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A REVIEW OF THE CURRENT STATE OF RENEWABLE ENERGY-POWERED MARINE VESSELS

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Abstract

Renewable energy-powered marine vessels represent an innovative and growing aspect of the maritime industry and the blue economy. This innovation and growth is driven by the need to reduce greenhouse gas emissions, comply with stringent IMO environmental regulations, and achieve sustainability in the area of maritime transportation. This paper reviews the renewable energy technologies available to power marine vessels, their development, and the challenges being faced currently. Renewable energy technologies, including solar, wind, and fuel cells, are discussed. Firstly, the different renewable energy technologies are described and then subsequently their current deployment potential is presented.

Keywords: Blue economy, renewable energy, marine vessels, solar, wind energy

1.0 INTRODUCTION

The concept of the blue economy draws a line between socioeconomic development and wanton environmental degradation of water bodies and the coastline (Bethel et al., 2021). The blue economy, thus, offers an intuitive way of monitoring and protecting the seas' resources while receiving benefits in a sustainable manner. Globally, the blue economic activities play a key role in the reduction of extreme poverty and hunger through the creation of jobs and other economic opportunities (Youssef, 2023). The term blue economy has been utilised in various ways (Yung & Dimitrios, 2023). However, it is known to comprise a variety of economic sectors, regulated by

interconnected policies, including security, environment, development and transportation. The transportation aspect involves the supply of seagoing personnel and ship crew recycling, ship owning and operating, shipbuilding and repairs, port services, among others (Ateme, 2021). Maritime transport is one of the more established sectors of the blue economy and all over the world, marine vessels are required to move people, commodities, fuels and products from one location to the other (Wang et al., 2023). Global markets and international trade depend on marine vessels for their success, and with 90% of the global trade being transported through the sea, shipping is characterised as a principal facilitator of global trade and economy. In addition, marine transport forms the spine of most national economic growth, and the Nigerian economy is not an exception (Ekong, 2021). Today, marine vessels are more sophisticated, efficient, safer and environment-friendly than ever before, moving much more cargo and (Adepoju, 2023). Marine transportation constitutes a significant source of pollution to the marine environment. This is due in part to the large amounts of air pollutants emitted from marine vessels, representing 2.6% of the total global emissions (Mitra et al., 2021). These emissions are expected to grow by 3.9% - 6.5% by 2050. A significant reduction in greenhouse gas (GHG) emissions could be achieved by implementing a series of measures and operational practices. The evolution of marine vessels from conventional power systems to renewable energy-based power systems will play a fundamental role in the reduction of marine vessel emissions and in the decarbonization of maritime transport (Pournara et al., 2019). The International Maritime Organisation (IMO) has introduced some regulations targeted at reducing GHG emissions for the global shipping industry, to safeguard marine resources (Gbadegesin & Simisola, 2021). Therefore, new marine vessel designs would target reduced emissions from the combustion of the ship's main engine, thereby increasing the propulsion efficiency of vessels through the incorporation of renewable energy in the design process (Adewuyi et al., 2020). This has become necessary due to the steady increase in world trade and its dependence on maritime transportation, which has increased fuel consumption for water transportation year on year. As a result of increased fuel consumption, by 2050, it is expected that the world's CO_2 emissions from the marine transport industry will reach 12% -18% of global CO_2 emission (Augustine & Okon, 2022). In addition, the emission of oxides of nitrogen (NO_x) from the shipping industry contributes up to 15% of global NO_x emissions. Almost 95% of the main propulsion of marine vessels of the world use diesel engines (Raheem, 2022). Therefore, the solution to reducing carbon dioxide (CO_2), NO_x and oxides of sulfur (SO_x) emissions and comply

