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MODELING OF ALBEDO FOR UNMANNED SURFACE VEHICLES POWERED BY RENEWABLE SOURCES IN VARIABLE HYDROMETEOROLOGICAL CONDITIONS

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Keywords: Unmanned surface vehicles (USV); Photovoltaic cell; LabVIEW simulation; Wind speed; Wave height.

This study introduces an innovative mathematical model developed to calculate albedo as a function of wave height and wind speed, two critical parameters for enhancing the efficiency of photovoltaic panels employed by unmanned surface vehicles (USVs) in dynamic hydrometeorological conditions. Albedo, defined as the proportion of energy reflected by a surface, significantly impacts the conversion of solar radiation into electrical power. The proposed model underwent validation through both simulations and experimental measurements using LabVIEW and DIAdem tools, demonstrating a 96% accuracy under real-world conditions. These results confirm the model's effectiveness in forecasting energy output and optimizing energy management for autonomous maritime operations.

1. INTRODUCTION

Currently, unmanned vehicles (UV) – autonomous or remotely controlled – regardless of their construction category (aerial, surface or submersible) have a wide range of applications, both civil and military, in both fields, aspects of scientific research, economic, industrial and commercial interests, information, safety and security objectives being concerned. Mobile renewable energy modules for powering unmanned surface vehicles (USVs) are compact systems designed to generate, store, and manage electricity from renewable sources [1–3]. These modules serve as power supplies for USVs and other unmanned vehicle types, offering the critical advantage of energy independence alongside the benefits of renewables [2,4]. To ensure efficiency, these modules must fulfill essential criteria: simple assembly and disassembly, high portability, and flexibility to operate in diverse settings, both onshore and offshore, where surface drones need power [5,6].

Photovoltaic panels represent an optimal solution, with research highlighting their diverse applications and performance challenges [7]. Key areas of interest include accurate estimation of total irradiation on photovoltaic module surfaces, durability and potential lifespan extension, and energy efficiency as a measure of feasibility. Rapidly changing shading conditions, influenced by the maneuvers of unmanned surface vehicles, significantly impact irradiation. Addressing this, studies focus on maximizing energy production, including implementing algorithms like maximum power point tracking (MPPT) to optimize performance under varying conditions [3,8–11].

On sustainability, addressed the issue of the amount of energy that must be provided by a photovoltaic system to ensure sufficient autonomy for the USV. Factors such as temperature, sun-tracking capabilities, and glass transparency have been analyzed through simulations and experimental tests to explore ways to enhance system efficiency [6,12–14].

In terms of yieldingness, feasibility and efficiency of photovoltaic modules, the authors considered the problem of the pulsing load mutation on the hybrid energy storage system (HESS) in the direct current (DC) microgrid. It was also pointed out that the electrical characteristics of photovoltaic modules are affected by solar radiation and the temperature that the module reaches in the external environment [15–17].

It should also be emphasized that, in the field of study approached by this paper, modeling and simulation process is essential, the literature highlighting MATLAB/Simulink software, LabVIEW software and PVSyst software as the most frequently used.

Note: the reason why only a few papers were considered about software simulation is the rational dimensioning of the work, the literature being quite rich.

USVs (sometimes called surface drones) equipped with mobile modules using renewable sources of electricity supply are intended for surveillance, monitoring, and inspection of riparian areas (onshore and offshore). Therefore, the navigation environment has a direct influence on the functional and efficiency parameters of the USVs [18]. Considering this perspective, the purpose of this paper is to develop a mathematical model, computer-assisted, for determining the albedo as a function of wave height and wind speed.

Albedo represents the reflected energy of a surface or a body, expressed as a fraction or percentage of the incident energy that is reflected into the surrounding environment. In the context of renewable electrical energy sources, particularly photovoltaic panels, albedo plays an important role as it can influence the efficiency with which photovoltaic panels convert sunlight into electrical energy [16,19,20].

2. DETERMINATION OF THE MATHEMATICAL MODEL

Conducting measurements – depending on different aspects of the interaction between light and reflective surfaces, albedo (Alb) can be defined in two ways [8,19]:

- as the ratio between the power of diffuse light reflected by the surface and the power of direct light incident on that surface; this expresses the efficiency with which the surface reflects light energy compared to the amount of solar energy received directly.

$$Alb = \frac{P_{ref}}{P_{dir}} = \frac{\frac{V_{ref}^2}{R}}{\frac{V_{dir}^2}{R}} = \left(\frac{V_{ref}}{V_{dir}}\right)^2. \tag{1}$$

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where P_{ref}[W] is the reflected power, $P_{dir[W]}$ the direct power, V_{ref}[V] the reflected voltage, and V_{dir}[V] the direct voltage in [V].

