

PHOTOVOLTAIC PANELS IN MARITIME SECTOR

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Abstract

With lower fuel consumption per ton, shipping is very efficient way of transport. However, fossil fuels utilization in maritime transport induces harmful effects on the environment (air and water quality) and public health. Due to rigorous sea environment protection requirements and increased fossil fuels prices, interest in renewable energy sources utilization in the marine power systems is growing. Photovoltaic (PV) technology emerged as suitable solution for utilization in maritime sector, making it more sustainable and efficient. The biggest challenge for installing PV panels on vessels is limited area and possible partial shading. For PV panels operation in maritime environment, the main challenges are salty conditions, high humidity and extreme wind that can decrease PV panels performance and reliability. At the Faculty of Maritime Studies Kotor, University of Montenegro, research on examining marine influence on PV panels performance is in its initial phase. For this purpose, two flexible monocrystalline silicon PV panels are installed on the roof of a tourist passenger vessel operating in the Bay of Kotor. One PV panel is a referent one and the other is exposed to the marine environment, allowing analysis of the effects of salt, humidity, and temperature on the electrical performance of the panels.

Keywords: PV panel, vessel, maritime environment.

INTRODUCTION

Living in the time of advanced technologies means that energy represents a base in all aspects of life [1]. Fossil fuels utilization for energy production releases considerable amounts of pollution into environment and great source of emissions is fuel oil consumption for power generation in energy and transport sectors. Although the main source of greenhouse gases (GHG) emission in transport sector is road transport, shipping influence is also considerable [2]. Shipping sector is diverse and represents significant share of international trade, and also of local and regional transport and activities (fishing, offshore construction and maintenance, etc.) [3].

In the framework of world trade, maritime trade accounts for over 80%, while maritime

transport represents over 75% of external trade and around 30% of internal trade in the European Union [4]. With lower fuel consumption per ton, shipping is more energy efficient means of transport compared to others. During previous 40 years, maritime transport extended by 250%. Every year ships use around 300 million tons of fossil fuels and release around 3.1% of the total global GHG emissions [5]. Expansion of maritime transport induces harmful effects not only on the environment, air and water quality, but also on public health [1].

Having in mind influence of maritime transport both on economy and health, creating legal and economic incentives, and raising public awareness are of extreme importance for generating environmentally responsible and sustainable marine systems [4].

Interest for utilization of renewable energy sources (RES) in the marine power systems is growing due to more rigorous sea environment protection requirements [6]. International Maritime Organization (IMO) and European Union brought in restrictive legislations that demand from designers and owners of vessels to find non fossil fuels solutions for vessels' propulsion systems [7] in order to raise environmental quality of shipping worldwide [8]. According to IMO, "green ships" are urgent solution and not only a trend [9]. Term "green ship" is already familiar, denoting vessels utilizing RES [8]. With all current initiatives and regulations, the International Maritime Organization aims to achieve net-zero greenhouse gas emissions from international shipping by 2050. In line with this goal, the IMO has also adopted interim targets to reduce total annual GHG emissions from international shipping by 20–30% by 2030 and by 70–80% by 2040, compared to 2008 levels [7]. In January 2023, one of the principal measures of International Maritime Organization named Carbon Intensity Indicator (CII) regulation started to be implemented in order to curtail GHG emissions. The CII regulation applies to all cargo, RoPax, cruise, and other vessels above 5000 gross tonnage (GT) that engage in international voyages. Smaller vessels, fishing boats, and domestic passenger ships are currently exempt but are expected to be included in future revisions of regulation [10].

Increased fossil fuels prices are another reason for considering RES application in maritime sector [1]. Vessels mostly use heavy fuel oil, but also diesel oil and low sulfur oil [1]. Due to progressive decrease in fossil fuels utilization and gradual rise in RES use, global energy mix changes and becomes more diverse. RES are natural, environmentally friendly and infinite sources [1] and among them solar, wind and fuel cell systems are the most convenient on-board RES, especially for SSS [10].

Among renewable energy sources, photovoltaic (PV) technology emerged as suitable solution for utilization in maritime sector [9]. PV technology is convenient solution for vessels to reduce their emissions [7]. PV technology has the potential to make marine sector more sustainable and efficient [1]. Since the available deck area on vessels is limited, the power generated from PV systems is constrained [7]. Additionally, besides the fact that PV systems are pricy and with low cost-effectiveness to satisfy CII requirements, their performance depends on vessel technical and operating characteristics (navigation circumstances and loading factor) [10]. Although initial costs of solar-powered vessels are greater compared to diesel-powered ships, their advantages are low operating costs, electricity production aligned with peak demand, cost savings, no emissions, etc. [4].

The aim of this paper is to show examples and challenges of PV panels application in maritime sector along with presentation of experimental setup prepared for measuring maritime environment influence on PV panels the Bay of Kotor, Montenegro.

