# SOLAR ENERGY UTILIZATION FOR POWERING SURFACE DRONES: STUDY ON MATHEMATICAL MODELS FOR ELECTRICITY PRODUCTION PREDICTION

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*This paper focuses on the use of solar energy for powering surface drones (USVs - Unmanned Surface Vehicles) through mobile modules powered by renewable energy sources. The study involved simulations using specialized LabVIEW software and a detailed analysis of the collected data with the help of DIAdem software. These efforts led to the development and validation of a mathematical model that determines albedo based on wave height and wind speed. Predicting electricity production based on hydrometeorological parameters is crucial for efficient planning of surface drone missions. This ensures the continuous and efficient powering of drones, contributing to the success of operations. This approach highlights the importance of integrating renewable energy sources into autonomous power systems, providing a sustainable and reliable solution for surface vehicles used in various applications, from maritime surveillance to scientific research.*

**Keywords**: photovoltaic panel, drone, albedo, data analysis, data acquisition

## 1. Introduction

Solar energy can be seen as an inexhaustible energy source, received directly from the sun (light and heat). Over time, thanks to research and human involvement, this type of energy has become fundamental for reducing pollution.

Technological advancements have allowed the transition from simple photovoltaic cells to complex systems, either independent or grid-connected/stand-alone. In terms of costs, this type of technology has become quite affordable and is spreading increasingly. Currently, the conversion of solar energy into electricity enjoys political support to reduce the amount of CO2 in the atmosphere, which means that research in photovoltaic systems continues to receive funding for a less

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polluted future (especially the member states of the European Union) [1], [2], [3], [4], [5].

Regarding the production and use of electricity derived from the conversion of solar energy, we recognize two types of systems:

**Grid-connected** – Electricity generated from renewable energy sources (such as photovoltaic panels, wind turbines, etc.) is consumed by the user, and any excess energy is transferred to the local or national grid. [6], [7]When electricity is not being produced due to various reasons (such as cloudy skies or very low wind speeds), the user will draw energy from the grid.[8], [9], [10]

**Stand-alone** – The energy produced can be stored in various types of batteries, properly stored, so that later this energy can power electrical consumers. [6], [8], [9], [10]

Electricity generated from photovoltaic panels can be utilized to power a variety of consumers. One example of such consumers is surface drones (Unmanned Surface Vehicles – USVs).

Surface drones are advanced platforms equipped with exceptional nautical and maneuvering capabilities, capable of safely navigating through channels, rivers, lakes, or open seas without requiring onboard personnel and without using a conventional propulsion source (internal combustion engine).[7], [11] They possess excellent tactical and technical features, including low displacement, radar invisibility, high maneuverability, and high speed. Surface drones (USVs) can undertake a wide range of missions, such as military operations (maritime surveillance, clearing of anchored or drifting mines, reconnaissance of objects or shapes present in the sea or lakes, electronic warfare, maritime interdiction, maritime traffic monitoring, etc.), missions specific to coast guards (surveillance, reconnaissance, access restriction, maritime/river traffic monitoring), and roles in education and science (education, oceanography, ecology, etc.) [12], [13], [14]

The authors of this paper aim to develop a mobile module for supplying electricity to surface drones. Mobile modules with renewable energy sources for powering surface drones represent an integrated system of equipment designed for generating, storing, and managing electricity produced from renewable sources. Another particularly important role, especially in the military field, is the reduced time required for disassembling and assembling these modules, with the objective of performing these operations as quickly as possible.

Mobile modules offer the advantage of energy independence and must be easy to assemble and disassemble, easy to transport, and capable of being positioned wherever electricity supply for surface drones is needed (lakes, deltas, swamps, etc.). Therefore, photovoltaic panels were chosen as the equipment for generating electricity.

Since the mobile modules for supplying surface drones are mounted at the edge of a water surface (lakes, deltas, sea), this paper studies the dependence of albedo on wind speed and wave height, and implicitly the dependence of the current generated by the system on these hydrometeorological parameters.

Surface drones are vessels designed to navigate specific maritime areas and carry out specific missions, using mobile modules placed on the water's edge to charge their batteries; when the drones return to base, the batteries are replaced to ensure operational continuity.

