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Immersed photovoltaic panels experiment for offshore maritime application

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***Abstract*— Due to the accelerated growth of worldwide interest in renewable energies, there is currently an impressive documentary base in this field, accumulated as a result of prolific research activity by engineering teams from countries around the world. However, the naval field has been very little touched by these researches and implicitly the recorded results are rare, which justifies us to say that the application of renewable energies in this field is at its early stage and requires more attention from researchers.**

Current technology allows stable powering of marine beaconing systems from photovoltaic panels, since mainly the aim is to emit a light of a certain color and this does not require high energy consumption. But, in areas with restricted access or during the period of prohibition of certain activities, the beacons can also serve other purposes, such as: video surveillance or radar monitoring of the aquatic space, data transmission via radio waves etc. The achievement of these objectives requires installation of equipment that will considerably increase energy consumption.

To ensure the necessary energy from photovoltaic panels, a number of environmental factors that can influence the electrical performance of the panels must be taken into account, such as: temperature, wind speed, water, wave movements, etc. The present paper studies the influence of water on the performance of photovoltaic panels, from the perspective of the degree of water coverage of the panel surface, namely: 0% coverage (the panel is completely out of water), 25%, 50% and 75%.

Keywords—renewable energy, photovoltaic panels, environmental factors, water coverage, electrical performance.

I. INTRODUCTION

Renewable energy sources, such as solar, wind, hydropower, geothermal, and bioenergy, have been gaining momentum as the world seeks to reduce carbon emissions and mitigate the effects of climate change [1]. Among these sources, solar energy has emerged as a key player in the quest for renewable energy solutions, with photovoltaic (PV) panels being a critical technology used to harness solar energy [2].

According to the International Energy Agency (IEA), PV energy is projected to become the largest source of electricity in the world by 2050, with the potential to contribute up to 16% of the global electricity supply. The IEA also notes that the global capacity of PV panels has grown significantly over the past decade, reaching over 700 gigawatts (GW) in 2020 [1]. This growth in PV capacity has been driven by several factors, including declining costs of PV panels, supportive policies and regulations, and technological advancements [3][4].

PV panels offer several advantages over other renewable energy sources. They can be installed on rooftops, on the ground, or even on water bodies, and can be used in a range of applications, from residential and commercial buildings to large-scale solar power plants. PV panels also have a relatively low environmental impact, as they do not emit greenhouse gases or produce waste products during operation [5].

In addition to their environmental benefits, PV panels offer economic benefits as well. As the cost of PV panels has declined, solar energy has become increasingly competitive with fossil fuel-based electricity generation. In many regions, solar energy is now the cheapest form of new electricity generation, and this trend is expected to continue as technology continues to improve and economies of scale are achieved [6].

Ultimately, PV panels are a critical technology used to harness solar energy, which is projected to become the largest source of electricity in the world by 2050. PV panels offer several advantages over other renewable energy sources, including their versatility, low environmental impact, and economic competitiveness. Understanding the factors that influence the performance of PV panels, such as marine environmental conditions, is crucial for the development of sustainable and efficient renewable energy systems.

PV panels are affected by environmental factors such as temperature, humidity, wind, and solar irradiance. However, in marine environments, additional factors come into play that can affect PV panel performance. For instance, saltwater corrosion and biofouling can damage the metal parts of the PV system and reduce the amount of light that reaches the panels, respectively. Furthermore, PV panels are partially or fully covered by water, the amount of solar irradiance that reaches the cells is reduced as water absorbs and reflects some of the incoming radiation. This leads to a decrease in

PV panel efficiency and power output. Furthermore, if the water is not clear but contains suspended particles or organic matter, this can further reduce the amount of light that reaches the panels.

Since marine environmental conditions can significantly affect the performance of PV panels, particularly when the panels are partially or fully covered by water, it is crucial to consider these factors when designing and installing PV systems in marine environments and implementing appropriate measures to mitigate their impact on the system performance [7].

The research problem of this scientific paper is to analyze the impact of water coverage on photovoltaic panel performance.