with international regulations is by introducing ways to significantly limit emissions from fossil fuel consumption in the future marine vessels' energy efficiency. One way of achieving this is by using renewable energy for the ship's main engine (Samsó et al., 2023). In recent times, renewable energy has emerged as a promising research area in the search for ways to overcome the global energy crisis and also reduce the effects of GHG emissions (Tuswan et al., 2022). This has led researchers to renewable energy and energy storage systems for marine vessels. New energy technologies for marine vessels' power systems have been widely developed by researchers and have also been implemented. Some of the more promising technologies are solar energy, wind energy, fuel cells and hydrogen energy (Zakiah & Selasdini, 2023). To meet the energy demands of marine vessels, renewable energy such as that mentioned can be deployed as the main energy source for small vessels, while for large ships, it can be used as auxiliary to supply power for lighting, navigation and communication devices (Onwumelu, 2023). Over time, marine vessels' power appears to have evolved full cycle. Wind energy sources and sails were used to propel marine vessels before the advent of the steam engine in the 19th century (Brusso & Paul, 2020). Recently, just like in the old times, wind energy technologies such as Flettner rotor systems, modern sails and sail kites have become viable alternative power sources to reduce emissions and increase vessel power and efficiencies. Also, solar energy technologies and fuel cells are viable alternative energy candidates for marine vessels (Lu & Ringsberg, 2019). The following paragraphs describe in more detail these technologies as they apply to marine vessels' power, including their challenges and current developments.

2.0 RENEWABLE ENERGY SOURCES FOR MARINE VESSELS

Fossil-based energy sources are thought to be depleting while the demand for more energy, by humans, is ever on the increase (Z. Wang et al., 2024). Therefore, renewable energy presents an alternative and a viable option in bridging the gap between energy demand and supply and also in reducing GHG emissions in the process (Tuswan et al., 2022). In this context, renewable energy refers to an alternative energy source with the capability to replenish itself while being environmentally friendly by reducing greenhouse gas emissions and environmental pollution of any kind (Nwaorgu & Ogbonnaya, 2023). Renewable energy technologies which have been proven and are currently in use are solar energy, wind energy, marine energy, hydropower, biomass and

biofuel, while hydrogen energy still remains one for the future. However, with particular application to marine vessels, solar, wind, and fuel cells are the front runners.

2.1 SOLAR ENERGY TECHNOLOGY

Solar energy refers to energy gotten from the sun and it is believed that most energy on earth comes from the sun or solar energy (Petrychenko et al., 2024). Broadly, the conversion of solar energy for use is divided into passive and active conversion technologies, as shown in Figure 1 (Barutcu et al., 2020). Active conversion technologies involve trapping or absorption of solar radiation, while passive technologies do not require trapping of the solar energy. The more developed conversion technologies are concentrated solar power (CSP) and photovoltaic (PV) technologies (Aroonsrimorakot & Laiphrakpan, 2020). Research shows that the use of solar PV technology is more suited to areas of the Earth in the medium to high latitudes, and CSP systems are better for thermal energy storage in dry areas with relatively low latitudes (Nyanya et al., 2021). However, with regards to marine vessels power solar PV technology is more suitable and easier to install on vessels, because of the limited area around the ship's deck.

