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Photovoltaic panels efficiency on the ships

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***Abstract*—In this paper, the main goal was to integrate photovoltaic panels in the power generation systems of ships in the marine environment in order to reduce pollution and make energy consumption more efficient. Taking into account the route of the ship with the help of which the experimental data was taken at 3 photovoltaic panels and thanks to the navigation equipment through which the parameters of the hydrometeorological conditions were extracted from the entire research period, the main influences of the environment on the obtained electrical yield were analyzed. This work directly contributes to future optimizations in terms of integration of solar power generation systems in the marine environment.**

Keywords*—*renewable energy sources, photovoltaic panel, marine environment, efficiency

I. Introduction

Renewable energy sources have emerged as a viable and sustainable solution for clean energy generation. Notably, the photovoltaic system has garnered considerable interest as a highly promising and effective means of harnessing renewable energy [1]-[4]. Photovoltaic panels (PV) offers the benefits of both a distributed resource and a clean energy source [5]. Photovoltaic energy system is attracting more and more interest, due to the use of non-polluting, renewable and free solar energy, has gained increasing attention in light of mounting environmental concerns and the global energy crisis. [6]-[8].

Photovoltaic generation systems encounter two significant challenges. Firstly, the efficiency of electricity generation tends to be low, particularly in states of low irradiance. Secondly, the electricity output from solar arrays fluctuates due to varying weather conditions, specifically the intensity of solar energy [9]-[11]. With technological improvements, the practicability and cost of solar power systems have become reasonable. In addition, with the intervention strategy and technological improvements, the world markets are rapidly developing in favor of renewable photovoltaic systems [12]-[14].

The application of solar photovoltaic generation technology in maritime settings represents a novel research avenue aimed at mitigating carbon dioxide emissions and enhancing energy efficiency [15], [16]. The position and orientation of a moving ship undergo changes while navigating the ocean or sea. Consequently, the total solar irradiance on the PV panels will differ from that experienced on land, exhibiting constant fluctuations. Also the fluctuating PV power output once the ship rolls, pitches has to be taken into account, which has increased the uncertainty of the initial power output [17]-[19].

The exploration of integrating solar energy with traditional electrical equipment has emerged as a novel research direction for ship power systems. The integration of solar energy into the power supply of ships theoretically contributes to the improvement of sustainability and environmental protection, while reducing the installed capacity of the marine gas turbine [17], [20], [21]. By enhancing the energy efficiency of a PV system instead of relying on motors or auxiliary generators, it is anticipated that the overall energy utilization efficiency can be improved, leading to reduced emissions [22]-[24].

A ship that employs various types of power sources is referred to as a hybrid electric ship. Hybrid electric ships offer several advantages over traditional ships, including enhanced energy efficiency, optimized power distribution and control, improved reliability, increased available space, and enhanced performance [25]-[29].

II. Presentation of the study experiment

The Sailing Training Ship “Mircea” is a 3 masted ship-type that performs training marches with the military students of the “Mircea cel Batran” Naval Academy. In 2022, the ship performed 2 training marches in the Mediterranean Sea. On board the ship, 3 photovoltaic panels model SL6TU-18MD were installed in the stern area oriented in 3 different positions stern, starboard stern and port stern at an angle of inclination of 80^{o} (Fig.1).

TABLE I. Technical specifications of the photovoltaic panel SL6TU-18MD type

Current number	Technical specifications	
	Characteristics	***Value***
1.	Maximum power	5W
2.	Open circuit voltage	22.64V
3.	Short circuit current	0.29A
4.	Maximum power voltage	18.57V
5.	Maximum power current	0.27A
6.	Working temperature	-40ºC la +85 ºC
7.	Tolerance	0~+3%

During the period 08.04-16.05.2022 approximately 2-3 measurements per day were taken with a multimeter noting the voltage and intensity of each photovoltaic panel. Thanks to the navigation equipment on board, the ship's position, ship's course, ship's speed, humidity, nebulosity, atmospheric pressure, true wind direction and speed, air and water temperature were also noted at each measurement. According to this information accumulated in a database, each parameter was analyzed in order to make photovoltaic panels more efficient and research the field in order to optimize photovoltaic systems.