The objectives of the paper are as follows:

- To investigate the influence of water coverage on the performance of PV panels.
- To study the difference in performance between PV panels when they are completely out of water, 25% submerged in water, 50% submerged in water, and 75% submerged in water.
- To determine the optimal water coverage level for maximum photovoltaic panel performance.
- To contribute to the development of sustainable energy solutions by provide scientific data and analysis to improve PV panel performance in water-covered conditions.

II. Literature Review

Previous research has shown that environmental conditions such as temperature, humidity, and irradiance can significantly affect the performance of photovoltaic (PV) panels. High temperatures can lead to a decrease in PV panel efficiency due to an increase in the semiconductor's resistance, while low temperatures can improve the panel's performance [8]. Similarly, high humidity can lead to a decrease in PV panel efficiency due to the formation of water droplets on the panel's surface, which can absorb and scatter incoming sunlight. However, some studies have shown that a small amount of humidity can actually improve the panel's performance by reducing the surface resistance [9][10].

Irradiance, or the amount of sunlight that reaches the panel, is the main factor in determining PV panel performance. High levels of irradiance can improve the panel's performance up to a certain point, beyond which the panel's output becomes saturated [11]. Additionally, the angle of incidence of the sunlight on the panel can affect the amount of light absorbed and reflected by the panel, which in turn affects its performance [12].

Research on the impact of environmental conditions on PV panel performance has also explored the effects of wind speed, dust deposition, and shading. High wind speeds can cause mechanical stress on the panel and lead to a decrease in efficiency [13]. Dust deposition on the panel's surface can reduce the amount of light absorbed and scattered by the panel, leading to a decrease in efficiency [14]. Shading caused by trees or buildings can reduce the amount of sunlight that reaches the panel, leading to a decrease in efficiency [15].

Marine environmental factors, including saltwater, high humidity, and intense sunlight, can significantly impact the performance and durability of PV panels deployed on marine structures. The corrosive effects of saltwater on the metallic components of these panels pose one of the major challenges to their optimal functioning in such environments. Saltwater can cause corrosion, which can reduce the panel's efficiency and lifespan. To mitigate the effects of saltwater, various coating materials such as polyurethane, epoxy, and Teflon have been investigated as protective measures for PV panels [16][17].

High humidity is another environmental factor that can negatively impact the performance of PV panels. High humidity can lead to moisture accumulation on the panel surface, which can reduce the panel's efficiency. Studies have shown that anti-reflective coatings can reduce the accumulation of moisture on PV panels and improve their efficiency in humid environments [18].

Intense sunlight is a third environmental factor that can affect the performance of PV panels installed on marine structures. Excessive heat can cause thermal stress, which can damage the panel's cells and decrease its efficiency. To combat this issue, various cooling methods such as passive cooling, forced air cooling, and water cooling have been investigated to enhance the performance of PV panels in marine environments [19].

Furthermore, the angle and orientation of PV panels in relation to the sun have a significant impact on their performance in marine environments. Studies have shown that PV panels installed at certain tilt, depending on latitude, can maximize their power output in marine environments [20].

Studies showed that PV panels have been found to work successfully when they are submerged in shallow water. The power of submerged PV solar panel has been simulated for depths between 0 and 50 cm, and at the maximum depth, a reduction of about 20% for crystalline technology and 10% for thin-film technology has been calculated. The striking point however is that, in shallow water, an increase in efficiency of 10–20% is achieved [21]. Another study found that the photovoltaic efficiency conversion increases by about 15% at a water depth of 4 cm due to the annulment of thermal drift and the lesser reflection [22].

Although there is a consistent body of research on the impact of marine environmental conditions on the performance of PV panels, there are still gaps in research in this area, including the performance of PV panels at various stages of immersion in water and their possible importance. This is a critical area of research since PV panels may experience partial or complete submersion in water due to tidal fluctuations, storms and other environmental factors. Therefore, understanding the effects of such immersion on the performance of PV panels is crucial for their efficient and sustainable operation in marine environments.

III. Methodology

To understand the impact of marine environmental conditions on the performance of PV panels an experiment was conducted. As the location for conducting the experiment was chosen Constanta, a coastal city located in southeastern Romania on the Black Sea. The city has a humid subtropical climate with mild winters and hot

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summers. The experiment was conducted on the roof of the Maritime Engineering Faculty in the Naval Academy, which is situated 3.1 km from the sea, making it a suitable location for observing the performance of the photovoltaic panels in a naval environment.