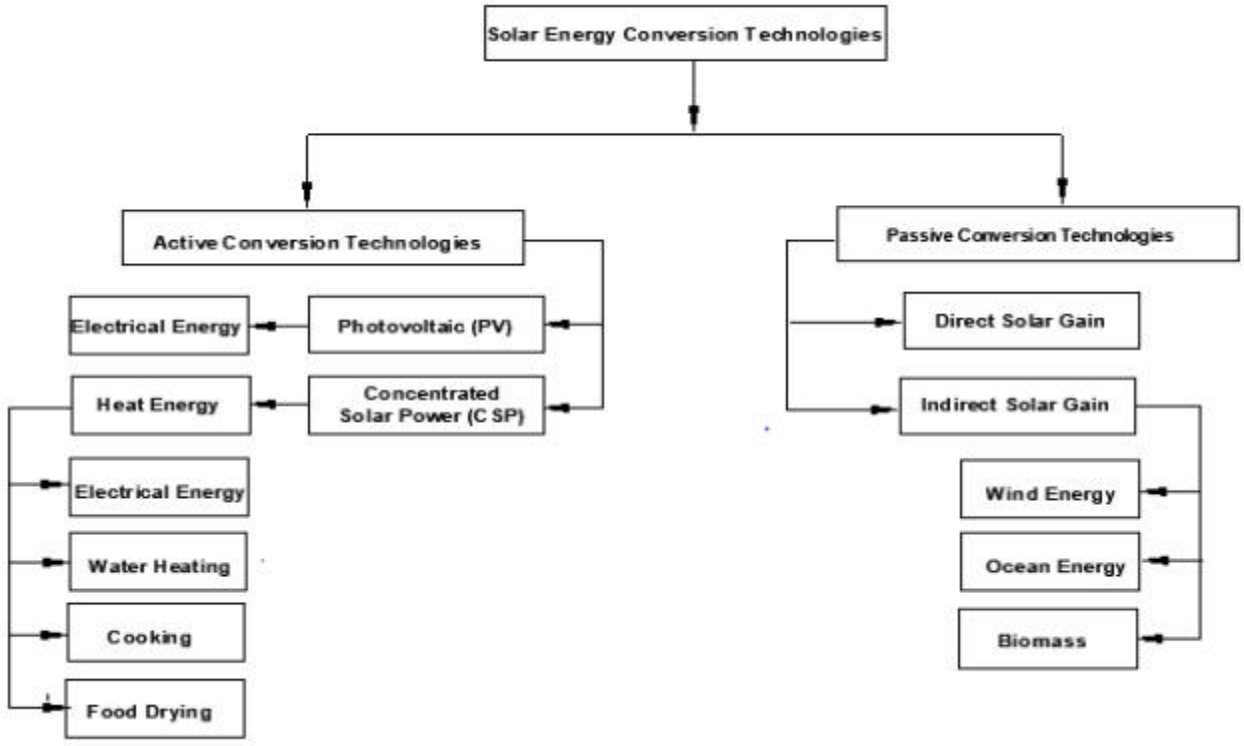


Fig. 1: Classification of solar energy conversion technologies (Barutcu et al., 2020)

Research shows that the Cost of Electricity (CoE) for Solar PV experienced a very significant decline from 2010 to 2023, showing a drop from around $0.37/kWh to $0.084/kWh (Zakiah & Selasdini, 2023). Also, it is predicted that by 2030 the cost of solar PV will be between $0.08/kWh and 0.02/kWh and by 2050, solar PV is expected to be one of the cheapest power sources available, with projected costs in the range of $0.014/kWh – $0.05/kWh. As expected, the prospect of using solar PV for marine vessels will increase along with competitive prices (Ilija et al., 2022). It is necessary to note, however, that due to the fluctuating energy requirements when the ship is operating, it is very necessary to put in place sustainable energy management and reliable energy storage systems.

2.2 WIND ENERGY TECHNOLOGY

Wind can be defined as the flow of air over the Earth's surface, occasioned by pressure differentials in the air from location to location (Bhuiyan et al., 2022). Since air is a fluid, its flow is expected to share the same principles as water in the ocean. The pressure differential in the air causes it to flow from high-pressure to low-pressure areas. These pressure differentials in the air is caused by uneven heating of land and oceans on the Earth's surface (Samsó et al., 2023). Therefore, the energy in wind can be taken as an indirect or passive form of solar heat energy. Broadly, wind turbines are of two main types: the vertical axis wind turbine (VAWT) and the horizontal axis wind turbine (HAWT), as illustrated in Figure 2. The most common type of HAWT is the 3-bladed aerofoil, and the most common types of VAWT are Savonius, Darieus, or Panemone (Usman et al., 2024).

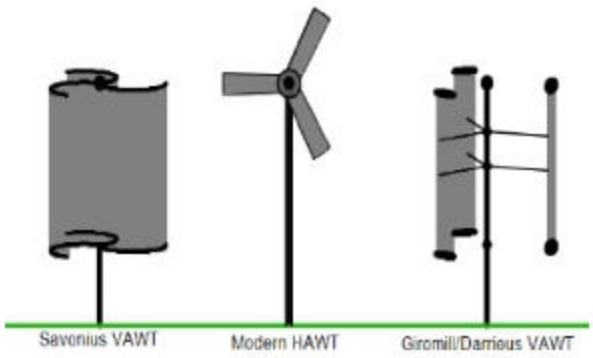


Fig. 2: Main Types of wind turbine (Usman et al., 2024)

Currently, wind energy is considered one of the fastest growing renewable energy sources, with wind energy costs now becoming competitive in comparison with the cost of power generated by thermal power plants such as coal and gas (Haomin & Decai, 2020). Wind energy generated varies from location to location. For example, the energy generated is quite large for countries in the subtropical hemisphere, whose winds are greater than countries in the tropics (Paulson & Chacko, 2019). However, the working principles of wind energy generation on land and at sea are quite similar, as they use the same basic forces of lift and drag. The main difference is the location of the installation (Zhang & Xu, 2020). For example, an offshore installation located in the middle of the sea would either be on a floating vessel or fixed.

