively impacts PV and causes generation efficiency losses, making the heat collector module the core working component. Making the system run efficiently and safely at high temperature represents the main difficulty in its application. Centralized photovoltaic thermal systems can operate stably at 170°C [?], but further research is still needed.

[Figure 4: see original paper] Concentrator type PV/T system

Hydrogen is an expensive fuel due to high electrolysis production costs. As one of the most developed renewable energy sources, solar-powered hydrogen production is undoubtedly one of the most promising methods. Hydrogen production by solar energy mainly includes photoelectric solution, photovoltaic (PV), photoelectric chemistry, thermal chemistry, and artificial photosynthesis [?]. PV hydrogen production is one of the most economical methods. This technology has matured for application after about 50 years of development [?], with efficiency reaching 25% [?]. Moreover, unlike other solar energy utilization methods, PV hydrogen production eliminates disadvantages of fluctuations and intermittencies by transforming solar energy into a stable resource.

2.2 Wind Energy Applications

Wind power is one of the most readily available renewable energy sources, with around 20,000 GW available worldwide—nearly eight or nine times the current global total. Wind power is also one of the fastest-developing renewable energy sources. Under development of related research and promotion of new energy policies in various countries, wind power costs are decreasing while scale is increasing. Over the past two decades, installed wind power capacity has increased more than seventy-fold, growing by about 442 GW from 180 GW in 2010 to 622 GW in 2020. Actual electricity generation increased nearly fourfold from 342,831 GWh in 2010 to 1,262,914 GWh in 2019. Currently, wind power utilization cost in various countries is generally lower than 0.1 USD/kWh.

[Figure 5: see original paper] Installed capacity and electricity generation

Wind power generation technology has been widely used on both land and sea. Offshore turbines have great potential due to advantages of continuity, steadiness, high speed, large capacity, and distance from living quarters. As the main tool for wind energy utilization, wind turbines have a long development history. In March 2017, DONG Energy decommissioned the Vindeby offshore wind farm, the world' s first offshore wind farm installed in 1991 that operated for about 25 years. In 2009, the first large deep-water floating fan was built at the Hywind wind field in Norway, with 2.3 MW power at 220 meters depth. Currently, only the United Kingdom, Germany, Denmark, the Netherlands, and China have offshore wind farms with capacity exceeding 400 MW. Table 1 shows countries with the largest installed offshore wind power capacity in recent years. The largest offshore wind farm is Hornsea 1 in the UK, with 1,218 MW capacity and turbines rated from 3.6 to 8 MW [?].

Installed offshore wind power capacity (MW) [6]

Figure 6 shows the three main types of offshore wind turbines, divided into horizontal axis and vertical axis according to shaft type. The most widely used is the horizontal axis wind turbine (HAWT). The main rotor shaft and generator of HAWT (Fig 6a) are located at the turbine’ s top. HAWT must be angled toward wind direction, so it is always equipped with wind direction sensors to help adjust turbine orientation. Currently, the largest HAWT is the Haliade-X wind turbine, rated at up to 12 MW [?]. The main rotor axis of vertical axis wind turbine (VAWT) (Fig 6b) is perpendicular to wind direction. This structure allows the generator and other equipment to be placed at the turbine’ s base, reducing installation and maintenance difficulty while increasing system safety. VAWT has no wind direction requirements but is less efficient than HAWT and produces much less power at the same wind speed. The cross-axis wind turbine (CAWT) (Fig 6c) is actually an improvement of VAWT [?]. It combines strengths of HAWT and VAWT while overcoming their weaknesses. Like VAWT, CAWT occupies much less space than HAWT, and the blade swept area of CAWT is much larger than VAWT, yielding higher wind energy conversion rates [?]. CAWT remains in the exploratory stage and has a long way to go before practical application.

[Figure 6: see original paper] HAWT (a); VAWT (b) [33]; CAWT (c)

Offshore wind power generation is very important for reducing carbon dioxide emissions and improving the global environment. However, due to the nature of wind resources, wind power generation is not particularly stable, and excess wind power must be discarded during generation, resulting in wind resource waste [?]. Using wind power to produce hydrogen and increasing on-site consumption of wind power plants represents an important way to reduce wind curtailment [?]. This not only ensures safety and stability of wind power plants and power grids but also avoids resource waste. Hydrogen production by wind power generation in ports can also provide large amounts of hydrogen for ships, promoting renewable development of ship energy systems.

People began exploring hydrogen production from wind power at the beginning of this century. Kassem [?] analyzed wind power hydrogen production feasibility in 2003, demonstrating great research value as an effective renewable hydrogen production method. Bartels [?] made a comprehensive economic analysis of wind-powered hydrogen production, analyzing feasibility from an economic perspective. After wind-powered hydrogen production gained recognition, related specific topics were widely studied. Takahashi et al. [?] proposed a coordinated control method for wind-powered hydrogen production that effectively reduces wind fluctuation impacts on power systems. Belmokhtar [?] proposed an optimized control method based on fuzzy logic for wind-powered hydrogen production, effectively improving system efficiency.