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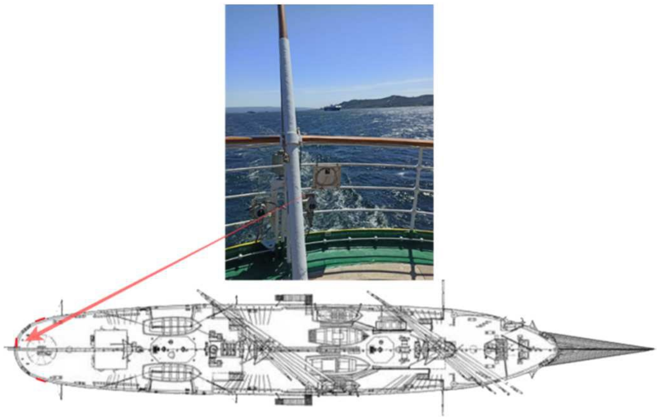

Fig. 1. Positioning of the 3 photovoltaic panels in the stern area

III. ANALYSIS OF THE EXPERIMENTAL DATA

A. Ship's course (the photovoltaic panel orientation to the sun)

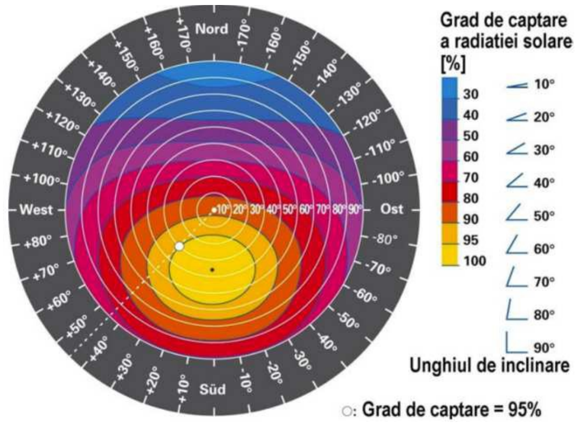

Fig. 2. The combined influence of the tilt angle and the azimuth angle, on the degree of capture of the available solar energy [30]

Analyzing figure 2, it can be seen that the optimal angle of inclination, which allows the optimal capture of solar radiation, is approx. 15...55°, and the deviation from the South direction can be between ±40° without affecting the ability to capture solar energy. For inclination angles of 5...65°, solar radiation can be recovered in proportion to 90...95% [30].

The survey started from the Tyrrhenian Sea with a view to docking in the port of Sete, continued with the port of Castellon, Naples, Istanbul and the march was completed with the port of Constanța (Fig.3). It can be noticed that the orientation of the ship given by the ship's course and the time at which the meter was taken constantly affects the production of PV electricity due to the azimuth angle on the degree of capture of the available solar energy. As we know that the tilt angle of the PV is 80° and that the sun rises from cardinal east at the time the measurement is performed when the ship is heading 300º, the probability would be that the PV on starboard would have a capture degree of solar radiation of 50%, PV from stern 80%, and PV from port side to have a degree of capture of 90% (Fig.3).

Fig. 3. Map of the voyage of the Sailing Training Ship "Mircea"

During actual sailing, the motion of the ship undergoes continuous variations over time, in addition to changing the ship's geographic position. The motion of the ship is defined by the movements of the ship heeling, rolling, pitching (Fig.4). The vessel's banding frequency and banding amplitude can be influenced by external factors, including wind, waves, sea currents and technical nautical characteristics of the vessel type such as vessel speed, maneuverability and draft [17]. Therefore, the positioning angle and tilt angle of PV panels installed on the ship also vary in response to the ship's changing motion.. The power output of the PV system exhibits additional fluctuations due to the ship's rocking motion. Hence, a research gap exists in neglecting the impact of changing PV panel positions and the lack of a comprehensive positioning plan in the design [17].

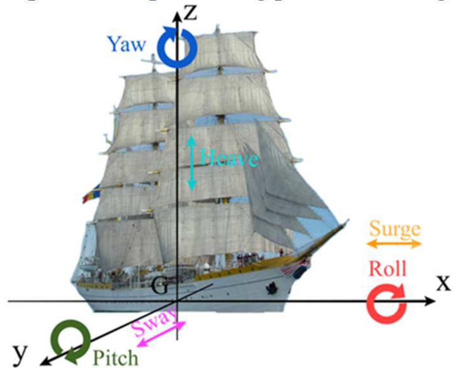

Fig. 4. The banding motion of the ship, roll, pitch

The research was carried out on board the Sailing Training Ship "Mircea" between 04.08.2022 and 05.16.2022. During this time, the ship performed:

During the period 08.04-12.04.2022, Augusta - Sete voyage;

During the period 12.04-18.04.2022, Sete harbor stationary;