2.3 FUEL CELLS (FC) TECHNOLOGY

Fuel cells (FC) are devices that convert chemical energy from elements such as hydrogen and oxygen into electrical energy (Xing et al., 2021). A fuel cell consists of two electrodes (anode and cathode) and an electrolyte. A chemical reaction is triggered at the contact between fuel and the anode as fuel and oxygen are supplied to the system. This generates direct current (DC) electricity that can be used for different applications, along with an outflow of heat and water (Brusso & Paul, 2020). Theoretically and practically, FC generation displays a much higher efficiency than conventional power generation. Also, FC has a lower Environmental Impact Scheme (EIS) than conventional technologies, is smaller in size, and is noise-free. Based on the choice of electrolyte and fuel, six main types of FCs are available (van Biert & Visser, 2022).

1. Proton Exchange Membrane Fuel Cell (PEMFC)

2. Alkaline fuel cell (AFC)

3. Phosphoric acid fuel cell (PAFC)

4. Molten carbonate fuel cell (MCFC)

5. Solid oxide fuel cell (SOFC)

6. Direct methanol fuel cell (DMFC)

Further classification can also be made based on operating temperature. The low operating temperature FCs are from (50–250) ^{o}C for PEMFC, AFC and PAFC, and high operating temperature FCs of (650–1000) ^{o}C for MCFC and SOFC.

3.0 APPLICATION OF RENEWABLE ENERGY TO MARINE VESSELS

In this section, we will discuss some of the applications of renewable energy to marine vessels. The renewable energy sources discussed earlier, such as the use of solar, wind and fuel cells, are considered.

3.1 APPLICATION OF SOLAR POWER TECHNOLOGIES TO MARINE VESSELS

Since the energy density of a PV plant and its energy conversion efficiency are relatively low, it will produce power of only a few hundred watts to a few kilowatts. Therefore, solar energy is usually applicable as the main power source in smaller vessels and as an auxiliary power source in larger vessels (Aroonsrimorakot & Laiphrakpan, 2020). However, for large power requirements and long operating times, a storage system or battery is needed. Medium and small-scale vessels using solar PV as vessel propulsion need a power system configuration using batteries for energy storage (Minak, 2023). The first solar-powered vessel capable of crossing the Atlantic was recorded in 2006 as the vessel Sun21, having a PV panel area of 65 m^2 above the hull (Figure 3).



Fig. 3: The Sun21 (Minak, 2023)

In 2010, the first cruise ship (Solar Ship of Love II illustrated in Figure 4) using solar power and saving energy from 1/3 to 1/4 of a diesel-fueled ship was designed and built in Taiwan (Zakiah & Selasdini, 2023). In 2012, the vessel Turanor Planet Solar (Figure 5) was recorded as the largest solar-powered marine vessel to complete a 60,023 km circumnavigation without using fossil fuels power



Fig. 4: Solar ship of love (Zakiah & Selasdini, 2023)



Fig. 5: Turanor Planet Solar (Zakiah & Selasdini, 2023)

The car carrier Auriga Leader, illustrated in Figure 6, uses a solar system having 328 PV panels supplying a power of 40 kW installed on the ship's deck (Mitra et al., 2021). The solar PV system contributes to an annual fuel reduction of 13 tons and CO_2 emissions reduction by 40 tons. The output power of the installed PV system can meet 6.9% of the demand load for onboard lighting and 0.2% – 0.3% of the demand load for vessel propulsion (Nyanya et al., 2021). Another ocean-going solar-powered vessel is The Emerald Ace (Figure 7), having 768 PV panels supplying a power of 160 kW.