Additionally, photovoltaic systems can be used to power consumers located on offshore oil platforms, or they can be installed on oil platforms to supply electrical power to aerial drones or surface drones.[15]

## 2. Determination of Albedo Based on Wave Height and Wind Speed

To determine the Albedo based on wave height (m) and wind speed (m/s), the method of successive measurements was chosen using the same photovoltaic panel (the characteristics of the panel and circuit will be presented later), in different locations (by the shore of lakes and the sea) at varying wave heights and wind speeds. For this experiment, a photovoltaic panel with a maximum power of 10 Wp connected to a 32 Ω circuit was selected to optimize the circuit.

To determine the albedo, the panel was placed inside a box to measure the direct radiation from the sun. The panel is powered only by direct solar radiation (Fig. 1), and the voltage at the circuit terminals will be noted as $V_{dir}$ – direct voltage – with the panel oriented so that the sun's rays are perpendicular to the panel's surface. For measuring the reflected voltage, the panel is removed from the box, the back part is covered with a plate, and it is positioned facing the water surface (Fig. 2), so it is illuminated only by the water's reflection (diffuse radiation). The voltage at the circuit terminals will be noted as $V_{dif}$. To find the albedo ($Alb$), either equation 1 or 2 can be used[16], [17]. As the voltage data at the PV terminals are recorded, the characteristics of the hydrometeorological parameters (wave height and wind speed) are also noted.

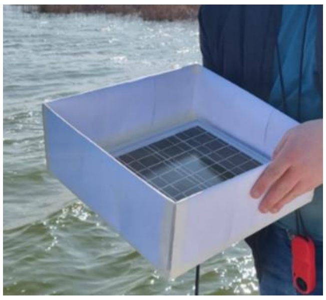


Fig. 1 – Capturing direct radiation

Fig. 2 – Capturing diffuse radiation

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

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

The data obtained from the measurements and calculations related to equations 1 and 2 are found in Table 1.

*Table 1*

**Albedo value and measurement data**

| Measurement No. | Albedo Eq. 1, eq. 2 | Direct Voltage (V) | Indirect Voltage (V) | Wind Speed (m/s) | Wave Height (m) |
|---|---|---|---|---|---|
| 1. | 0.261170 | 18.8 | 4.91 | 5.8 | 1.5 |
| 2. | 0.250262 | 19.02 | 4.76 | 5.2 | 1.23 |
| 3. | 0.232631 | 19 | 4.42 | 4.9 | 1.1 |
| 4. | 0.217391 | 18.4 | 4 | 4.8 | 1 |
| 5. | 0.216216 | 18.5 | 4 | 4.75 | 0.9 |
| 6. | 0.214285 | 18.2 | 3.9 | 4.7 | 0.9 |
| 7. | 0.175531 | 18.8 | 3.3 | 4.6 | 0.8 |
| 8. | 0.172972 | 18.5 | 3.2 | 4.5 | 0.6 |
| 9. | 0.165957 | 18.8 | 3.12 | 4.4 | 0.5 |
| 10. | 0.158730 | 18.9 | 3 | 4.2 | 0.5 |
| 11. | 0.156756 | 18.5 | 2.9 | 4.1 | 0.4 |
| 12. | 0.155080 | 18.7 | 2.9 | 4 | 0.3 |
| 13. | 0.135135 | 18.5 | 2.5 | 4 | 0.2 |
| 14. | 0.132978 | 18.8 | 2.5 | 3.9 | 0.2 |
| 15. | 0.121052 | 19 | 2.3 | 3.8 | 0.2 |
| 16. | 0.115364 | 19.0 | 2.2 | 3.5 | 0.2 |
| 17. | 0.112903 | 18.6 | 2.1 | 3 | 0.1 |
| 18. | 0.105820 | 18.9 | 2 | 2.3 | 0.1 |
| 19. | 0.095744 | 18.8 | 1.8 | 2 | 0.1 |
| 20. | 0.069148 | 18.8 | 1.3 | 0 | 0 |

To create the mathematical model of albedo for variations in wind speed and wave height, Excel software can be used. However, for greater accuracy, the DIAdem software from National Instruments was chosen. DIAdem is a complex software designed for engineers and scientists to efficiently manage, deeply analyze, and systematically report large datasets collected during experiments and tests. It offers advanced data visualization functionalities, including 3D graphs and diagrams, powerful analysis tools such as statistics and signal processing, and the capability to create customized and automated reports, thus optimizing engineering workflows and supporting data-driven decision-making.[18]

To determine the mathematical model of the influence of wind speed and wave height on albedo, the equation was approximated in three stages. The first stage involved determining the albedo equation based on wave height (Fig. 3, Equation 3). The mathematical model provided by DIAdem shows an accuracy of

98.4% (as shown in Fig. 3). The second stage involved determining the mathematical model of the influence of wind speed on albedo (Fig. 4, Equation 4) with a precision factor of 99.6% according to DIAdem analysis. The third stage involves creating the mathematical model for both hydrometeorological parameters (Equation 5).

