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# Comprehensive analysis of offshore wind-photovoltaic hybrid systems: unveiling state-of-the-art autonomous components for maritime applications

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**Abstract**. This paper conducts a comprehensive analysis of offshore wind-photovoltaic hybrid systems, presenting autonomous components tailored for maritime applications. Focusing on the critical role of these systems in supplying electricity to regions with limited infrastructure, particularly maritime zones, the study explores economic advantages over traditional power line installations, emphasizing remote areas. Key components, including battery storage, autonomy, battery selection (with a spotlight on lead-acid batteries), charge controllers, inverters, and the integration of Automatic Identification System (A.I.S.) for maritime safety, are discussed. The article concludes by underscoring the significance of power supply buoys for ship safety and efficient refueling near hybrid systems.

**Keywords**. Offshore wind-photovoltaic hybrid systems, autonomous components, maritime applications, remote areas, battery storage, lead-acid batteries, charge controllers, inverters, automatic identification system, power supply buoys, photovoltaic and wind systems, hybrid system, renewable energy

## 1. Introduction

The distinction lies between two primary classifications of photovoltaic and wind systems: off-grid (autonomous) systems and grid-connected systems. Off-grid (autonomous) systems find their primary application in regions lacking electrical network infrastructure. They demonstrate high efficiency in delivering electrical power to secluded areas, such as maritime zones [1], [2], [3].

Photovoltaic and wind systems can offer a much more cost-effective alternative than building power lines and transformers, especially in remote areas. Solar panels generate clean electrical energy without pollutant emissions, unpleasant odors, noise, or vibrations, unlike wind turbines, which can produce sound and vibrations. However, when evaluating this hybrid system in an isolated environment, such as the maritime zone, any inconveniences related to noise and vibrations become less relevant [2], [4],[5], [6], [7].

Solar and wind energy can be integrated into a hybrid system for electricity generation. Although solar energy is not available 24 hours a day, and the wind does not blow constantly, a hybrid system that combines these energy sources is designed to compensate for these limitations and has proven to be a reliable and cost-effective solution for many regions with unreliable electricity supply from the traditional grid [8], [9], [10].

In coastal regions with strong winds, the system may also include a wind energy converter. Thus, the photovoltaic generator and the wind energy converter significantly complement each other when properly sized (see Fig.1.). Hybrid systems represent the most economically viable solution for supplying ships with electrical energy in the outer areas of ports, contributing to reducing marine environmental pollution as much as possible [5], [11], [12].

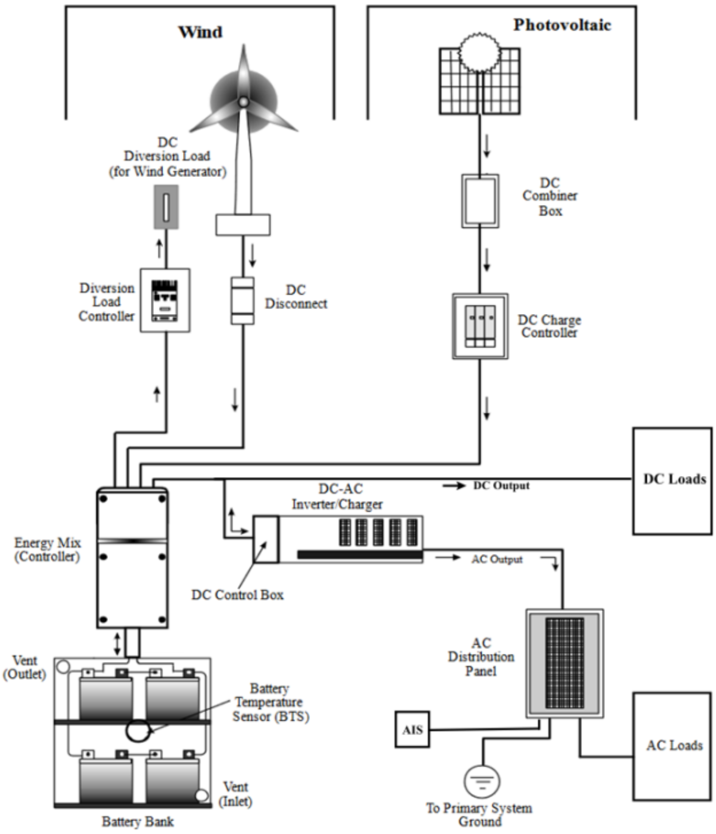

**Figure 1.** Schematic diagram of the autonomous hybrid wind-photovoltaic system [2]

Considering our commitment to advancing the maritime sector, our research centers on large and medium-sized vessels. In recognition of the fluctuating solar radiation levels experienced throughout the day, as well as the impact of seasonal and weather variations, an effective autonomous photovoltaic system supplying electrical energy to these vessels necessitates a configuration that integrates both battery storage and a charge controller [11], [13].

## 2. Battery storage

It's important to note that neither solar cells nor the wind system itself have the capacity to store energy. To retain surplus energy for times when the sun isn't shining or the wind isn't blowing, we utilize direct current voltage to charge an appropriate set of rechargeable batteries [14], [15].