At the national level, the United States, European Union, and China have all initiated wind-powered hydrogen production projects. The United States was first to carry out such projects but did not receive sufficient attention at the time. The EU has conducted numerous wind power hydrogen production projects and remains in a leading position in wind power utilization, planning to achieve sustainable development fully reliant on renewable energy by 2060. China actively promotes university-enterprise cooperation in wind-powered hydrogen production and successfully completed the Hebei Guyuan Hydrogen Production Project hydrogen production station in 2017—China’ s first wind-powered hydrogen station and the world’ s largest at that time.

2.3 Fuel Cell Applications

A fuel cell is a device that directly converts chemical energy into electrical energy through fuel and oxygen reactions, producing electricity and water as products. Depending on the fuel used, some produce carbon dioxide and other emissions. Fuel cell waste heat is much less than direct fuel combustion, with energy conversion efficiency as high as 90% and heat recovery rates of 30%-40% [?]. If hydrogen is used as fuel, no carbon dioxide appears in reaction products, making it more environmentally friendly. Fuel cells consist of a cathode, anode, and electrolyte. According to different electrolytes used, common fuel cells divide into three types: alkaline fuel cells (AFC), solid oxide fuel cells (SOFC), and proton exchange membrane fuel cells (PEMFC) [?].

AFC was designed and published by Francis Thomas Bacon in 1959, and NASA began using AFC to power the Apollo space program in the mid-1960s. Among these three technologies, AFC has advantages of low cost and simple, stable structure, requiring only continuous water supply at room temperature during operation. AFC has developed relatively well [?] and is widely used in current commercial applications. SOFC is highly efficient and can use different fuels such as methanol and biogas [?]. However, it usually requires operation above 500°C, causing the electrolysis system to start slowly and necessitating solutions to internal problems generated under high-temperature conditions. Current research focuses on developing low-temperature operation while increasing system life and reducing operational costs.

PEMFC has advantages of low operating temperature, low noise, high power density, and fast start-up [?]. PEMFC typically uses Pt as a reaction catalyst to increase reaction rates and gain more economic benefits [?]. Materials used in this technology are more easily degradable and environmentally friendly [?]. PEMFC has been used to replace automobile and aero engines [?], but its high cost and poor durability require further research and improvement [?]. A large portion of PEMFC’ s high cost stems from expensive Pt material and hydrogen supply [?]. Exploring Pt alloys to replace pure Pt represents an important cost-reduction approach. Using renewable energy to produce hydrogen for PEMFC is also undoubtedly an important way to reduce costs. Only by gradually reducing usage costs can PEMFC technology achieve greater practical application prospects and create greater commercial value.

As the cleanest energy source, hydrogen plays a vital role in reducing carbon dioxide emissions and improving the current environment. Electrolyzing water to produce hydrogen through electricity generated by solar and wind power represents an important form of collecting and storing these renewable energy sources. For ships and offshore platforms, using hydrogen-oxygen fuel cells can effectively reduce EEDI and greatly optimize offshore platform energy structures. Additionally, using hydrogen-oxygen fuel cell devices instead of batteries as energy storage devices for renewable energy power generation systems can solve intermittency problems, reduce costs, and make systems more environmentally friendly.

Fuel cells and electrolyzers using the same electrolyte generally follow the same structure. Common hydrogen production methods by electrolysis mainly include alkaline water electrolysis (AWE), solid oxide electrolysis (SOE), and polymer electrolyte membrane electrolysis (PEM). Table 2 shows specific attributes and parameters.

Details of different electrolysis

AWE has the longest development time and is the most complete method, generally using Ni-based metals as electrodes. The two electrodes are placed in alkaline solution and separated by a diaphragm. The system can operate between 20%-150% of design capacity. For solar and wind power generation systems with intermittent and large power fluctuations, AWE has advantages of low cost and system stability. The Utsira wind/hydrogen demonstration plant installed a 600 kW wind generator, using AWE to produce hydrogen at 10 Nm^3/h [?]. However, compared with other methods, AWE' s current density is not high, and the corrosive electrolyte used is environmentally unfriendly and prone to hazards.

Solid oxide electrolysis (SOE) generally uses Ni-doped YSZ as cathode electrode material and lanthanum strontium manganate (LSM) as anode electrode material. This hydrogen production method has advantages of high efficiency, long life, and high stability, but electrolysis must occur at extremely high temperatures. Currently, it is possible to consider using concentrated solar energy to provide a high-temperature environment for the reaction while using other new energy technologies to provide electricity, enabling renewable energy use throughout the reaction for better economic benefits.

The PEM system has simple structure and higher current density—about four times that of AWE. PEM can accept dynamic energy, making it well-suited for solar and wind energy hydrogen production systems [?]. Table 3 shows some PEM electrolysis hydrogen production projects worldwide.