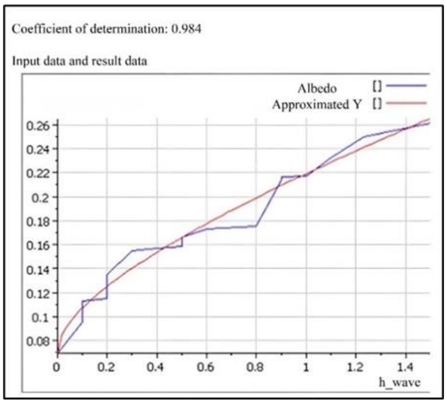



Fig. 3 – Albedo equation based on wave height; Vertical Axis - Albedo Value

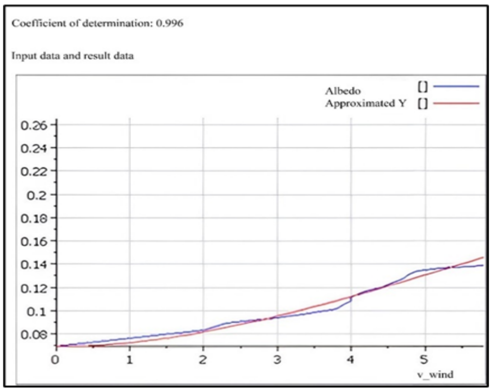



Fig. 4– Mathematical model of the influence of wind speed on albedo; Vertical Axis - Albedo Value

$$Alb_{val} = 0.104 \cdot \sqrt{h_{val}} + 0.0459 \cdot h_{val} + 0.0697 \quad (3)$$

$$Alb_{vânt} = 0.008 \cdot v_{vant}^3 + 0.0017 \cdot v_{vant}^2 + 0.0729 \quad (4)$$

Both mathematical models are given a weight of 0.5 (i.e., 50%) because wave height is directly proportional to wind speed and contributes equally to the changes in the atmosphere around the photovoltaic panel, which affects the albedo of the marine surface. This simplified hypothesis allows for a direct and simpler calculation, avoiding the complexity of modeling the detailed interactions between wind speed and wave height.

$$Alb = \frac{1}{2}\left(0.104 \cdot \sqrt{h_{val}} + 0.0459 \cdot h_{val} + 0.008 \cdot v_{vant}^3 + 0.0017 \cdot v_{vant}^2 + 0.1426\right) \quad (5)$$

Equations 3 and 4 were derived and validated under specific experimental conditions, using photovoltaic panels placed on the shore of a lake with predetermined solar incidence angles. During the experiments, environmental conditions such as cloud cover were not varied significantly. Therefore, the models are most accurate under clear sky conditions.

### 3. Electricity Production – LabVIEW Simulation

To simulate the photovoltaic cell with variations in Albedo based on wave height and wind speed, we start from relationships 6 and 7 and the determined relationship 5. Equations 6 and 7 are found in specialized literature [19], [20], [21].

$$I_{ph} = \left(I_{sc} + K_i \cdot (T - T_{ref})\right) \cdot \frac{S + S \cdot Alb\,(1 - \cos\theta)}{S_{ref}} \tag{6}$$

$$I = I_{ph} - I_0\left(e^{\frac{qV}{nkT}} - 1\right) \tag{7}$$

This simulation aims to obtain the values of the current generated by photovoltaic cells according to the determined equation. By substituting equation 5 into relationship 6, and then substituting the result into relationship 7, we obtain equation 8 – the equation of the current generated by a photovoltaic cell subjected to changes in albedo based on wave height and wind speed.

$$I = \left(I_{sc} + K_i \cdot (T - T_{ref})\right) \cdot \frac{S + S \cdot \left(\frac{1}{2}\left(0.104 \cdot \sqrt{h_{val}} + 0.0459 \cdot h_{val} + 0.008 \cdot v_{vant}^3 + 0.0017 \cdot v_{vant}^2 + 0.1426\right)\right) \cdot (1 - \cos\theta)}{S_{ref}} - I_0\left(e^{\frac{qV}{nkT}} - 1\right) \tag{8}$$

Fig. 5 represents the block diagram of equation 8 – the influence of wind speed and wave height on albedo, and implicitly on the current generated by photovoltaic panels, as written in the LabVIEW software. For mobile modules providing electrical power to surface drones using renewable energy sources, specifically photovoltaic panels, anticipating electricity production is a crucial pillar for the success of the drones' operations/missions.