The experiment was conducted between February 19 and March 3, 2021.

The experimental setup consists of three primary components, which are:

- Four 5W PV panels.
- Four loads.
- A data acquisition system that employs National Instruments' LabView.

A. Photovoltaic System

The experimental study was conducted on four identical 5W PV panels with a rigid mounting system, which were placed on the roof of the Maritime Engineering Faculty in the Naval Academy in Romania. The panels were mounted at an angle of 45 degrees from the horizontal, facing south, as shown in fig. 1.

The technical specifications were configured to reflect standard testing conditions, which include an air mass value of 1.5, irradiance of 1000W/m^2, and a temperature of 25°C.

The following steps were taken to determine the influence of water coverage degree on photovoltaic panel performance:

Fig. 1. The experimental setup.

TABLE I. CHARACTERISTICS AND PERFORMANCE DATA FOR A 5W PV MODULE

Model	MP-005WP
Technology	monocrystalline
Cells number	6
Peak power	5W
Tolerance	+3%
Voltage	17.85 V
Current	0.28 A
Open circuit voltage	22.18 V
Short circuit current	0.32 A
Working temperature	-40°C ÷ +85°C
Maximum rated system voltage	1000 V dc
Weight	0.8 Kg
Dimensions	210X210X23 mm
Wind resistance	2400 Pa

- The first panel was positioned completely out of the water as a reference panel.
- The second panel was submerged in water to a depth of 25% of its surface area.
- The third panel – to 50%.
- The fourth panel to a depth of 75%.

B. The Load

To ensure consistency in the load of each photovoltaic system, an equivalent resistance was used for each load, which was created by connecting two identical resistors in series. A thermal stable type of resistor with a rating of 30Ω and 5W was used, which ensured the maximum current through the circuit at 5Wp of PV panel.

Since the voltage measuring range of the USB-6008 data acquisition module is limited to -10V to +10V, and the output voltage of the PV panel is around 18V, a voltage divider was created. As a result, the data acquisition system measures the voltage drop across only one resistor and then multiplies the acquired signal by 2.

C. The Data Acquisition System

The data from the PV panels' output voltages were acquired using National Instruments equipment. The data acquisition system consisted of a personal computer with LabView software and a USB-6008 data acquisition module. As the USB-6008 module is not embedded, the entire data acquisition system was installed in the building, and an uninterruptible power supply (UPS) was added for the computer.

1) Module NI USB-6008

The data acquisition card has an analog to digital converter and a 32-bit counter with a full-speed USB interface, providing connections to eight analog input (AI) channels, two analog output (AO) channels, and 12 digital input/output (DIO) channels. The experiment required four analog input channels and one ground channel.

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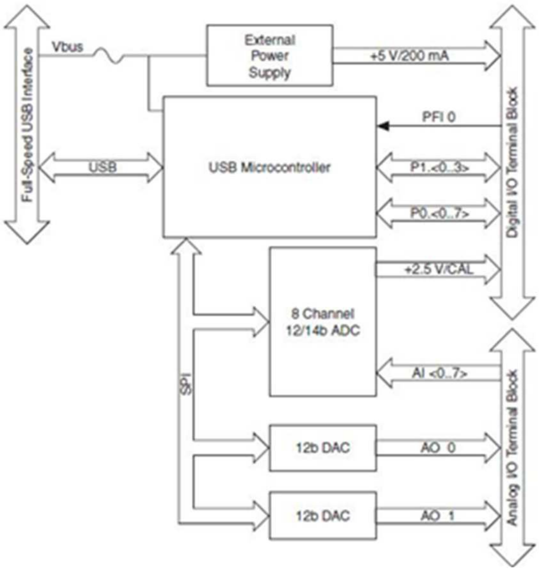

Fig. 2. USB-6008 block diagram.