PEM projects

3.1 Solar for Ship

Solar energy applications on ships first appeared last century. In 1997, Modular Mouldings manufactured the S B Collinda, the first solar ship to cross the English Channel. In October 2006, the Swiss 'Sun 21' all-solar powered ship completed an Atlantic crossing. In November 2009, the world' s first solar-powered large-scale cargo ship "Auriga Leader" launched for sea trials with 40 kW PV capacity, including 328 solar panels. The electricity generated could meet 6.9% of lighting requirements or 0.2% of power requirements. PlanetSolar launched on March 31, 2010, at a cost of up to 24 million dollars. It is 31 meters long, equipped with solar cells covering 537 m^2, with speed up to 10 knots. In May 2012, it completed the first solar-powered boat trip around the world. MetaltecNaval' s solar-powered commercial passenger ship EcoCat launched in 2018, accommodating 120 passengers with speed up to 9 knots. Solar power for ships is growing, with applications spreading from small cruise ships to large cargo and ro-ro ships in just two decades.

Over the past 20 years, research focus has shifted from simply using solar energy on ship platforms to efficiently using solar PV systems to provide stable power supply for ships. Currently, ship solar PV systems mainly divide into off-grid and grid-connected types. Off-grid PV systems operate independently of the ship' s power grid, relying on batteries to ensure continuous power supply. Advantages include high security and simple system structure, while disadvantages require battery capacity several times the PV system' s generation capacity for stable power output [?, ?]. Grid-connected PV systems integrate solar-generated electricity into the ship' s main power grid, avoiding the above problems and enabling more complete utilization of PV-generated electricity. Disadvantages include more complex grid-connected system structure and principles, and for power grid safety, classification societies stipulate that PV system capacity shall not exceed 10% of diesel generator capacity. After comprehensive consideration of actual situations, people still prefer grid-connected systems in most cases.

Sun et al. [?] proposed basic principles for applying solar PV systems to ship integrated power grids by analyzing technical characteristics of off-grid and grid-connected ship PV systems. Combining off-grid and grid-connected PV systems, they designed and installed a hybrid PV system with battery storage for the 'COSCO TENGFEI' . The system can flexibly switch between off-grid and grid-connected operation modes according to electric load and battery state of charge, operating stably under various modes. This solar PV system' s peak power reaches 143 kW, saving 0.46 tons of fuel oil daily and 40,000 dollars annually [?]. ÇağlarKaratuğ et al. [?] designed a PV array layout for a ro-ro ship. The designed solar system can meet 7.38% of the ship' s fuel demand, providing 334.06 MWh of electricity to the ship' s power grid annually, reducing emissions by approximately 232.393 tons of CO_2, 0.312 tons of SOx, and 3.942 tons of NOx per year. Yuan et al. [?] designed 135 PV panels in 'Anji204' with 37.12 kW total capacity. All generated electricity supplies only the vehicle warehouse lighting system and living area lighting system on board. The PV system can generate about 45,000 kWh annually, reducing fuel consumption by about 16 tons and CO_2 emissions by about 28.5 tons, SOx by 0.63 tons, and NOx by 0.05 tons each year.

As more solar modules are applied to ships, improving PV efficiency has become the research focus. Zeńczak [?] proposed increasing ship PV system efficiency by adding cooling modules. The PV system of ship ś Winoujścle was renovated with cooling modules, and operation results were analyzed. Results show this method provided 17% more economic benefits than PV modules without cooling systems. Wen et al. [?] proposed a hybrid integrated method based on random ship motion models to predict optimal onboard solar energy intervals, reducing impacts of weather changes and ship position on solar systems and improving efficiency. A hybrid prediction model combining machine learning technology and particle swarm optimization (PSO) was tested on a large oil tanker' s power system. Results show the system is very effective in improving ship solar energy system efficiency and can serve as an important reference for ship energy management systems. Divyajot [?] used variable inertia weight belt (TVIW) of the particle swarm optimization (PSO) method to study mutual influence relationships between PV, energy storage systems on tankers, and diesel generator output, determining a proposed PV module assembly for ships.

Solar PV technology application on ships has matured, with operating strategies and efficiency improvement methods currently hot topics. This represents one of the most accessible renewable energy sources on ships and will be an important method for improving ship energy structures.

3.2 Wind for Ship

Wind power equipment occupies substantial space, making it difficult to use on relatively compact ships. Therefore, using different types of sails to provide auxiliary power represents one of the best ways for ships to utilize wind energy. A good wind-assisted propulsion device can reduce ship CO_2 emissions by up to 20% [?] and save 1%-30% of fuel consumption [?], representing significant environmental and economic improvements.