Fig. 6: The Auriga Leader (Marques et al, 2020)



Fig. 7: The Emerald Ace (Sunaryo & Imfianto, 2019)

3.2 APPLICATION OF WIND POWER TO MARINE VESSELS

With regards to the application of wind energy to marine vessels the two main technologies today are Wind Assisted Ship Propulsion (WASP) and Wind Power Generation (WPG) (Julia et al., 2020). Comparing the energy of wind, offshore wind energy is more suitable for power generation

than onshore wind energy because the frictional effect is less, resulting in greater wind speeds and reduced energy losses (Guzelbulut et al., 2024).

For the purpose of marine vessel propulsion, there are two types of WASP technologies used to capture wind energy, namely traditional and modern technologies (Arief & Fathalah, 2022). Examples of traditional WASP technologies are rectangular sails and triangular sail vessels. Examples of modern WASPs are Walker Wingsail vessels, Flettner rotor sail ships and skysail ships (Fabian & Ringsberg, 2023). The Shin Aitoku Maru (Figure 8) was the first oil tanker with modern sail technology mounted on its deck. More recently, the University of Tokyo researchers have built the "Wind Challenger" (Figure 9), which has four large sails installed to harness maximum wind energy over the sea.



Fig. 8: Shin Aitoku Maru having modern sails on deck (Samsó et al., 2023)



Fig. 9: The Wind Challenger (Fabian & Ringsberg, 2023)

The "Wind Star" (Figure 10), built in 1986, is a passenger ship with the largest triangular sail. It has a total of 4 masts installed on its deck having each length of 50 meters each covering an area

of 2000 m^2 (Lu & Ringsberg, 2019). The sails can propel the vessel to a maximum speed in the region of 12-13 knots and can supply power to propel the ship for 90% of operating or sailing time, increasing energy efficiency by about 25%. The Walker Wingsail technology (Figure 11) makes use of a multi-element, three-plane sail in the form of symmetrical foil, having a flap to adjust the angle of attack of the sail (Zakiah & Selasdini, 2023). The foil and the flap gap create a greater lifting force, thus producing a high-energy airflow from the lower surface to the wing's upper surface.



Fig. 10: The Wind Star triangular sail ship (Lu & Ringsberg, 2019)



Fig. 11: The Walker Wingsail technology (Zakiah & Selasdini, 2023)

The Flettner rotor technology works with the principle that a cylinder exposed to the wind, when rotated, generates a Magnus force that converts wind energy into thrust (Melnyk et al., 2024). Initially, Flettner rotor sail technology did not perform very well because the very large screen size of the Flettner rotor caused two serious drawbacks (Tillig & Ringsberg, 2020). One is that more deck space is required, and the other is an adverse effect on ship stability. Figure 12 shows a 10,000

DWT cargo ship "E-Ship I" with Flettner rotor sails. Having four Flettner rotor sails, 27 m high and 4 m in diameter installed on deck, its efficiency can increase 30%, under favourable working conditions (Paulson & Chacko, 2019). Built in 2015 the "M/V Estraden" (Figure 13) is another Flettner rotor sailing vessel. Equipped with two Flettner rotor sails 18 m high and 3 m in diameter, it can produce a main engine equivalent of 2 MW for propulsion.



Fig. 12: The E-Ship I (Melnyk et al., 2024)



Fig. 13: M/V Estraden (Paulson & Chacko, 2019)

The working principle of the skysail technology converts wind power into useful force to propel a vessel by a rope connected to a kite flying in front of the vessel at a high altitude (Rutkowski, 2020). The skysail propulsion technology requires several components for its smooth operation. These include equipment to control the launch or release method, equipment to roll the skysail and equipment for optimisation of wind route settings (Florin et al., 2024). One key advantage of the skysail propulsion technology is that it does not reduce deck space or change the vessel's main dimensions. Another advantage is that it can reduce the forces that cause wave slamming and torque on the ship thus increasing performance and vessel safety (Park et al., 2024).

The main challenge encountered in implementing the Skysail technology is in achieving automatic control to manage kite flight, which includes managing launch and recovery operations and keeping the kite flying at an optimum position (Sun et al., 2025). The Skysail technology was first implemented in 2007, on the "Beluga" (illustrated in Figure 14), using a skysail area of 160 m^2. Its implementation successfully reduced engine load by 20% and fuel cost by $1000 on its maiden voyage from Hamburg to Houston (Z. Wang et al., 2024).