- as the ratio between the voltage of a photovoltaic panel when exposed to diffuse reflected light and the voltage when exposed to direct sunlight.

$$Alb = 1 - \frac{\Delta V}{V_{dir}} = \frac{V_{dir} - V_{dif}}{V_{dir}}. \quad (2)$$

The albedo was determined by conducting successive measurements with the same photovoltaic panel across various locations, considering wave height and wind speed as key factors.

As can be seen in Fig. 1, a 10 Wp photovoltaic panel connected to a 32 Ω circuit, consisting of two 16 Ω resistors in series, was used. The panel was placed in a box to measure the direct solar radiation, and the resulting voltage, V_{dir} was recorded, as observed in Table 1.

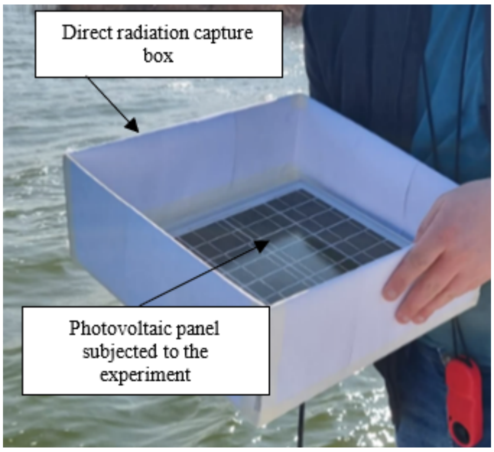

Fig. 1 – Measurement of direct radiation.

For the measurement of reflected radiation, the panel was taken out of the box and oriented towards the water surface (as shown in Fig. 2). The resulting voltages (V_{dif}) were also recorded in Table 1. In Fig. 2, the structure referred to as "Box for measuring reflected radiation" is depicted. During the experiments, the photovoltaic panel was positioned facing downward, remaining parallel to the water surface. This image was included in the article because this angle provides a clearer overall view of the box configuration. However, during the actual measurements, the box was oriented downward, ensuring its alignment parallel to the water surface.

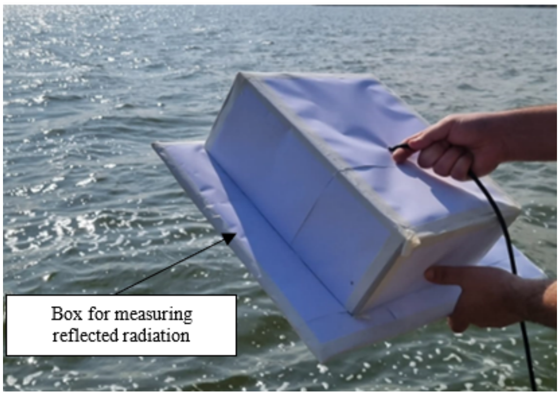

Fig 2. – Measurement of radiation reflected by water.

Table 1 also illustrates the measured values of wind speed and wave height. The collected data allowed for the determination of albedo values (see column II of Table I), which were obtained using the mathematical models of eq. (1) and (2).

Table 1

Determined albedo value.

Measurement no.	Albedo accordingly eq. (1) and (2)	V_{dir}(V)	V_{dif} (V)	Wind speed (m/s)	Wave height (m)
1	0.26117021	18.8	4.91	5.8	1.5
2	0.25026288	19.02	4.76	5.2	1.23
3	0.23263158	19	4.42	4.9	1.1
4	0.2173913	18.4	4	4.8	1
5	0.21621622	18.5	4	4.75	0.9
6	0.21428571	18.2	3.9	4.7	0.9
7	0.17553191	18.8	3.3	4.6	0.8
8	0.17297297	18.5	3.2	4.5	0.6
9	0.16595745	18.8	3.12	4.4	0.5
10	0.15873016	18.9	3	4.2	0.5
11	0.15675676	18.5	2.9	4.1	0.4
12	0.15508021	18.7	2.9	4	0.3
13	0.13513514	18.5	2.5	4	0.2
14	0.13297872	18.8	2.5	3.9	0.2
15	0.12105263	19	2.3	3.8	0.2
16	0.11536445	19.07	2.2	3.5	0.2
17	0.11290323	18.6	2.1	3	0.1
18	0.10582011	18.9	2	2.3	0.1
19	0.09574468	18.8	1.8	2	0.1
20	0.06914894	18.8	1.3	0	0