During the period 18.04-21.04.2022, Sete – Castellon voyage;

During the period 21.04-25.04.2022, Castellon harbor stationary;

During the period 25.04-30.04.2022, Castellon – Napoli voyage;

During the period 30.04-04.05.2022, Napoli harbor stationary;

During the period 04.05-11.05.2022, Napoli – Istanbul voyage;

During the period 11.05-15.05.2022, Istanbul harbor stationary;

During the period 15.05-16.05.2022, Istanbul – Constanța voyage;

If it is compare the 2 situations, the time when the ship was stationed in the ports and the time when it was out at sea in a continuous movement of tacking, rolling, pitching, with changes in geographic latitudes, changes in gyration relative to the direction of the sun's rays, etc., it can be seen that a stable environment, without continuous system fluctuations, has a 3% higher yield.

TABLE II. THE 2 STATES OF THE SHIP, THE AVERAGE POWER PRODUCED AND THE EFFICIENCY

Situation	Average power produced PV Stern [W]	Average power produced PV Starboard [W]	Average power produced PV Portside [W]	Total average power produced by PV [W]	Efficiency
Ship stationary in ports	0.971	1.174	0.713	0.953	19%
Ship at sea between ports	0.821	0.922	0.719	0.820	16%

B. *Geographical latitude*

The solar energy received per unit area from the Sun, measured at the Earth's surface perpendicular to the sun's rays, under clear sky conditions and negligible pollution, can reach a maximum of 1000 W/m^2 around noon in Western Europe, Central Europe, and Eastern Europe. This value encompasses both direct and diffuse radiation. Solar radiation is subject to continuous variations influenced by several key parameters, such as [30]-[32]:

•The solar elevation angle (the angle between the direction of the sun's rays and the horizontal plane);

• The tilt angle of the Earth's axis;

• The variation in Earth-Sun distance (approximately 149 million km on an elliptical, slightly eccentric orbit);

• Geographical latitude [30]-[32].

Due to the fact that the ship will never remain at a fixed point, its position relative to geographic latitude must be taken into account, since the equatorial zone has the strongest total solar irradiance, compared to the polar areas where the sun has a lower total solar irradiance. If we compare the position of the ship in the southernmost and northernmost point at which the measurement was taken at the same time, the ship's course did not vary by more than 30 degrees, respectively the nebulosity was 0/8, we can see that the power of output of all PV is higher in the mediterranean climate zone with a yield of 32.58%. (Table III, Fig.5.)

TABLE III. MEASUREMENT DATA AT THE SOUTHERNMOST AND NORTHERNMOST POINT

Date/Time	The power produced PV stern	The power produced PV starboard	The power produced PV port side	Latitude (φ)	Longitude (λ)	Ship's course	Nebulosity	Yield
05.05.2022 17.50	3.16	1.40	1.29	37° 48' N	016° 04' E	90°	0/8	39%
14.05.2022 17.50	0.25	0.45	0.24	40° 31' N	010° 15' E	69°	0/8	6.4%

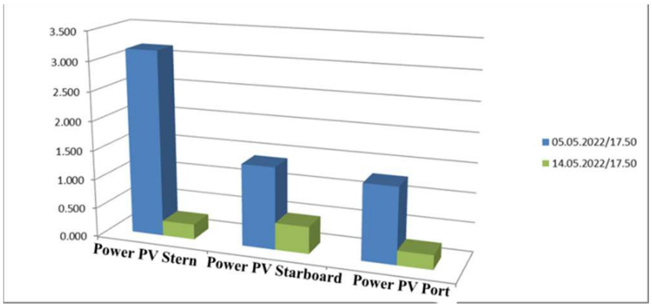

Fig. 5. The power produced by the 3 photovoltaic panels (PV) in the southernmost point on 05.05/17.50, respectively in the northernmost point on 14.05/17.50

C. *The power produced by the 3 pv*

If the power produced by the 3 photovoltaic panels is analyzed over the entire period, we obtain for all of them an identical minimum power with a value of 0.001 W and a maximum power of 4.83 W at PV portside, 4.51 W at PV starboard, respectively 4.32 W at PV stern (Fig.6.). For the minimum value, the measurement was made at an hour towards sunset when the sun had a low radiation power, on the other hand, at the maximum values of the power produced, on different days, respectively hours, the cloudiness was identical to a value of 0/8, the atmospheric pressure had the same value of 763.6 mm Hg, and the gyro track showed that the ship was oriented at that time approximately with PV perpendicular to the direction of the sun's rays. From this interpretation we can deduce that for a maximum value of the power produced by PV must be respected a cloudiness of 0/8, an atmospheric pressure of 763.6 mm Hg and an orientation of PV approximately perpendicular to the direction of the sun's rays.