Current wind-assisted propulsion methods mainly include Rotors, Towing kites, Suction wings, and Rigid sails. Rotors usually refer to Flettner rotors. Figure 7 shows basic Flettner rotor principles, which use the Magnus effect to generate thrust by installing rotating cylindrical sails on ships. Towing kites are driven mainly by high-altitude sea breezes that haul ships forward. Suction wings are similar to airplane wings, achieving upward lift through boundary layer suction. Current technologies such as Rigid sails, Soft sails, and Hull sails remain immature, with very limited practical applications. Among these technologies, Flettner rotors in Rotor sails are most suitable for large ships.

Michael Traut et al. [?] concluded that towing kites can bring about 1%-2% power gains to the main engine, while a single Flettner rotor can provide about 2-3% power benefit. In comparative analysis of multiple examples, Flettner rotors' average power range mainly ranges from 193 kW to 373 kW, while towing kites range from 127-461 kW. Flettner rotors can provide more power and are more stable than towed kites, but kites occupy less deck space and are more economical.

Nader R. Ammar et al. [?] researched Flettner rotors for a bulk carrier. By adding four Flettner rotors, they investigated economic and environmental benefits of three different routes. Results show Flettner rotors' average power ranges between 608 kW and 1,096 kW, reducing fuel consumption by 8.5-16.2%. Lu et al. [?] studied Flettner rotor technology for an oil tanker based on actual sailing data, analyzing that using Flettner rotors can save 8.9% fuel consumption. After analyzing Flettner rotor efficiency under different working conditions, they demonstrated that Flettner rotor use is greatly affected by ship type, speed, sailing route, and corresponding weather conditions. These factors must be comprehensively considered to select optimal Flettner rotor size and quantity.

Ibrahim et al. [?] took a bulk carrier between Damietta and Dunkirk as an example, studying economic benefits with different paths and Flettner rotor sizes. Research shows that under optimal conditions, each rotor' s average output power on the bulk carrier is 384 kW/h, with three rotors together saving up to 22.28% fuel consumption, reducing NOx and CO_2 emissions by 270.4 tons and 9,272 tons annually, bringing absolute benefits in both economic and environmental aspects.

Tillig et al. [?] proposed a ship performance model called ShipCLEAN to control Flettner rotors and analyze their impact on ships. The model was applied to an oil tanker and ro-ro ship for analysis and verification. Results showed an oil tanker equipped with six Flettner rotors can save up to 30% fuel consumption, while four Flettner rotors saved 14% fuel consumption. Marcel et al. [?] developed an intelligent assistance system to enhance wind-assisted ship propulsion capability, enabling automatic optimization of energy system operation. Using a ship equipped with Flettner rotors as the experimental object, they studied and analyzed data acquisition, processing, and storage modules in the system architecture, using the system' s human-machine interface (HMI) for visualization. They concluded the system can optimize wind-assisted ship propulsion working capability, laying the foundation for further improving fuel-saving ability.

3.3 Fuel Cell for Ship

Fuel cells exhibit excellent energy properties such as low noise, low vibration, high efficiency, and environmental friendliness, making them suitable as main energy supply in various applications. In recent years, fuel cell research has gradually matured, with practical applications in residences, ships, power plants, and other locations greatly stimulating research on fuel cell systems for offshore platforms. Currently, most ships are powered by diesel generators, producing large amounts of greenhouse gases, nitrates, and sulfides that are environmentally unfriendly. Using fuel cells instead of diesel engines to supply electricity can not only reduce CO_2 and gaseous pollutant emissions but also reduce primary energy form conversion, thereby greatly improving fuel utilization efficiency.

Figure 8 shows the PEMFC system working principle. PEMFC has high efficiency, fast start-up, and easily achievable operating temperature, making it suitable as main power supply energy for ships. In the 1970s, Germany developed PEMFC systems for military equipment such as submarines [?]. However, because PEMFC systems require continuous pure hydrogen fuel supply, long sailing times create hydrogen supply shortages. Therefore, using PEMFC on ships requires comprehensive and rigorous hydrogen storage and replenishment scheme design [?]. In an experiment near a hydroelectric power plant, two 180 kW PEMFC systems were installed on a ship accommodating 200 people. Electricity produced by nearby hydroelectric power plants was used to produce hydrogen, solving the hydrogen source problem while controlling hydrogen production costs well. However, PEMFC does have disadvantages of high cost and low power generation, requiring further research and improvement on power generation capacity and hydrogen production technology for ship applications and increased economic benefits.

[Figure 8: see original paper] Working principle of PEMFC

Figure 9 shows the SOFC working principle. SOFC has relatively loose fuel requirements. Besides hydrogen, SOFC can use methane, biogas, and even diesel as energy supply [?], making it more flexible in practical applications. Currently, many applications integrate SOFC into ship power systems, proving that ship power systems using SOFC can achieve good economic benefits and are more environmentally friendly.

[Figure 9: see original paper] Working principle of SOFC

L. van Biert [?] proposed that combining SOFC with current generator systems can achieve lower fuel consumption and has better development prospects. Francesco Baldi [?] also proposed that SOFC ships using LNG can reduce greenhouse gas emissions by up to 34%, representing one of the most effective ways to reduce greenhouse gas emissions.