2.1. DETERMINING THE MATHEMATICAL MODEL FOR ALBEDO BASED ON WAVE HEIGHT AND WIND SPEED

To create the mathematical model of albedo based on wind speed, (v_{wind})and wave height (h_{wave}) the DIAdem software from National Instruments was chosen due to its high precision. DIAdem is a complex software offering advanced functionalities for visualizing, analyzing, interpreting, and reporting large databases. The data were imported from an Excel file into DIAdem, where measurement units were assigned according to the international system. The approximate function from the Analysis menu was used to determine the mathematical equation.

For the albedo value based on wave height (Fig. 3), the mathematical model expressed by eq. (3) provides a coefficient of determination value of 0.984, indicating an accuracy of 98.4 %.

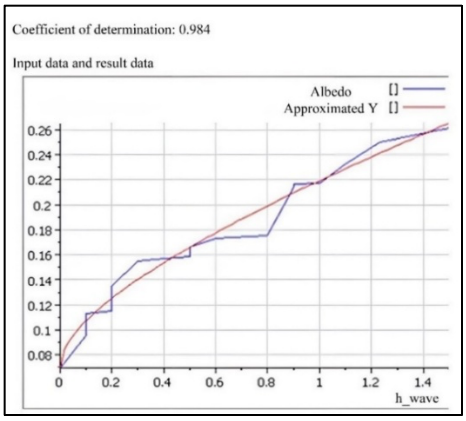

Fig. 3 – Determination of albedo on wave height.

$$Alb_{wave} = 0{,}104 \cdot \sqrt{h_{wave}} + 0{,}0459 \cdot h_{wave} + 0{,}0697 \quad (3)$$

For the albedo value based on wind speed (Figure 4), the mathematical model expressed by equation (4) provides a coefficient of determination value of 0.996, indicating an accuracy of 99.6 %.

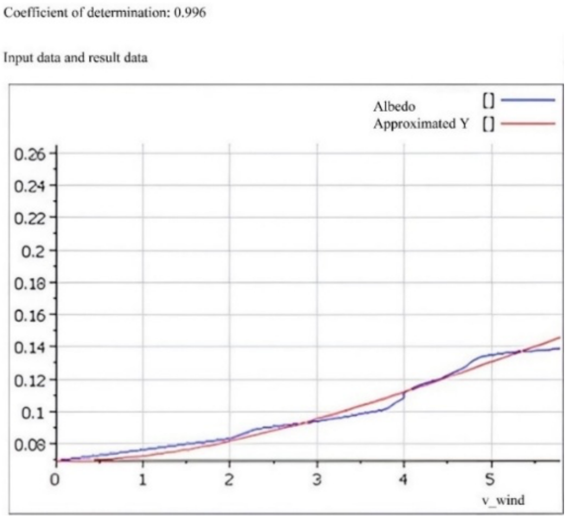

Fig. 4 – Determination of albedo on wind speed.

$$Alb_{wind} = 0{,}008 \cdot v_{wind}^3 + 0{,}0017 \cdot v_{wind}^2 + 0{,}0729. \quad (4)$$

To generate the combined mathematical model for albedo, which depends on both wind speed and wave height, we consider that eq. (3) and (4) are given equal weights of 0.5 (50 %). Wave height is closely linked to wind speed, with both factors significantly influencing the atmospheric conditions surrounding the photovoltaic panel and, in turn, affecting the albedo of the marine surface. By considering this proportional relationship, the calculation is simplified, eliminating the need to model intricate interactions in detail. Thus, the mathematical model determined for the albedo value based on wave height is given by

$$Alb = \frac{1}{2}\left(0{,}104 \cdot \sqrt{h_{wave}} + 0{,}0459 \cdot h_{wave} + 0{,}008 \cdot v_{wind}^3 + 0{,}0017 \cdot v_{wind}^2 + 0.1426\right). \quad (5)$$