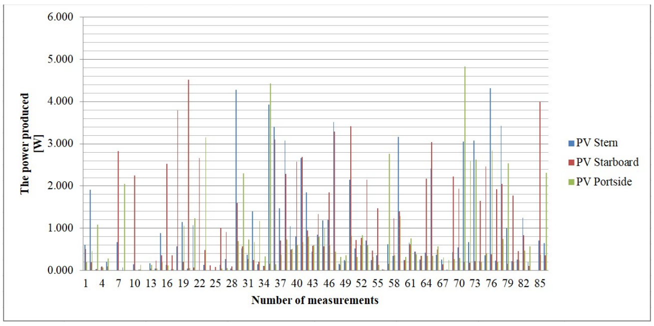

Fig. 6. The power produced by the 3 PV's over the entire experimental period

D. *Nebulosity*

We aim to estimate and analyze the impact of solar panel efficiency, taking into account cloudy periods, on electricity generation [33]. Nebulosity being the degree of coverage of the sky with clouds, it can be seen that at the value of 8/8, when the sky is 100% covered with clouds then the power produced by each individual PV is lower. The peak values of PV power are consistent with a cloudiness of 0/8 when the sky is clear (Fig.7.). For all measurements where there was a degree of maximum cloud cover the average power produced by PV was 0.33W, compared to a minimum cloud cover (clear sky period) when the average power produced by PV was of 1.22W. If we were to compare the yield between the 2 situations, the power produced with a maximum nebolosity

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would show a yield of 6.62%, compared to the minimum nebulosity where a yield of 24.46% was achieved. From this analysis it follows that when it is desired to implement a PV electricity generation system on board the ships, the generation system will have a yield of 17.84% higher percentages at the time of a nebulosity with a value of 0/8 .

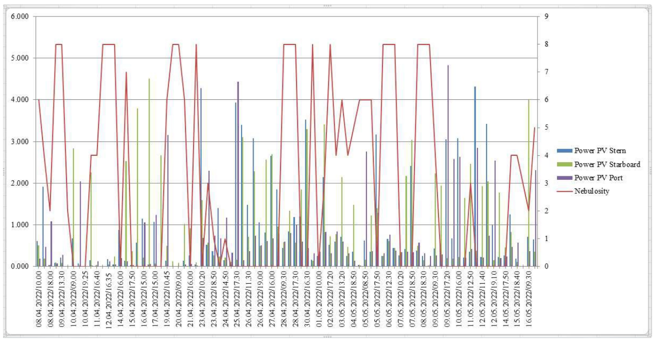

Fig. 7. Values of power generated by PV's according to nebulosity

E. Air temperature

In the photovoltaic generation system, the photoelectric conversion is facilitated by photovoltaic networks, which exhibit fluctuating and intermittent efficiency owing to changes in solar irradiance and surface temperature [34]-[36]. The power generated by the photovoltaic energy system fluctuates dynamically, during the ship's voyage, when the environmental factors (solar radiation, temperature, etc.) change [37].

From a physical point of view, the decrease in the electrical efficiency of the collector with the increase in its temperature is explained by the simultaneous manifestation of two negative effects:

- The intensity of the electric current produced, decreases strongly when the temperature of the p-n junction increases;
- The electrical voltage produced decreases when the temperature of the p-n junction increases [38].

The temperature of the photovoltaic collector, respectively the working temperature of the p-n junction, is on the one hand difficult to determine in real operating conditions and on the other hand is dependent on the following factors that influence it in a decisive manner:

- The intensity of solar radiation incident on the photovoltaic collector (normal on the planecollector) (Igt [W/m^2]);
- The ambient temperature of the collector (Ta [K]; ta [°C])[38].

As it is specified above that the electrical efficiency decreases with the increase of ambient temperature, our study based on the analysis of parameters such as air temperature can highlight a fairly solid conclusion. In real operating conditions, although it is complicated to establish the working temperature of the p-n junction, respectively the temperature of the photovoltaic collector in the graph in figure 8, it can be seen that the power peaks produced by PV on different days have a maximum electrical yield at an ambient temperature of approximately 16-18º C.