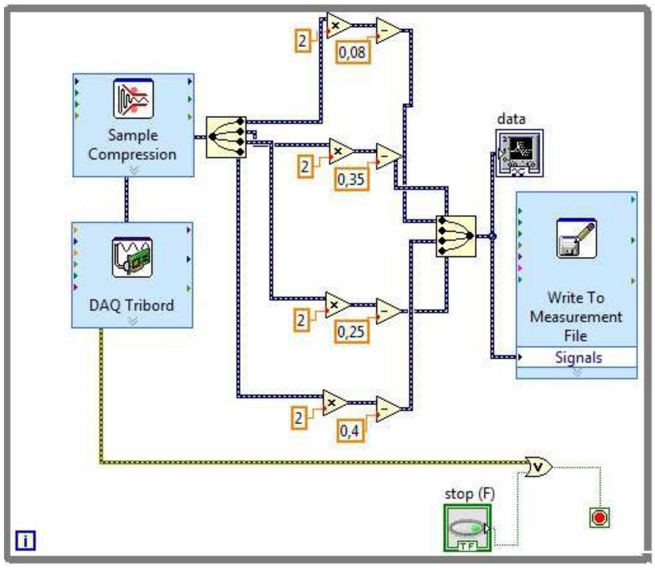

Fig. 3. LabView-based Virtual Instrument Data Acquisition Program for PV panels testing in marine environment.

2) *Data Acquisition Program*

The LabView program was developed using National Instruments' NI-DAQmx and VI Logger modules. The block diagram contained several components, including:

- DAQ Assistant: the interface between the USB-6008 module and LabView that converted the PV panels' voltage output into dynamic data that can be processed by LabView virtual instruments. It measured 100 samples at a 1 kHz frequency for each channel.
- Sample Compressions: reduced the number of measured samples to one value to ensure correct voltage output measurement and minimize the data base memory.
- Multiply: multiplied the measured voltage by 2 to obtain the PV panel output voltage.
- Add: added a calibration value for each PV panel output voltage.
- Write to measurement file: wrote the voltage and current values to a TDM (Toad Data Modeler) document.
- Waveform charts: displayed voltage and current data in real-time.
- While loop: repeated the entire loop until the STOP button was pressed or the system encountered an error.

IV. Mathematical Approach

The use of mathematical models is an essential tool for understanding and optimizing the performance of PV panels. These models simulate the behavior of solar cells in response to different environmental conditions, using various mathematical equations.

Because they share a similar basic structure, a diode can be considered as an ideal photovoltaic cell. A photovoltaic cell consists of a PN junction, which generates a potential difference when exposed to light, and a current source connected in parallel, representing the photocurrent produced by the solar irradiation. Similarly, a diode also has a PN junction that creates a potential difference when forward-biased, and it can also produce a photocurrent when exposed to light. Therefore, by using the diode equation, we can describe the behavior of an ideal photovoltaic cell.

Two commonly used mathematical models are the single-diode model and the double-diode model. The single-diode model describes the current-voltage characteristics of a solar cell, taking into account factors such as sunlight intensity, temperature, and material properties of the solar cell. The double-diode model incorporates additional parameters to improve accuracy.

The general equation of an ideal photovoltaic cell is presented using the diode equation (1), which includes factors such as photocurrent (I_{PH}), indirect diode bias current (I_0), elementary charge (q), PV cell terminal voltage (V), Boltzmann's constant (K_B), and temperature (T) expressed in Kelvins (K).

$$I = I_{PH} - I_0(e^{\frac{qV}{K_B T}} - 1) \tag{1}$$

Equation (1) is used to determine the open-circuit voltage V_{OC} and the short-circuit current I_{SC} of the cell. By replacing the current I with the current density J and solving (1) for J=0 and V=0, the following two equations can be obtained:

$$V_{OC} = \frac{nK_B T}{q}\ln(\frac{J_{PH}}{J_0} + 1) \tag{2}$$

$$J_{SC} = J_{PH} \tag{3}$$

Equation (2) shows that the open-circuit voltage V_{OC} depends on the photocurrent, and hence, increases with the increase of the irradiation. However, the open-circuit voltage also depends on temperature, the band gap of the irradiation absorbing material, the doping level of the intrinsic material, and the quality of the material.

Equation (3) shows that the short-circuit current density J_{SC} depends on the photocurrent density J_{PH}, and is affected by the spectrum of the incident light, absorption coefficient of the absorbing material, and probability of absorption.