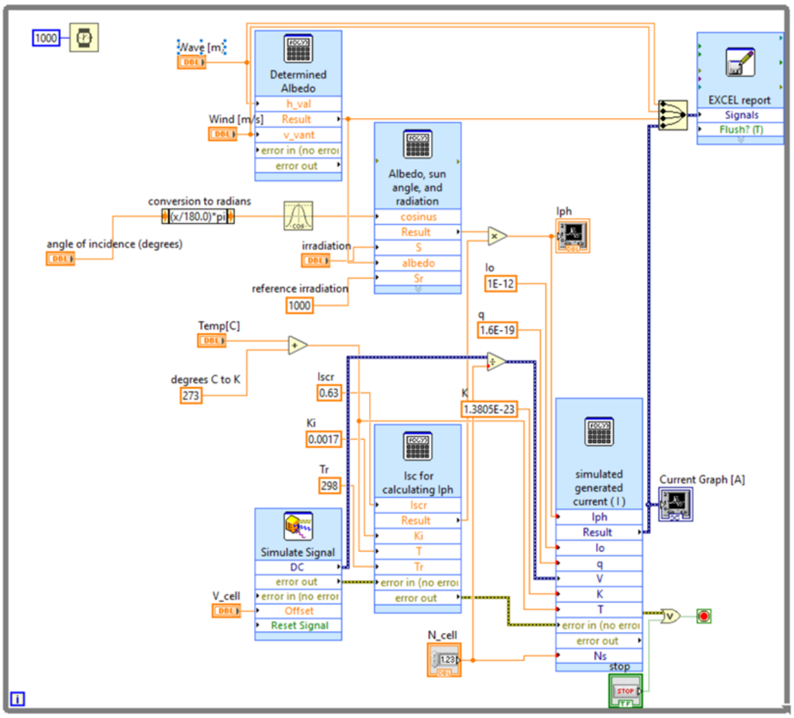



Fig. 5 – The block diagram of equation 8

For the analysis using DIAdem software from National Instruments, the data obtained from the simulation in LabVIEW, which was centralized in the Excel report, were used. In Fig. 6, the graph marked in brown represents the current generated by a photovoltaic panel according to equation 8 for an incidence angle of 60°; the red color represents the current graph defined by the same equation for an incidence angle of 45°, and blue represents the current graph for an incidence angle of 30°.Analyzing these data, one can observe the dependency of the current generated by a PV on albedo, implicitly indicating the current's dependency on hydrometeorological factors.

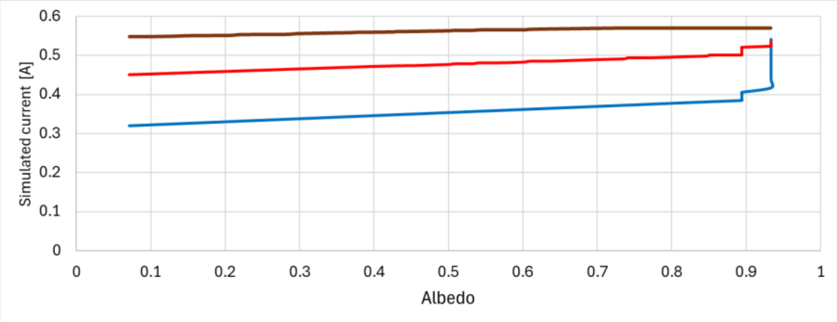



Fig. 6 –The graph of the dependency of the current generated by a photovoltaic panel on the albedo defined by equation 8

In Fig. 7, the dependency of the current generated by a photovoltaic panel on Albedo can be observed for all 10 incidence angles used in the simulation (10°, 20°, 30°, 40°, 45°, 50°, 60°, 70°, 80°, and 90° - the ideal case) for a 10 Wp and 18 V panel.