3. SIMULATION OF PHOTOVOLTAIC CELL OPERATION AT ALBEDO VARIATIONS IN LABVIEW

LabVIEW allows for the writing and simulation of complex equations through an intuitive graphical interface, facilitating the modeling and analysis of system behavior without the need for traditional programming. In the specialized literature [9,22,23], the mathematical model for the current generated by a photovoltaic panel is defined by

$$I = I_{ph} - I_0\left(e^{\frac{qV}{nKT}} - 1\right). \quad (6)$$

The current I_{ph} is given by

$$I_{ph} = \left(I_{sc} + K_i \cdot (T - T_{ref})\right) \cdot \frac{S + S \cdot Alb\,(1 - \cos\theta)}{S_{ref}}. \quad (7)$$

By incorporating the derived albedo equation into the current equation and integrating it into the broader mathematical model, a final expression is obtained. This expression delineates the relationship between the current output of a photovoltaic panel situated near a water body and the environmental factors influencing it, specifically wind speed and wave height. This integration highlights how these variables impact energy generation, offering valuable insights for optimizing photovoltaic performance in dynamic environments.

$$I = \left(I_{sc} + K_i \cdot (T - T_{ref})\right) \times \left(\frac{S}{S_{ref}} + \frac{S \cdot (1 - \cos\theta)}{S_{ref}}\right) \times \left(\frac{1}{2}\left(0{,}104 \cdot \sqrt{h_{wave}} + 0{,}0459 \cdot h_{wave} + 0{,}008 \cdot v_{wind}^3 + 0{,}0017 \cdot v_{wind}^2 + 0.1426\right)\right) - I_0\left(e^{\frac{qV}{nkT}} - 1\right). \quad (8)$$

Figure 5 presents a screenshot of the front panel window, which expresses the dependence of the current on the determined mathematical model (yellow, current; red, albedo).

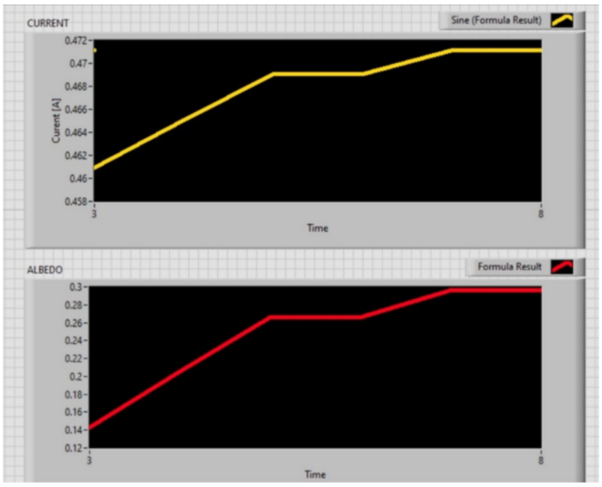

Fig. 5 – Dependence of current on the determined mathematical model.

Figure 6 illustrates the block diagram corresponding to eq. (8), highlighting the interplay between wind speed, wave height, and albedo, which collectively impact the current output of photovoltaic panels. This visualization underscores the dynamic relationship between environmental conditions and energy generation efficiency.

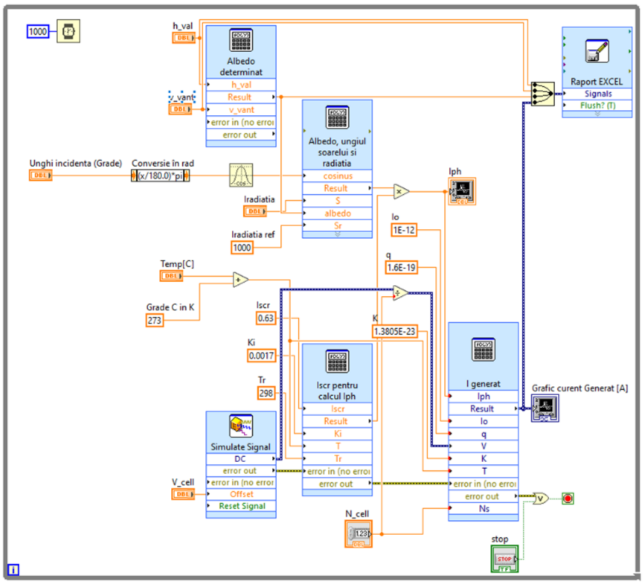

Fig. 6 – Block Diagram of eq. (8) written in LabVIEW.