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These mathematical equations are crucial for optimizing the design and performance of PV panels by providing insights into the behavior of solar cells under different environmental conditions. However, it is important to validate these models through experimental measurements and field testing, as they may not accurately reflect real-world conditions.

V. RESULTS

A. Environmental conditions

The experiment was conducted between February 19 and March 3, 2021. Constanța experienced a mix of different weather conditions during this period, with temperatures ranging from -1°C to 11°C. It was mostly cloudy with some occasional rain or snow, and temperatures remained relatively cool throughout the period.

B. Data collected on panel performance

The experiment took place over 13 days, 24 hours a day, averaging around 5,610 measurements per day for each PV panel. Fig. 4 and fig. 5 illustrate that the electric current production values for all four PV panels are similar and exhibit a common trend of decreasing as the panel's water coverage increases. The PV panels that had half and three-quarters of their total surface covered with water experienced a reduction of about 10% and 20%, respectively, in their electric current production compared to the panel placed outside the water (see fig. 6).

On the other hand, a deviation from this trend is observed for the panel covered by water in proportion to 25%. Its electricity output not only does not decrease, as expected, but almost every day it exceeds the output of the reference photovoltaic panel (the one not covered by water).

TABLE II. THE EFFICIENCY OF EACH PANEL RECORDED AT NOON ON FEBRUARY 23, 2021

Time	PV00	PV25	PV50	PV75
11:32	76.65%	78.75%	75.03%	72.28%
11:50	82.76%	86.38%	81.56%	78.16%
12:24	68.61%	71.68%	68.56%	65.69%

C. Interpretation of results and their implications

Two out of three PV panels registered a decrease in electricity production because water absorbs and scatters sunlight, reducing the amount of light that reaches the solar cells in the panel. As the coverage of the panel with water increases, the amount of light absorbed and scattered by the

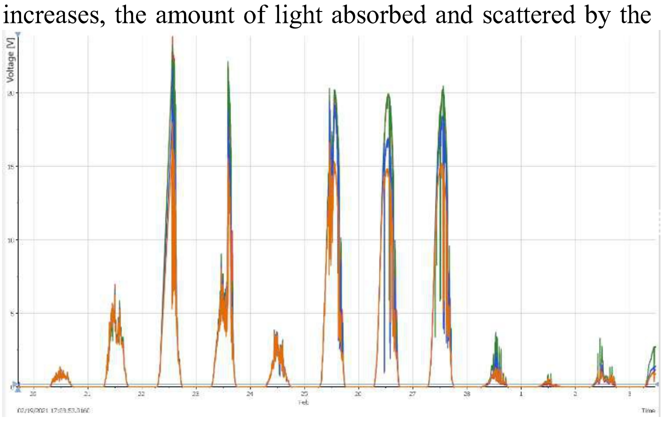

Fig. 4. Output voltage of the four PV panels.

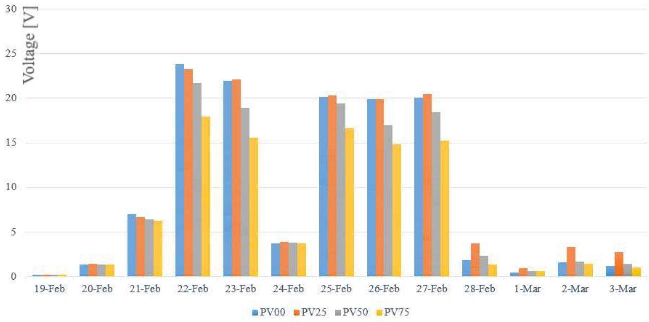

Fig. 5. The voltage produced by the four PV panels.

water also increases, which reduces the amount of light that can penetrate the panel and generate electricity.

When the panel is submerged to a depth of 50%, the decrease in electricity production is about 10% because the water layer absorbs and scatters a significant portion of the sunlight, reducing the amount of light that can penetrate the panel. When the panel is submerged to a depth of 75%, the decrease in electricity production is about 20% because the thickness of the water layer is greater, and hence, more sunlight is absorbed and scattered.

However, it is possible to submerge a certain percentage of the surface of a photovoltaic panel in water without reducing the production of electric current. In fact, submerging the panel to a depth of 25% of its surface area can actually increase the production of electric current by up to 3.69%, as shown in fig. 6 and fig. 7.