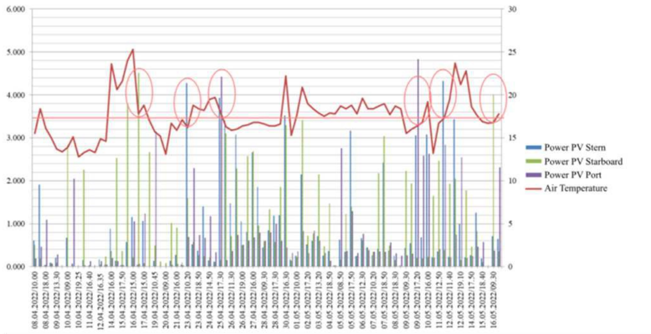

Fig. 8. Peaks of power produced by PV's according to air temperature

F. Humidity

Solar radiation undergoes a series of transformations as it interacts with the terrestrial atmosphere and the Earth's surface, as depicted in Figure 9. The total global radiation reaching the Earth's surface on a clear day comprises both direct and diffuse solar radiation. Direct solar radiation varies based on the orientation of the receiving surface, while diffuse solar radiation can be considered relatively consistent irrespective of the surface orientation, although minor variations may exist. [30].

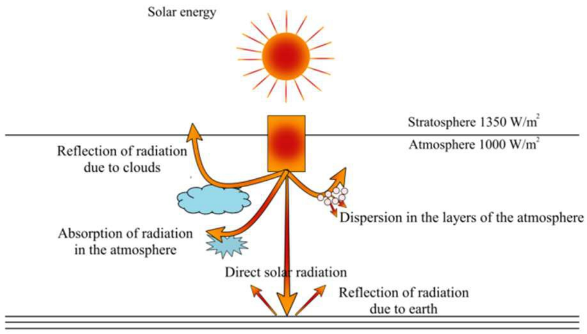

Fig. 9. The scheme of interactions between solar energy and the atmosphere, respectively the earth's surface [30]

As a polluted terrestrial atmosphere or with high cloudiness, it will decrease the values of direct solar radiation, turning it into diffuse radiation. We considered that the humidity in the air can also play a rather important role for a low, respectively optimized electrical efficiency. Investigating the experimental parameters, it was found that at the time of the maximum power production of PV from portside, the humidity had a value of 70% RH and on other days at the values of the maximum power produced by the other 2 PVs, the humidity varied from 40 to 50% RH (Fig.10.). From this graph it can be concluded that humidity is not a parameter that has a major influence on the electrical efficiency, but more likely to have an imperceptible effect.

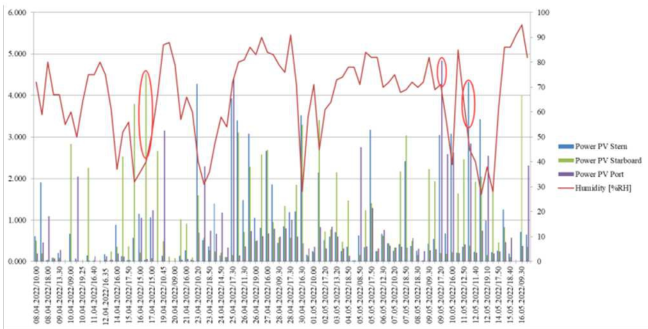

Fig. 10. Maximum power produced by PV's according to humidity

IV. Final conclusions

There is a flaw in the research that does not take into account the change in the position of the photovoltaic panels on the design and the positioning plan due to the rocking and turning of the ship. From the experimental analysis, it was found that a stable environment, without continuous system fluctuations, has a 3% higher yield.

We compared the position of the ship in the southernmost and northernmost point where the measurement was taken at the same time and we can state that due to the geographical latitude, the output power of all PV is higher in the Mediterranean climate area with an additional yield of 32.58%. The power peaks produced by the 3 PVs during the research have a maximum electrical yield at an ambient temperature of approximately 16-18º C.

In order to obtain a maximum value of the power produced by PV, it was demonstrated from the experimental data that the existence of ideal conditions such as a nebulosity of 0/8, an atmospheric pressure of 763.6 mm Hg and an orientation of PV approximately perpendicular to the direction of the sun's rays is necessary. The PV generation system will have a 17.84% higher efficiency at the time of a nebulosity with a value of 0/8.

By studying the values of air humidity in accordance with the output power of the PV, it turned out that it is not a parameter that has a major influence on the electrical efficiency, but more likely there is an imperceptible effect.

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