For mobile modules powering USVs with renewable energy sources, particularly photovoltaic panels, the ability to predict electricity production is a critical factor for the operational success of missions. Accurate forecasting enables efficient energy management, ensuring that the USV remains powered throughout its operation. This requires accounting for variables such as environmental fluctuations, shading, and the mobility of the platform itself. By integrating advanced modeling and simulation tools, these systems can better adapt to real-world conditions, optimizing energy output and contributing to the reliability and autonomy of USVs in both onshore and offshore scenarios.

The Formula blocks represent the interface of the equations. The Simulate Signal block in LabVIEW generates the electrical voltage of the photovoltaic cell (as found in eq. (6), (8)).

The generated current was simulated for different hydrometeorological conditions (as shown in Table 1) and angles of incidence of direct radiation (10°-90° – ideal case). The resulting data were visualized graphically (Fig. 5) and saved in an Excel report (Table 2).

Table 2

Data obtained through simulation

Wave height [m]	Wind speed [m/s]	Albedo	Incident angle	Wave height [m]
0	0	0.0713	30	0.320615
0.1	3.1	0.217371	30	0.332118
0.1	3.2	0.229815	30	0.333098
0.2	3.5	0.281058	30	0.337133
0.2	3.6	0.296785	30	0.338372
0.2	3.5	0.281058	40	0.425284
0.2	3.6	0.296785	40	0.426422
0.2	3.8	0.330907	40	0.42889
0.1	3.2	0.229815	45	0.46047
0.2	3.5	0.281058	45	0.463813

4. ANALYSIS OF SIMULATED DATA IN DIADEM SOFTWARE

The data obtained from the LabVIEW simulations were used for the analysis using DIAdem software from National Instruments[24]. The data was compiled into Excel reports to emphasize the relationship between the current generated by a photovoltaic panel and the albedo, as defined by the mathematical model. In Figure 7, the graph in brown illustrates the current produced at an incidence angle of 60°. The red graph corresponds to 45°, and the blue represents 30°.

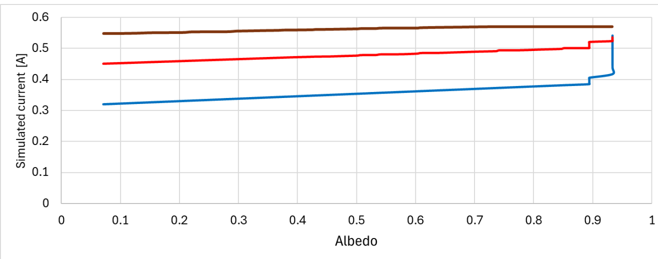

Fig. 7 – Current graphs obtained from the simulation for three angles of incidence.

Figure 8 shows the relationship between the generated current and albedo for all 10 simulated incidence angles, ranging from 10° to 90°, for a 10 Wp photovoltaic panel. The results highlight that albedo significantly impacts electric current production, with its influence being more pronounced at incidence angles below 60°. This effect can be attributed to the fact that, at lower angles, the panel captures a more significant portion of the surface-reflected light, thereby enhancing energy generation. Conversely, at higher angles, the impact of albedo diminishes as reflections become less critical for solar energy absorption.

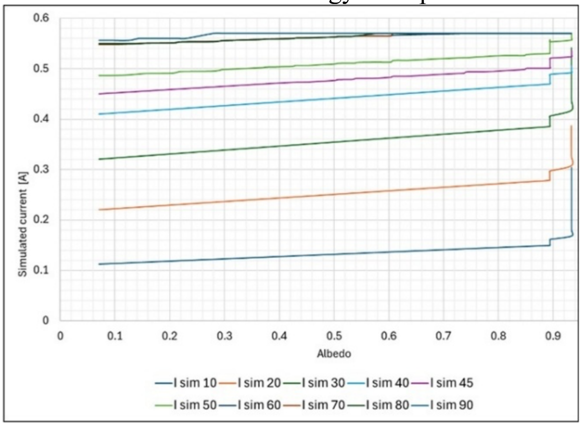

Fig. 8 – Current graphs obtained from the simulation for ten angles of incidence.