Martinić et al. [?] used three 3,700 kW SOFC units to replace same-power turbine generators on LNG carriers, analyzing and calculating energy efficiency after replacement. Results show that using the SOFC system increased power generation efficiency from the original 32.9% to 44.8%, significantly improving energy utilization efficiency. Moreover, since the SOFC system generates substantial heat, reusing waste heat is equivalent to saving 2.6% of natural gas consumption.

M. Díaz-de Baldasano [?] designed and installed two 250 kW SOFC systems on a platform supply vessel (PSV), using methanol to provide energy for the fuel cell and integrating generated electrical energy into the ship' s power grid. The SOFC system can provide up to 20% of total ship energy supply, and they also use SOFC system waste heat to produce hot water. The system greatly reduces ship fuel consumption and brings good economic benefits.

Rafiei [?] proposed using fuel cells as ships' main power source, using batteries to cope with rapid load changes, and constructed a zero-emission ferry structure. According to the ship' s own power generation and shore power received when docking, the scholar studied ship specifications and waterways, evaluated energy limitations, and optimized the energy management system. Based on the ferry' s daily route, the energy management problem was implemented as hourly average values, using the improved sine cosine algorithm (ISCA) to obtain the best energy management mode for the ferry.

In general, PEMFC' s power generation capacity and volume are very suitable for ship energy structure optimization. However, PEMFC requires pure hydrogen supply and relatively high cost. Producing hydrogen through renewable energy will be an important method to reduce hydrogen price, which is also an urgently needed problem to solve. SOFC can use more fuel types and has greater power generation capacity, making it suitable for large ships such as oil tankers, container ships, or ships with long routes to transform energy structure. However, SOFC faces problems of slow start-up and excessively high operating temperature, requiring further research and solutions.

3.4 Shore Power

There are more than 2,000 ports worldwide, with 80% of global trade conducted through port transportation. Improving energy structure during docking can greatly improve port environment and reduce ship-caused pollution. During port docking, container ships, bulk carriers, and other ships' diesel generator power ranges between 2,000-5,000 kW [?], while cruise ship diesel generator power is several times greater than ordinary ships. Providing sufficient shore power to ships during docking can reduce diesel generator use, greatly reducing ship fuel consumption and CO_2, SOx, and NOx emissions while improving port environment.

Many global ports actively promote shore power use. Many container terminals in the United States and United Kingdom have achieved considerable environmental benefits through shore power, promoting shore power development in many European and North American ports [?]. Chinese ports also use shore power. Since 2010, Lianyungang Port has used shore power to supply cruise ships, and Shanghai Waigaoqiao Port began providing shore power to moored ships. Since 2015, Dalian Port has renovated most container ship berths to provide shore power to container ships [?]. Currently, nearly half of China' s ports can provide shore power for docked ships.

For ports, the easiest way to increase shore power is direct export from the national grid. Although operation is simple and work is stable, it remains environmentally unfriendly, not fundamentally changing environmental pressure caused by docked ships. Using renewable energy for shore power supply can solve this problem well. Solar PV can be installed in open areas near ports or even at sea [?] to provide substantial energy for port shore power. Wind farms near ports can also provide large amounts of energy. Itiki et al. [?] proposed using renewable energy such as solar and wind to build offshore power generation systems, constructing a system framework that can provide power output to the coast. The proposed power system can well provide renewable energy for shore power. Gutierrez-Romero [?] installed 163,866.6 m^2 of solar panels in Cartagena Port, Spain, obtaining a maximum of 1,378.15 MWh of electricity monthly, reducing total carbon emissions by 10,000 tons annually. This demonstrates that using renewable energy to provide shore power to ships is very valuable.

4. Hybrid Energy System Applications

PV is the most extensively applied renewable energy source on ships. With rapid development of wind energy and fuel cell technologies, more applications for assembling hybrid energy on ships are emerging. As early as June 2000, the “Solar Sailor” ferry used combined solar and wind energy in propulsion system power supply. Fuel cells were used in military submarines in early days. In 2003, Siemens created a hybrid power system for the Navy integrating fuel cells and diesel, using it in submarines at that time. The abundant solar and wind resources on oceans are very conducive to renewable energy development. Making full use of available resources benefits both environment and shipowners. Comprehensive use of various renewable energy technologies on ships helps further improve ship energy structures and reduce fuel consumption and pollutant emissions. Moreover, well-designed hybrid renewable energy systems can bring considerable economic benefits to ships. Table 4 summarizes recent research on hybrid renewable energy on ships.