Fig. 14: The Beluga skysail

3.3 APPLICATION OF FUEL CELL (FC) TECHNOLOGY FOR MARINE VESSELS PROPULSION

In contrast to how diesel engine generators work, converting chemical energy to electrical energy through combustion, fuel cells function by converting chemical energy directly to electrical energy (van Biert & Visser, 2022). Traditionally, renewable energy sources on marine vessels usually supplies power for auxiliary equipment such as lighting, while diesel generators supply the main power for propulsion. However, with the advancement in renewable energy technologies like the FC, renewable energy applications on marine vessels can now be extended to cover vessel propulsion. Table 1 presents a summary of some of the vessels operating FC with their installation capacity (Xing et al., 2021).

Table 1. Marine vessels currently deploying FC technology (Guan et al., 2024)

SN	VESSEL	FC TYPE	FUEL	CAPACITY (kW)
1.	USCGC Vindicator	MCFC	F-76	2500
2.	Viking Lady	MCFC	H2, LNG, Biofuel, Methanol	330
3.	Hy-Ferry	PEMFC	H2	240
4.	e4ship PA-X-ell	HT-PEMFC	Methanol	120
5.	e4ship SchIBZ	SOFC	Diesel	100
6.	NedStack	PEMFC	H2	60
7.	Nemo H2	PEMFC	H2	60

Due to its advantages, including abundant materials, environmental friendliness and sustainability, several countries like the US, Japan, Germany, Austria, France, Australia, the Netherlands, Canada, and the UK, have started programs targeting increased use fuel (Guan et al., 2024). This has made FC a promising research area for both academia and industry players. For example, as part of FC development and demonstration, the United States warship USCGC Vindicator, shown in Figure 15, has replaced four of its diesel generators with FC to boost the electrical power needs of the vessel (Xing et al., 2021).



Fig. 15: The US Vindicator (Guan et al., 2024)

However, the world's first commercially operated fuel cell-powered passenger vessel, the Alsterwasser (Fig. 16), runs successfully on inner-city waterways in Hamburg, Germany (Samsó

et al., 2023). The PA-X-ell e4ships project, also in Germany, targets an increase in the energy supply of large vessels by integrating a 120 kW fuel cell for propulsion.



Fig. 16: The Alsterwasser (Samsó et al., 2023).

The current industry leader in FC systems development is ABB (Sun et al., 2025). They have developed a system based on a hydrogen proton exchange membrane (PEM). The technology is applicable to both high and low voltage, as well as AC and DC power systems, and can be used in combination with battery storage (Babaremu et al., 2022). Also, these systems can be fully hydrogen-electric or integrated as part of a hybrid power system, in combination with other renewable energy technologies (Michalina et al., 2023). In Japan, Yanmar is developing a future powertrain that runs on hydrogen as fuel. The company in conjunction with Toyota Motor Corporation, is developing a hydrogen FC system for maritime applications based on the MIRAI, a hydrogen FC car manufactured by Toyota (Sharp & Gavin, 2024). Yanmar targets the installation of a maritime FC system on its own vessels and extends the technology to various other applications. Figure 17 summarily shows the contribution from various renewable energy sources to a marine vessel's energy efficiency. The different renewable energy technologies discussed can be deployed in several commercial vessels such as passenger ferries, container/cargo vessels, bulk carriers, tankers and chemical products. However, the feasibility of installing any particular technology on a vessel will depend on the available space on the vessel's deck area. Marine vessels such as containers/cargo vessels and bulk carriers would require a lot of free area during operations such as loading and unloading so that installation of renewable energy technologies can only be around the bow, stern, and poop decks which are smaller in area than the vessels main deck.