5. TESTING AND VALIDATION OF SIMULATED DATA IN REAL CONDITIONS

Data acquisition involved mounting a 10 Wp panel on the shore of Lake Siutghiol at the Marine Training and Water Sports Section of the Mircea cel Bătrân Naval Academy in Constanța, from March 15, 2024, to May 15, 2024, connected to an optimal load for the 10 Wp capacity. LabVIEW software and the USB 6008 [25] data acquisition board were used for data acquisition, as shown in Fig. 9. As previously mentioned, the data acquisition board (USB 6008) supports a maximum voltage measurement of 10 V, so a voltage divider was implemented.

USB 6008 data acquisition board is a compact device for gathering and monitoring analog and digital signals. It offers multiple analog input channels with a 12-bit resolution, enabling precise measurements for signals with a maximum voltage of 10 V. Additionally, the board includes a few analog outputs and digital channels, valid for a range of control and data acquisition applications.

The USB connectivity ensures easy integration with a computer, while compatibility with LabVIEW software allows users to configure, monitor, and process data within an intuitive graphical interface. With sampling rates of up to 10 kS/s, the USB 6008 is commonly used in educational applications and laboratory projects where an affordable and flexible data acquisition solution is needed.

Figure 10 shows the block diagram of the data acquisition algorithm created in the Block Diagram window of the LabVIEW software.

The DAQ Assistant block is a software interface for the USB 6008 board designed to measure the voltage applied to the circuit's voltage divider. Once the voltage is recorded, the signal is sent to the Sample Compression block, which standardizes the obtained values, significantly improving measurement accuracy. The measured signal is then multiplied by 2 to calculate the voltage at the terminals of the photovoltaic panel. To determine the current in the circuit, this terminal voltage is divided by the circuit resistance, which is 32 Ω. Like the simulation phase, the actual voltage and current data were collected and stored in an Excel file. Additionally, these parameters were displayed in real-time on the Front Panel window, allowing continuous monitoring and assessment of the circuit's performance. This approach ensures a detailed and reliable analysis of the photovoltaic panel's operation under real-world conditions.

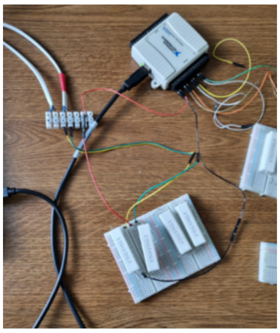

Fig. 9 – Connecting the USB 6008 to the circuit powered by the photovoltaic panel.

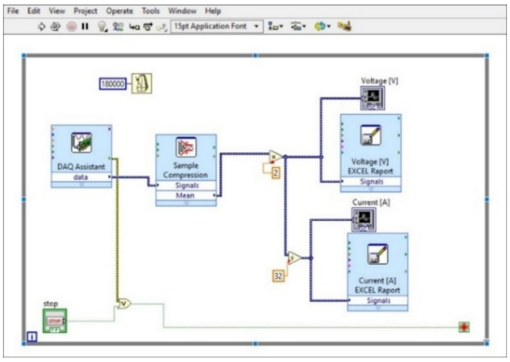

Fig. 10 – Data acquisition program using USB 6008 and LabVIEW.

Figure 11 presents an analysis of the behavior of the current generated by the photovoltaic panel at high solar radiation incidence angles, ranging from 60° to 90°. Observations indicate an almost complete overlap of the graphs, showing similar current values for these large angles, suggesting reduced panel sensitivity to angle variations within this range. Figure 11 provides a detailed illustration of the current curves generated by the photovoltaic panel for various angles of solar radiation incidence, allowing for a comparative assessment of the recorded values. Meanwhile, Fig. 12 offers an integrated analysis that includes the actual currents generated by the panel and the simulated currents for the same incidence angles. This dual representation enables an accurate evaluation of the alignment between theoretical and experimental values, providing a robust validation of the simulation model used to predict photovoltaic performance under variable lighting conditions.

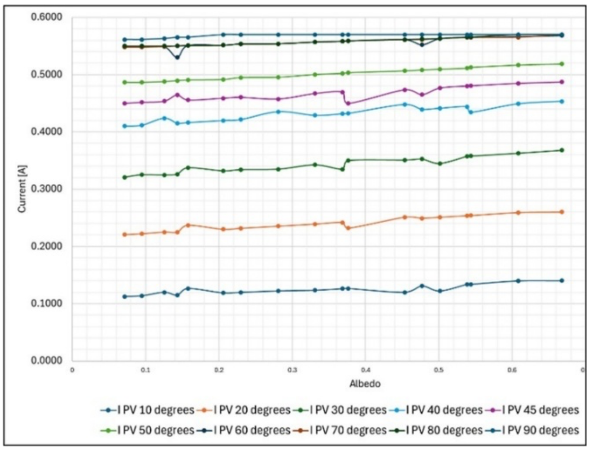

Fig. 11 – Graph of actual currents generated by the photovoltaic panel.