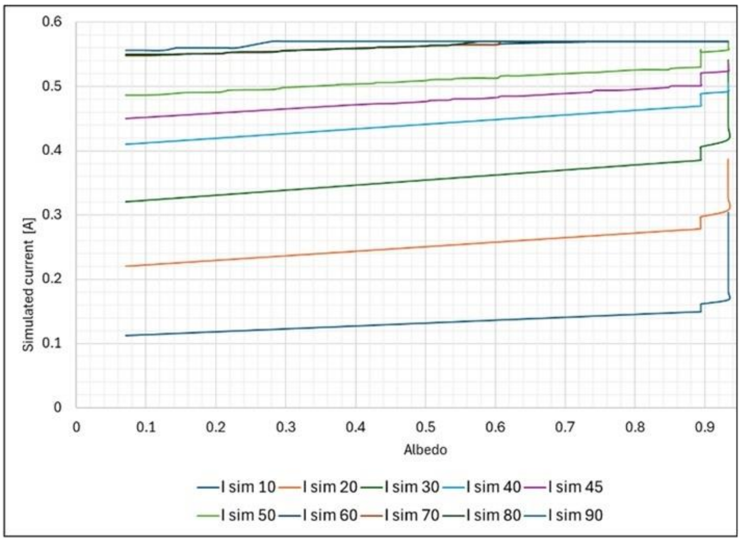



Fig. 7 –The graph of the dependency of the current generated by a photovoltaic panel on the albedo defined by equation 8

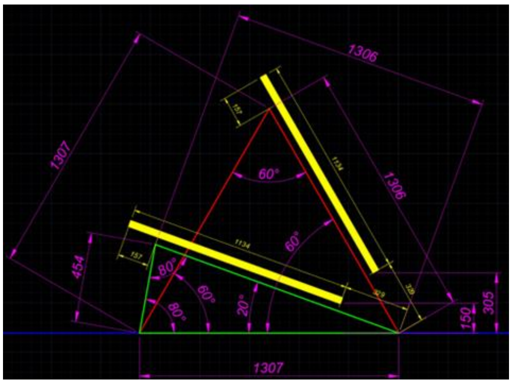
According to the analysis conducted using DIAdem software, it can be seen that the Albedo defined by equation 8 influences the production of electric current for all cases. This variation/dependency is more noticeable at incidence angles below 60°, as a smaller incidence angle of direct radiation corresponds to a larger angle formed between the photovoltaic panel and the ground, significantly increasing the influence of Albedo.

## 4. Practical Implementation of the Mobile Electric Power Supply Module

As previously mentioned, the mobile modules represent an integrated system of equipment capable of producing and storing electric energy in any operational area for charging the batteries of surface drones. For the practical implementation, the system was placed on the shore of Lake Siutghiol at the "Marine Training and Water Sports Section Palazu-Mare" - Romanian Naval Academy "Mircea cel Bătrân".

Equipment used for the system:

- 4 Photovoltaic Panels – Canadian Solar 395 MS – 395Wp- 35.5V
- MPPT 150/45
- Mobile Support for Photovoltaic Panels
- Lithium Iron Phosphate Batteries – 25.6V, 200Ah




a)

b)

Fig. 8 – Technical Drawing of the Support for the Photovoltaic Panels and the Panels' Support Mounted in Position

From Fig. 8, it can be observed that the angle formed by the PV panel with the ground, and implicitly with the Sun's rays, can be adjusted according to the hydrometeorological situation at the time the system is activated. In Fig. 8b, the photovoltaic panels were set at different angles only to demonstrate the ability to adjust the panel's angle. During the experiment, all panels were set to the same position on the mobile support. In Fig. 8a, the AutoCAD drawing of the panel support can be observed.

Fig. 9 – Mounting the system on the lakeshore

The presented system operated on the shore of Lake Siutghiol for 5 days (June 8, 2024 - June 12, 2024). During its operation, the influence of the previously mentioned hydrometeorological parameters (wind speed and wave height) on electricity production was monitored. This was achieved through two methods:

The first method involved connecting a mobile phone to the MPPT and batteries via Bluetooth. However, these data are in real-time and cannot be stored or downloaded; once the phone is disconnected from the MPPT, the activity history is erased.

The second method involved connecting the Cerbo GX equipment to the system's terminals for monitoring and downloading data for subsequent analysis.

The data analysis continues with generating a graph containing the values of the simulated currents and those generated by the 395Wp and 35.5V photovoltaic panel – Fig. 10. In Fig. 10, it can be observed that the dependency of the current on the determined albedo, according to the mathematical model defined by equation 5, is maintained.