Research on hybrid renewable energy on ships

5. Modeling and Analysis of HES

Ships have two main operating states: sailing at sea or berthing. For these two states, we designed corresponding comprehensive renewable energy supply structures and carried out economic analysis and evaluation based on parameters from a large oil tanker reported in [?]. Figure 10 shows the schematic diagram of the ship’ s integrated energy system designed in this paper. For the power system, we designed solar PV modules and fuel cell modules for ships. During voyages, electricity generated by PV modules is input into the ship’ s power grid, supplying the ship together with diesel generators. To ensure stable ship operation, battery modules are equipped to reduce PV module power fluctuation impacts. Fuel cells serve as backup power sources equipped with hydrogen storage tanks, and excess electricity from the power generation system supplies hydrogen electrolysis for hydrogen production. For propulsion systems, installing Flettner rotors for auxiliary propulsion can reduce substantial fuel consumption and emissions.

[Figure 10: see original paper] Hybrid energy system for ship

In the other state, when the ship is in port, the diesel generator stops working and the grid connects to shore power. The ship uses shore power as the main source to supply equipment operation while simultaneously charging batteries.

PV modules continue supplying power as a supplement. Figure 11 shows the working principle of the hybrid renewable energy system for ports. For ports, to optimize energy structure, wind power plants can be set up nearby to collect abundant coastal wind resources while providing large power sources. According to construction conditions around ports, installing solar PV power plants can also provide considerable power resources. When wind and solar power are sufficient, using electricity for electrolytic hydrogen production can provide large hydrogen supplies for marine fuel cells.

The system is relatively complex and huge. This article focuses on economic analysis of the ship' s hybrid energy system equipped with solar PV modules, diesel generator, fuel cell, and batteries. Analysis of fuel cell modules and wind-assisted propulsion modules is only briefly mentioned.

[Figure 11: see original paper] Hybrid renewable energy system for ports

5.1 Basic Information

The hybrid system object is an oil tanker 330 m long, 62 m wide, and 100,000 tons in weight. Table 5 shows the tanker load under different working conditions, with maximum load of 1,790 kW. Its sailing route is Qingdao, Shanghai, Hong Kong, Singapore, Sri Lanka, Yemen, and finally Egypt. Load is sorted according to actual working status. Sailing and freight tasks between Qingdao and Egypt are completed in 25 days each month, with remaining days at month-end docked in port for rest. The obtained operating load throughout the year is shown in Figure 12.

The load of the tanker

[Figure 12: see original paper] Ship electrical load

Diesel generators must independently supply power to the entire ship. Considering the need to leave at least 10% power generation margin, a 2,000 kW diesel generator is selected as the main electrical power source. According to China Classification Society requirements, grid-connected PV capacity on ships should be less than 10% of diesel generator sets [?], resulting in selected PV module capacity of 200 kW. PV system power generation status is closely related to solar radiation, necessitating accurate description of ship solar radiation status [?]. According to NASA Prediction of Worldwide Energy Resource solar data, solar radiation passing through cities is shown in Figure 13. The PV module output power calculation method is as follows:

$$P_{PV} = Y_{PV} \cdot f_{PV} \cdot \left(\frac{G_T}{G_{T,STC}}\right) \cdot \left[1 + \alpha_P \cdot (T_C - T_{C,STC})\right]$$

Where:
Y_{PV} = rated capacity of PV array, meaning power output under standard test conditions [kW]

f_{PV} = PV derating factor [%]
G_T = solar radiation incident on PV array in current time step [kW/m^2]
$G_{T,STC}$ = incident radiation at standard test conditions [1 kW/m^2]
α_P = temperature coefficient of power [%/°C]
T_C = PV cell temperature in current time step [°C]
$T_{C,STC}$ = PV cell temperature under standard test conditions [25°C]

[Figure 13: see original paper] Solar radiation passing through the city

HOMER software is used to model and simulate the hybrid renewable energy power system studied in this paper. Developed by the U.S. Department of Energy' s National Renewable Energy Laboratory (NREL), HOMER constructs complex hybrid energy power generation, energy storage, and load management systems. It reliably and efficiently analyzes and optimizes ship integrated system energy structures and performs economic analysis to provide optimal system configuration plans. Main energy system components—including diesel generators, PV modules, batteries, and converters—are selected according to ship load. Specific parameters are shown in Table 6. Figure 13 shows the structure of the built hybrid renewable energy power system.

[Figure 13: see original paper] Hybrid renewable energy power system

Parameters of main components

5.2 Main System Result Analysis

Weather condition changes significantly impact photovoltaic systems. Given current well-developed weather forecasting technology, it is necessary to determine power plans through forecasts, making power system operation strategy adjustment very important. Using the Predictive Dispatch Strategy (PDS), more reasonable power system operation strategies can be formulated by comprehensively considering upcoming load and energy supply situations. Based on hybrid renewable energy system basic information, several system schemes with different configuration capacities that can operate reasonably are determined, and their hourly operating data is analyzed and calculated to obtain the most economical system scheme.