The data analysis presented in Fig. 11 and Fig. 12 indicates a distinct relationship between the current produced by the photovoltaic panel and the albedo value across all solar radiation incidence angles. This dependency shows that, under typical conditions, albedo plays a significant role in influencing the panel's current output. However, as the incidence angle increases to larger values (between 60° and 90°), the impact of albedo on generated current becomes negligible, indicating reduced sensitivity of the panel to albedo variations within this range.

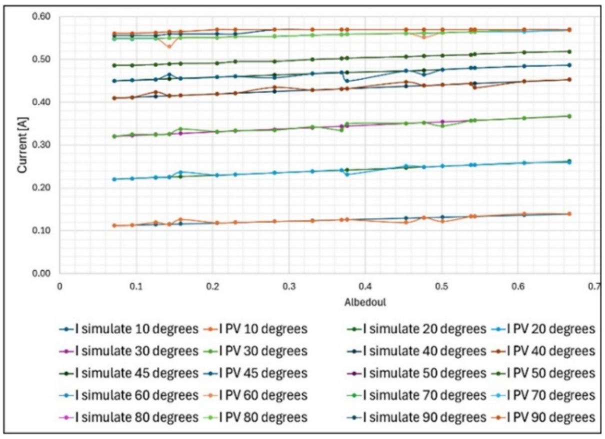

Fig. 12 – Graph of simulated and real currents.

The mathematical model developed to describe albedo variation based on wave height and wind speed, presented in eq. (5), directly impacts the electrical output capacity of a photovoltaic panel located near a body of water. This influence can be attributed to the fact that hydrometeorological factors, such as waves and wind, alter the light reflection from the water surface, affecting the intensity of radiation reflected toward the panel. The proposed model is essential for understanding and predicting the energy behavior of photovoltaic panels in coastal or marine environments, contributing to optimizing energy production in response to specific environmental conditions.

6. CONCLUSIONS

The mathematical model was validated with impressive precision through simulations, data acquisition, and comprehensive analysis. Predictions generated using DIAdem software showed an accuracy of 98 %, while real-world data validation achieved approximately 96 % accuracy. The mean absolute error of 0.011 and the mean relative error of 4.17 % reveal minimal discrepancies between simulated and observed values. These results demonstrate the model's reliability for accurately predicting and applying mobile power supply systems for surface drones powered by renewable energy sources.

Thus, the determined mathematical model can accurately predict the behavior of the analyzed system, being satisfactorily validated and demonstrating considerable precision in both simulations and experimental measurements. This highlights the added value of the mathematical model and justifies its use in future analyses and predictions, ensuring accuracy in the decision-making process for a drone's mission.

The originality of this work lies in developing a mathematical model for predicting albedo based on wave height and wind speed (essential characteristics of the navigation environment). The validated model optimizes the performance of photovoltaic panels that equip USVs in variable hydrometeorological conditions, and the validation performed with accurate, practical measurements demonstrates an accuracy of 96 %.

The method proposed by the authors of this work allows for the anticipation of electricity production and efficient energy management in monitoring missions, facilitating the adoption of renewable sources in autonomous maritime applications.

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CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Nicolae-Silviu Popa: Coordinated the design and installation of the system, contributing to component selection and technical solutions. Managed correspondence with the editorial team, ensuring journal requirements were met and the publication process was completed on time.

Ciprian Popa: Responsible for the technical integration of components and design optimization, coordinated data collection, and contributed to the article's drafting by organizing content and formulating conclusions.

Ovidiu Cristea: Developed the data acquisition system, implementing hardware and software solutions for efficient monitoring and storage—validated system functionality through rigorous testing.

Florențiu Deliu: Developed the experimental methodology and system dimensioning to ensure optimal performance, establishing experimental guidelines and proposing technical improvements.

Mihaela-Greti Manea: Conducted a comprehensive literature review, synthesizing relevant information and drafting the introduction to highlight the research's context and significance.

Mihai-Octavian Popescu: Analyzed the collected data, validating results and interpretations. Reviewed the manuscript, enhancing its clarity, structure, and style for publication.

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