MARINE ENVIRONMENT

Unlike PV panels in land, panels operating in maritime sector experience certain specificities [8]. Marine environment's particularity has to be accounted when applying PV panels on boats and ships [9]. Due to long-term direct contact with marine environment, PV panels performance and reliability can be decreased [9]. PV panels in maritime environment [11] installed on vessels should be tolerant to sea (ocean) environment [8] including salty conditions, high humidity, extreme wind [11] and large temperature difference between day and night [9]. However, the principal factors influencing PV panels in marine environment are seawater and salt spray [9].

Seawater and salt spray effect on PV panels is dynamic process. Salt spray and

seawater create a layer (water film) on the PV panels cover glass. After evaporating, salt particles remain on PV panels cover surface [9].

Bearing in mind that PV panels are usually installed above the vessel's deck, ocean atmosphere is their principal contact environment with high salinity and humidity caused by the seawater evaporation [9].

In salty conditions, water vapor and salt mixed with acid and basic substances have influence on PV panels. Even though PV panels are protected with glass cover in such complex and harsh environments as sea (ocean), corrosion and coloring can appear. In changing state of dry and wet conditions, salt particles retain on PV panels front surface, reducing the light transmittance of the glass cover and creating partial shading effects. Due to seawater presence, black spots of corrosion on the PV panels front cover glass can be created, with farther reduction of spectral transmittance or sometimes with creating unimprovable physical damage. Marine environment can cause a formation of a layer that cannot be easily removed, but coating of the glass cover can be applied [9].

Although solar radiation intensity getting to the PV panel surface is changing during the day, due to cloudy weather, shading, etc, for PV panels mounted on vessels solar radiation additionally varies due to different routes. Fluctuations of the sea (waves) may change the angle of incidence between the solar radiation and PV panel front surface. Thus, assessment of electricity generation is not easy [8].

PV SYSTEMS ON VESSELS

Solar-powered ships incorporate photovoltaic (PV) technology into their onboard power systems [8]. The biggest challenge for installing PV systems on vessels is limited area for PV panels mounting and partial shading [4].

Due to strict space limitations, PV systems on vessels should be installed in easily accessible areas for maintenance, while ensuring that their installation does not, under

any circumstances, compromise the safety of navigation, cargo operations, passengers, or crew [8]. Vessels with large upper deck surface are very convenient for mounting PV panels [5]. Also, due to limited space for installation, PV panels should be mounted on areas with no shading, if possible [8].

Wind on vessels varies in their direction and speed, thus mounting PV panels has to be thoroughly considered and it is preferable to concur with the keel in order to follow the vessel aerodynamic. It is usually recommended to install PV panels tangentially to the vessel surface [11].

Due to mounting difficulties and safety requirements, PV panels on vessels are typically installed with zero tilt angles (in a horizontal position), and only in rare cases in vertical configurations, such as on superstructures or side surfaces. Horizontal orientation is not optimal for maximizing energy yield, it is generally preferred in maritime applications because it minimizes aerodynamic loads and ensures operational safety [8].

Vessels can be fully solar-powered, solar-assisted and solar-powered integrated with other RES. Fully solar-powered vessels represent absolutely green option due to zero fuel and zero emissions [5], using electric motors for propulsion instead of internal combustion engines [8]. However, the space available on vessels for PV panel installation is usually insufficient to generate the energy required to supply the entire ship. Therefore, PV systems can only provide a partial contribution to the vessel's total energy demand, which may be suitable primarily for small-scale or auxiliary applications. Hybrid energy-powered vessels combine two or more alternative energy sources (such as solar, wind, fuel cells, or wave energy) with conventional systems in order to compensate for the limitations of each individual source.

According to the International Convention for the Safety of Life at Sea (SOLAS), Chapter II-1, all passenger ships and cargo ships of 500 gross tonnage and above are required to be equipped with emergency

sources of electrical power. These systems must be capable of supplying essential services, such as navigation lights, communication systems, fire detection, and steering control in case of failure of the main power supply. Consequently, ships cannot rely solely on a single energy source, redundancy and reliability are critical aspects of ship power system design. Although hybrid solar-powered vessels involve high initial investment costs, they offer significant long-term benefits through improved operational safety, system redundancy, and minimal environmental impact [5].

Combination of energy storage systems (ESS) with RES on vessels enhances system reliability, improves energy utilization, and supports the transition toward low-emission maritime transport. Energy storage systems, most commonly battery-based, have an important role in balancing the intermittent nature of solar energy by storing excess power generated during favorable conditions and supplying it when generation is low or demand is high. This integration enables smoother power flow, reduces the load on conventional generators, and increases the overall energy efficiency of the vessel's power system [8].