Simulation calculations yielded the configuration comparison results shown in Figure 15. With diesel generator capacity and PV module capacity determined at 2,000 kW and 200 kW respectively, required battery capacity is 220 kWh and converter capacity is 114 kW. Results show diesel engine power generation operating conditions in Table 7: 7,296 total operating hours, 2,687,266 L fuel consumption, and 10,176,139 kWh power generation. The PV system generated 306,123 kWh total during this operation. Figure 16 shows specific monthly average power generation of PV systems and diesel engines. It can be seen that 97.1% of ship power system power is provided by diesel generators, while PV modules provide 2.92%.

[Figure 15: see original paper] The optimization result of HRE system components

Generator data

[Figure 16: see original paper] The monthly average power generation

Figure 17 shows specific ship power system operation, including total load for ship operation and idle load for hydrogen production by electrolysis, plus power supplied by diesel generators, PV modules, and batteries. Ship electrical load mainly relies on diesel generators, ensuring power grid safety and stability. Solar PV power is greatly affected by environment, but battery addition effectively reduces auxiliary power supply volatility, overall providing considerable power input for the ship' s power grid. Supplying electrolysis devices with electricity during idle time effectively increases energy utilization rate, and produced hydrogen has high economic value, providing certain supply for fuel cell components.

[Figure 17: see original paper] Ship electrical system operation status

Figure 18 shows system economic evaluation results, including Return on Investment (ROI) and Simple Payback. HOMER reflects new energy system economic benefits by comparing with the initial system relying only on diesel generators. ROI is annual cost savings relative to initial investment, calculated as follows:

$$ROI = \frac{C_{i,ref} - C_{i,proj}}{C_{cap,proj} - C_{cap,ref}}$$

Where:
$C_{i,ref}$ = nominal annual cash flow for base system
$C_{i,proj}$ = nominal annual cash flow for current system
R_{proj} = project lifetime in years
$C_{cap,proj}$ = capital cost of current system
$C_{cap,ref}$ = capital cost of base system

Simple payback period refers to years required for cumulative cash flow between current system and base case system to change from negative to positive—that is, how long it takes to recover investment cost difference. Analysis results show the proposed system can save 39% of initial investment annually and achieve same capital consumption as the initial basic system when running for 2.3 years, filling the proposed system' s additional cost.

[Figure 18: see original paper] Economic Metrics

Figure 19 shows capital consumption comparison between proposed system and basic system. Net Present Cost (NPC) means total installation and operation cost throughout entire life cycle minus all income obtained during project life cycle. System costs mainly include infrastructure costs, replacement costs, operation costs, maintenance costs, and fuel costs. After analysis and calculation, the proposed system can save 200,000 USD. Initial capital is total installation cost of proposed system—365,310 USD, which is 65,310 USD more than basic system for renewable energy module construction. O&M represents system operation and maintenance costs. Adding renewable energy systems can improve daily operating status of ship power grids and power generation diesel engines. Meanwhile, optimizing operation and maintenance strategies can also reduce equipment loss, so system operation and maintenance costs tend to decrease.

[Figure 19: see original paper] Cost Summary

Levelized Cost of Energy (LCOE) is average cost required for system to generate useful electricity per kWh. The proposed system' s LCOE value is 0.141 $/kWh, which less than the LCOE of the basic system by 1.4%. It means proposed system gets good economic benefits and is of great significance for improving the energy structure of ships and protecting the environment. The calculation formula of LCOE is as follows:

Where = total annualized cost of the system ($/kWh.

Table 8 shows ship emission comparison results. After installing PV modules, the new system can reduce emissions by 151,467 kg of CO_2, 370 kg of SOx, 150 kg of NOx, and large amounts of other harmful gases annually, greatly improving ship environmental performance and significantly impacting ship exhaust emission improvements.

Emission comparison

The Energy Efficiency Design Index (EEDI) is a measurement tool characterizing inherent CO_2 emission levels of ships during design and construction phases. Renewable energy transformation of ship energy systems helps reduce ships' performance. Increasing renewable energy is conducive to improving ship energy systems and effectively reducing EEDI. Reference EEDI is a standard, and EEDI calculated according to ship actual conditions must be less than Reference EEDI. Reference EEDI calculation formula is as follows:

For tankers:
$a = 1218.8$
$capacity = Shipcapacity$
$c = 0.488$

After calculation, the research object's Reference EEDI is 4.425 g CO_2/ton-mile—that is, current tankers must meet values less than 4.425 to satisfy requirements.