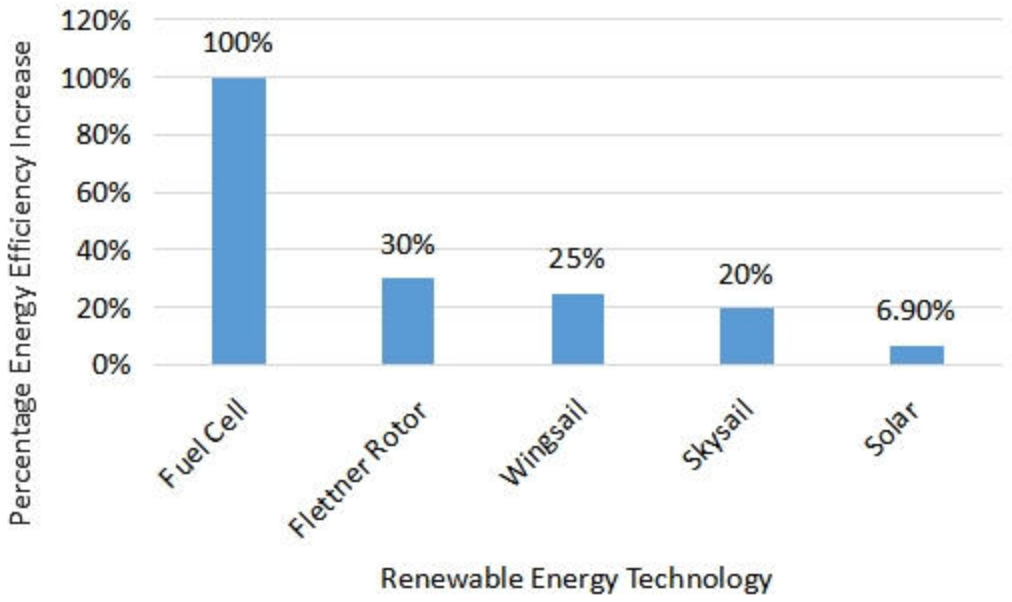


Fig. 17. Increase in energy efficiency from the use of different renewable energy technologies

4.0 CONCLUSION

With regards to renewable energy power for marine vessels, wind, solar PV and fuel cells technologies have made significant progress and are currently being deployed to boost the efficiency of the vessels' energy demands. For example, wind energy technology using skysail technology increases efficiency by up to 20%, while Wingsail technology integration can increase energy efficiency by 25%, and the Flettner rotor technology can boost efficiency by up to 30%. Large marine vessels making use of Solar PV technology mainly achieve a reduction on the use of fossil fuels and an increase in energy efficiency by 6.9%. However, smaller vessels can deploy solar PV technology as the main vessel power with a great degree of success. Although these renewable energy technologies can be deployed on different types of marine vessels, deployment of solar PV requires a large area for panel installation and largely depends on daylight and sunny weather, compared to other renewable energy technologies. On the other hand, wind energy in the sea can be captured as a renewable energy source at any time as long as there is a wind speed.

While other forms of renewable energy technologies only target the replacement of fossil-based energy sources to some percentage, fuel cell energy for marine vessels is targeted at replacing 100% fossil energy. Tankers have a large space on their main deck, so installing renewable energy has more prospects because it does not interfere with loading and unloading. However, because of the high level of safety required on tankers, any installation must be reviewed with the existing regulatory system. Thus, renewable energy such as wind energy, solar energy, and fuel cells can serve as vessels' main power source for propulsion, especially for medium or small-scale vessels or as additional power on large vessels for lighting, navigation, and communication needs, reducing dependence on fossil energy in the process. The main conclusions from this review of renewable energy-powered marine vessels are;

1. With regards to solar technology, the Solar PV, and not CSP, is suitable for marine vessel applications. However, since solar energy density is low, on larger vessels it is deployed as auxiliary power for lighting, navigation, and other electrical needs.

2. Wind energy technologies with great potential with regards to marine vessel application are the Walker Wingsail, skysail and Flettner rotor. However, the Flettner rotor has reduced prospects since it affects the vessel's stability and requires more deck space for installation.

3. The proper deployment of wind energy technology can increase a vessel's energy efficiency anywhere from 20%-30% compared to solar PV, which only achieves 6.9%.

4. Fuel cells show more promise as a renewable energy alternative for marine vessels, whether for the vessel's main power for propulsion or for the vessel's auxiliary electrical power demands. Therefore, the implementation of fuel cells has a greater prospect in new vessel designs.

5. While vessels such as cargo, bulk carrier, and container vessels have limited area to install renewable energy equipment, tankers have a large main deck area for the deployment of renewable energy resources.

6. Hybrid technology, which is a combination of two or more renewable energy technologies is very good for optimizing the potentials of renewable energy sources for vessel propulsion or auxiliary demands.

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