There could be several possible causes of the exceptional behavior of the panel submerged 25% in water. One possible reason could be that the water layer acted as a cooling mechanism, preventing the panel from overheating and improving its efficiency. Another possible reason could be that the water acted as a magnifying lens, concentrating the sunlight onto the panel and increasing its output. Additionally, the reflection of sunlight off the water could have increased the amount of light that reached the panel, further improving its efficiency.

To clarify the problem and confirm these causes, future experiments could be conducted to investigate the effect of water as a cooling mechanism or magnifying lens on the performance of photovoltaic panels. These experiments could involve controlling the temperature and amount of light received by the panels by using different water depths and different types of water (e.g., distilled water, seawater).

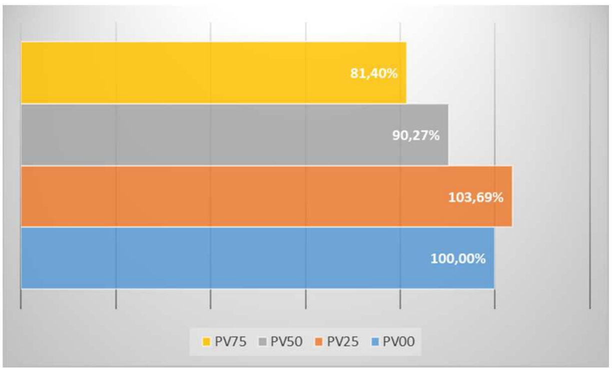

Fig. 6. The voltage produced by the four panels in relative values in respect to the panel placed outside the water .

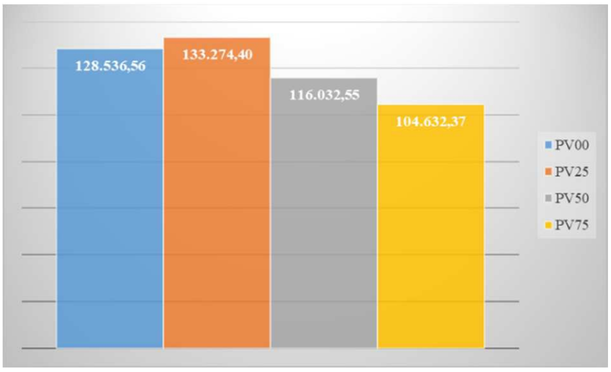

Fig. 7. The voltage produced by the four panels in absolute values.

Another potential direction for future experiments could be to investigate the effect of different angles of water submersion on panel performance. For example, panels could be submerged at angles other than 45 degrees and at different depths to determine whether the effect of water on panel performance is dependent on the angle or depth of submersion.

Furthermore, the effect of water on the durability and longevity of photovoltaic panels could also be investigated. Specifically, future experiments could determine whether prolonged exposure to water has any adverse effects on the panels' materials, and whether this could lead to a decrease in efficiency over time.

Overall, these experiments could provide valuable insights into the potential benefits and drawbacks of submerging photovoltaic panels in water, and could inform the development of more efficient and durable solar power systems in the future.

VI. Conclusions

The experiment involved submerging identical photovoltaic panels at different depths in water to investigate the effect of water coverage on panel performance. The results showed that submerging the panels to a depth of 25% increased the production of electric current by 3.69%, while submerging the panels to depths of 50% and 75% resulted in decreases in production of 10% and 20%, respectively. The findings suggest that submerging solar panels in water can have adverse effects on electricity production due to light absorption and scattering by water, which reduces the amount of light that reaches the solar cells. However, submerging panels to a depth of 25% could potentially improve their efficiency.

Understanding the influence of marine environmental conditions on photovoltaic panel performance is important for designing and operating solar energy systems in coastal and marine environments. Marine conditions such as salt spray, humidity, and water coverage can have adverse effects on panel performance, reducing the amount of electricity produced. This knowledge can help in selecting the appropriate materials and components for solar panels and designing systems that can withstand these conditions, which is particularly important in offshore renewable energy systems. Additionally, understanding the optimal position for solar panels and the degree of water coverage that maximizes electricity production can increase the efficiency of solar energy systems, making them more cost-effective and sustainable.

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