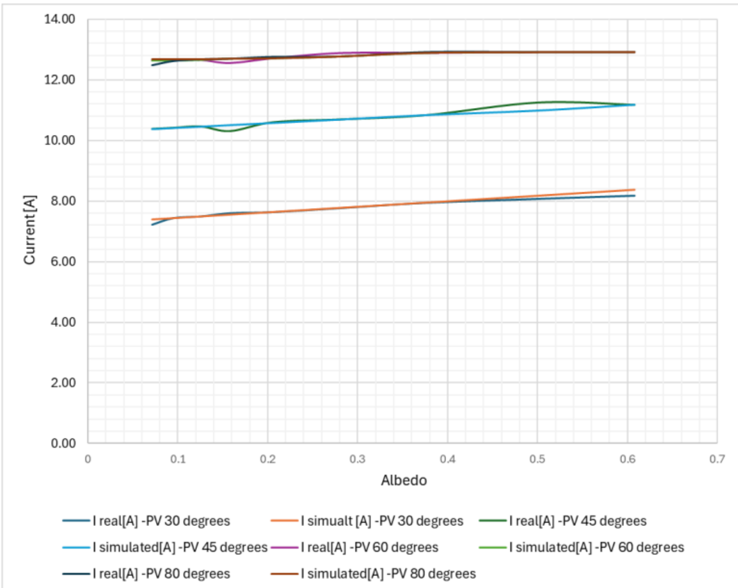



Fig. 10 - dependency of the current on the determined albedo

The explanation is that at a large incidence angle of solar radiation, the photovoltaic panel receives the necessary energy directly from the sun, and the albedo (diffuse radiation) does not significantly affect the electricity production as it does at smaller angles.

The next step involves calculating the relative error (according to equation 9) and the absolute error of the system (according to equation 10). The data resulting from the application of these equations to the values with discrepancies between the simulated current and the real current generated by the photovoltaic panel are presented in Table 2.

$$Er_{rel} = \frac{|I_{sim} - I_{real}|}{I_{real}} \times 100 \tag{9}$$

$$Er_{abs} = |I_{sim} - I_{real}| \tag{10}$$

As a result of the simulations performed, data acquisition, and detailed analysis, it can be confidently stated that the developed mathematical model, which considers the influence of wind speed and wave height (equation 5), has been validated with exceptional precision. According to the predictions made using DIAdem software, the model demonstrated an accuracy of 98%, and validation with real data indicated a precision of approximately 98.7%. The Mean Absolute Error of 0.135 and the Mean Relative Error of 1.306% indicate a minimal discrepancy between the simulated and real values, suggesting that the model can be reliably used for predictions and applications in the context of mobile modules for supplying electric power to surface drones using renewable energy sources.

*Table 2*

**The value of the absolute error and relative error – PV 395Wp**

| $I_{sim}$ [A] | $I_{real}$ [A] | Absolute error | Relative error [%] |
|---|---|---|---|
| 7.39 | 7.21 | 0.18 | 2.50 |
| 7.55 | 7.60 | 0.05 | 0.66 |
| 8.17 | 8.08 | 0.09 | 1.11 |
| 10.51 | 10.30 | 0.21 | 2.04 |
| 10.99 | 11.26 | 0.27 | 2.40 |
| 12.70 | 12.56 | 0.14 | 1.11 |
| 12.77 | 12.88 | 0.11 | 0.85 |
| 12.68 | 12.49 | 0.19 | 1.52 |
| 12.68 | 12.62 | 0.06 | 0.48 |
| 12.71 | 12.76 | 0.05 | 0.39 |

## 5. Conclusions

As a result of the simulations performed, data acquisition, and detailed analysis, it has been demonstrated that the developed mathematical model, which takes into account the influence of wind speed and wave height (equation 5), has been validated with exceptional precision. According to the predictions made using

DIAdem software, the model showed an accuracy of 98%, and validation with real data indicated a precision of approximately 98.7%. The Mean Absolute Error of 0.135 and the Mean Relative Error of 1.306% indicate a minimal discrepancy between the simulated and real values. This suggests that the model can be reliably used for predictions and applications in the context of mobile modules for supplying electric power to surface drones using renewable energy sources. These results highlight the value and applicability of the mathematical model in optimizing electricity production under varying hydrometeorological conditions.

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