Solar vessels can be utilized for various purposes and can be of different designs. Catamaran Tûranor (Fig. 1) is the first solar-powered vessel that circumnavigated the world in 2012. It is 31 m long, 15 m wide and has 537 m² with PV panels generating maximum power output of 93 kW. Maximum speed is 26 km/h and daily travel ranges up to 350 km [12].



Fig. 1. Tûranor solar boat [12]

In Fig. 2, an example of unmanned ship with horizontally mounted PV system on the deck is presented [13].



Fig. 2. Unmanned ship with horizontally mounted PV panels [13]

Figure 3 shows fully electric catamaran(s), CAT-10, 10 m long. PV panels on the roof supplement the battery levels leading to slower electricity consumption [14].



Fig. 3. Vessels Ecoboat [14]

At the Faculty of Maritime Studies Kotor, University of Montenegro, research on the influence of the maritime environment on PV panel performance is in its initial phase. For this purpose, two flexible DAS Energy 11×6M project PV panels are installed on the roof of a tourist passenger vessel operating in the Bay of Kotor (Fig. 4).

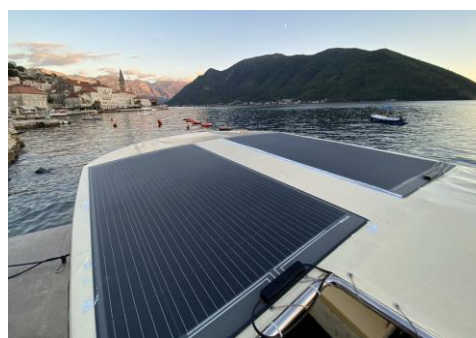


Fig. 4. Experimental setup

Each 11×6 project panel consists of 66 monocrystalline silicon cells and provides a maximum output of 330 Wp. The junction box is mounted on the front side of the module, centrally positioned, while the lightweight design of only 3.8 kg/m² enables easy installation and handling. The main technical parameters of the installed PV panels are presented in Table 1.

Table 1. Main technical parameters of the flexible DAS Energy 11×6M PV panels

Parameter	Value
P _{mpp}	330 Wp
V _{oc}	45.19 V
V _{mpp}	37.29 V
I _{mpp}	8.95 A
I _{sc}	9.48 A
Operating temperature range	-40°C to +85°C
Temperature coefficient of P _{mpp}	-0.34 % / °C
Temperature coefficient of V _{oc}	-0.25 % / °C
Temperature coefficient of I _{sc}	+0.03 % / °C

The innovative bonding system significantly reduces installation time, making such panels ideal for applications where weight and flexibility are critical factors. One PV panel serves as a reference panel, while the other is exposed to the ambient marine environment, allowing a detailed analysis of the effects of salt, humidity, and temperature on the electrical performance of the panels during future research.

The upcoming experimental phase will involve continuous monitoring of both PV panels over several months using an I-V checker for recording I-V characteristics, maximum power point (P_{mpp}), voltage (U_{mpp}), current (I_{mpp}), open-circuit voltage (U_{oc}), and short-circuit current (I_{sc}). Simultaneously, solar irradiance (G) and panel surface temperature (T) will be measured to correlate environmental conditions with electrical behavior of PV panel. Before each measurement, the reference panel will be cleaned, while the exposed panel will remain in its natural state, enabling assessment of degradation and

fouling effects caused by the marine atmosphere. These measurements aim to quantify the long-term influence of salt deposition, humidity, and temperature fluctuations on the performance degradation of PV panels in maritime applications.

CONCLUSION

Harmful environmental and health effects of maritime transport, along with increased fossil fuels prices, initiated interest in renewable energy sources application.

No matter the higher initial costs, PV technology represents suitable solution for vessels due to their advantages such as low operating costs, electricity production aligned with peak demand, cost savings, and no emissions.

When installing PV panels on vessels, the biggest challenge is limited area and possible partial shading. Also, aerodynamic loads and safety have to be considered thoroughly. Therefore, PV panels on vessels are typically installed in a horizontal position, and only in rare cases in vertical configurations, such as on superstructures or side surfaces. When it is up to PV panels operation in maritime environment, the main challenges are salty conditions, high humidity and extreme wind that can lower PV panels performance.

Available space on vessels for PV panel mounting is mostly insufficient to generate the energy required to supply the entire ship. Thus, photovoltaic systems usually can provide a partial contribution to the vessel's total energy demand, that can be suitable for small-scale or auxiliary applications.

The first stage of studying marine influence on the PV panels performance has started at the Faculty of Maritime Studies Kotor, University of Montenegro. Two flexible monocrystalline silicon PV panels are installed on the roof of a tourist passenger boat sailing in the Bay of Kotor. One PV panel is exposed to the marine environment, allowing analysis of the influence of salt, humidity, and temperature

on the electrical performance, and the other panel is a referent PV panel. This experiment is planned to be carried out for at least one year with additional plans for PV panels mounting on more vessels for future research.

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