To explore the proposed system' s energy structure improvement, system superiority is reflected by calculating reduced EEDI value. ΔEEDI calculation formula is as follows:

$$\Delta EEDI = \frac{\sum_{i=1}^{n} f_{eff,i} \cdot P_{AE,eff,i} \cdot C_{FAE} \cdot SFC_{AE,i}}{f_{capacity} \cdot f_{ref} \cdot V_{ref} \cdot f_w}$$

Where:
$f_{eff,i}$ = ratio of average PV power generation in main global shipping routes to nominal PV power generation specified by manufacturer
$P_{AE,eff,i}$ = required auxiliary engine power to supply normal maximum sea load, including necessary power for propulsion machinery/systems and accommodation
$P_{eff,i}$ = total net electric power (kW) generated by PV power generation system [?]
C_{FAE} = nondimensional conversion factor between fuel consumption and CO_2 emission
$SFC_{AE,i}$ = certified-specific fuel consumption
$f_{capacity}$ = capacity correction factor
f_{ref} = cubic capacity correction factor
$capacity$ = DWT at maximum summer load draft as certified in vessel stability booklet approved by Administration for tankers
V_{ref} = ship speed measured in knots
f_w = weather factor accounting for speed decrease in representative sea conditions of wave height and frequency

Parameter values are shown in Table 9 by consulting relevant specifications. After calculation, the proposed system can reduce ΔEEDI = 0.0888 g CO_2/ton-mile for the ship. Tanker construction generally uses Reference EEDI as the standard, and slight reduction requires large capital investment. Therefore, actual tanker EEDI is generally very close to Reference EEDI. The calculated ΔEEDI value is equivalent to 2.0% of oil tanker construction standard (4.425 g CO_2/ton-mile), achieving very good improvement effects for large ocean-going ships that can effectively improve tanker energy structure and reduce large amounts of CO_2 emissions.

Values of EEDI calculation parameters

5.3 Other Proposals

The proposed system includes using electrolyzers to produce hydrogen for fuel cells, Flettner rotor wind-assisted propulsion, and improving shore power structure with renewable energy. The following provides only brief description to offer ideas and initial structural concepts for future work.

In the proposed system, we used an electrolytic hydrogen production device operating during idle time. Figure 20 shows device operation within one year. The electrolysis device’ s hydrogen production capacity is 40 kWh/kg, electrolyzing 1,000 kg of hydrogen annually. Since supplying fuel cells with hydrogen produced by electrolysis on ships is very uneconomical, fuel cells are used only in special circumstances. PEMFC has no operating temperature requirements and can meet power system fast start-up requirements, providing 25,000 kWh of flexible, efficient power supply annually. Moreover, for electric propulsion ships using fuel cells as main power sources, the transformation scheme described in this article will have good redundant electric energy recovery benefits.

[Figure 20: see original paper] Operation status of electrolysis device

For large ocean-going ships, installing Flettner rotors is an important method to reduce main engine fuel consumption. After researching and collating relevant literature, each Flettner rotor can generally reduce ship fuel consumption by 2%-8.9%. Installing four Flettner rotors for the tanker described in this article can theoretically reduce fuel consumption by 8%-35.6%, which is of great significance for reducing ship operating costs and pollutant emissions.

The ship described in this article stays in port nearly 14% of time throughout the year, with electrical load during loading and unloading as high as 1,290 kW —only 290 kW less than during normal voyages. Using shore power in this state can save substantial fuel consumption. Additionally, if shore power consists of renewable energy, building large-scale solar and wind farms around ports and combining solar with wind power to build an overall renewable energy system can greatly improve port energy structure. Constructing an electric hydrogen production plant near ports to produce hydrogen from excess electric energy during low-load periods can provide hydrogen for ships equipped with hydrogen-oxygen fuel cells, making ships and shore power more environmentally friendly. This proposal greatly impacts shipping industry energy structure improvement.

6. Conclusions

The shipping industry currently faces increasingly stringent laws and regulations, with rising standards for ship energy consumption and emissions. Coupled with sluggish global shipping industry development, survival of traditional shipping has become increasingly difficult. Under these circumstances, gradually maturing renewable energy technologies bring important opportunities to the shipping industry. Using renewable energy technologies such as solar, wind, and fuel cells to optimize ship energy structures has become a main approach for the current ship industry to reduce emissions and pressure on the natural environment. Meanwhile, well-designed new energy systems can also reduce considerable long-term operating costs for ships, providing very good economic benefits.

This article summarizes development and research status of solar energy, wind energy, and fuel cells, focusing on their applications and research in the ship industry. A hybrid solar/wind/fuel cell ship power system model is constructed for ships, and a hybrid solar/wind power supply and hydrogen production model is proposed for port shore power. Simulation analysis optimizes renewable power system design, focusing on emission reduction and economic benefits from solar photovoltaic for ships. Results show the proposed hybrid renewable energy system can reduce emissions by 151,467 kg of CO_2, 370 kg of SOx, 150 kg of NOx, and large amounts of other harmful gases annually for 100,000-ton tankers. Calculations show the proposed system can also reduce EEDI value by 2.0%, achieving good environmental protection performance. Additionally, the system can provide 2.92% of electricity for 100,000-ton tankers annually, with a payback period of only 2.3 years, bringing good economic benefits to ships.

Future plans will continue modifying the proposed hybrid power model to determine the best balance between different energy sources. Operation mode calculations under shore power state will be performed to investigate whole-process economics of ship sailing and berthing. Experimental validation on the modified calculation model will also be carried out.

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