The reserve capacity of these batteries is denoted as the system's autonomy, and it fluctuates based on the particular needs of the applications. Batteries employed in autonomous photovoltaic and wind systems are crafted to function effectively under deep discharges and generally do not necessitate upkeep [14]. It is essential to emphasize that batteries in autonomous photovoltaic or wind systems operate in challenging environments, particularly during instances of low solar illumination or when there is no wind [11].

The required autonomy period depends on the specific application. For instance, remote telecommunications and telemetry stations may require a two-week autonomy, while a ship docked in a port may only need a few days. Careful battery selection is necessary to store enough energy for daily demands [14]. The necessary battery size hinges on several factors, including the amount of stored energy, the maximum discharge rate, and the minimum operating temperature for the batteries. All these factors must be considered when designing an autonomous solar or wind energy system and choosing the battery size [2]. When calculating the battery's ampere-hour rating and storage capacity, additional factors such as cloudy conditions, absence of sunlight, and lack of wind should also be taken into account [14].

Lead-acid batteries are commonly used in photovoltaic systems owing to their cost-effectiveness and widespread availability. Deep-cycle batteries are explicitly engineered to withstand repetitive discharges of up to 80% of their capacity, making them highly suitable for power systems. [2]. These battery variants rely on mature and established technology, finding extensive use in various rechargeable battery applications [16].

Throughout the discharge, lead sulphate crystals develop on both the negative and positive terminals, liberating electrons due to alterations in lead's valence charge. This mechanism utilizes the sulphate found in the sulfuric acid electrolyte enveloping the battery, causing a decrease in the electrolyte's concentration. Although complete discharge would lead to both electrodes being coated with lead sulphate and water instead of the typical sulfuric acid, protective measures prevent batteries from attaining this condition to prevent damage. Nevertheless, in real-world scenarios, discharge halts at a cutoff voltage well before approaching this stage to avert battery damage. [16].

**Table 1.** Discharge levels of a 12-volt lead-acid battery.

| The state of charge | 12 V | Observations |
|---|---|---|
| 100% | 12.70 | The battery cycle within this discharge range will contribute to an acceptable lifespan. |
| 95% | 12.60 | |
| 90% | 12.50 | |
| 80% | 12.42 | |
| 70% | 12.32 | |
| 60% | 12.20 | |
| 50% | 12.06 | |
| 40% | 11.90 | Occasionally, a decrease in this range may be tolerated, but consistent discharge at this level is not recommended. Repeated discharge at this level will have a negative impact on the battery's lifespan. |
| 30% | 11.75 | |
| 20% | 11.58 | |
| 10% | 11.31 | It may cause permanent damage. |
| <10% | 10.5> | |

In the transitional phase from a fully discharged state to a fully charged state, a lead-acid battery undergoes a gradual decline in its voltage. Traditionally, the voltage level serves as an indicator of the battery's state of charge. The correlation between the battery's state of charge and its voltage is illustrated in Fig.2. If a battery is kept at low charge levels for extended periods, large lead sulfate crystals may form, resulting in a permanent reduction in the battery's capacity [16].

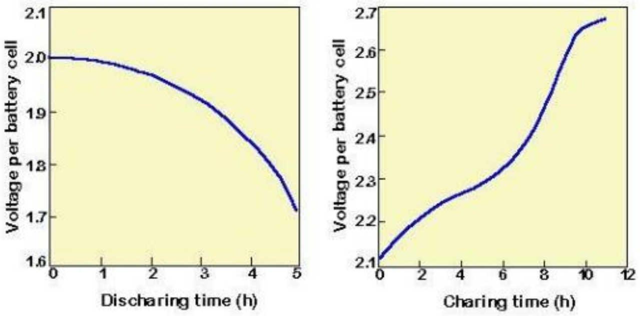

**Figure 2**. The battery's dependence on its state of charge [16]

The battery voltage can be affected by three primary factors: state of charge, current, and temperature. While we focus on the state of charge, we should not overlook the impact that current and temperature can have on the battery voltage [17]. Therefore, it is essential to have a temperature sensor in the area dedicated to accumulator batteries so that they can operate under optimal conditions. When temperatures rise, this sensor should activate the appropriate cooling system to maintain the batteries within a suitable temperature range.

## 3. Controller

Charge controllers are electronic devices designed to protect batteries from overcharging and deep discharging. They are absolutely essential for the efficient operation of the battery and the entire photovoltaic and wind system. These controllers are installed between the terminals of the photovoltaic, wind systems, and the battery storage [11],[14].

The diversion charge controller's role is to divert the electrical energy produced when the charging source has fully charged the battery storage. In most wind systems, the charging source cannot be disconnected from the battery storage during use, as there is a risk of damage due to overvoltage. Essential criteria encompass ensuring that the diversion load has the capacity to dissipate a higher wattage than the charging source can deliver. Additionally, it is crucial that the maximum amperage the load can absorb remains below the charge controller's maximum diversion rating. In diversion mode, the total current consumption (measured in amperes) of the diversion load should surpass the maximum output of the charging system, while still staying within the charge controller's designated capacity [14].

## 4. Inverters

Photovoltaic panels generate electricity in the form of direct current (D.C.), which can only be used by a limited range of equipment. Most devices and appliances for residential, commercial, and industrial use are designed to operate on alternating current (A.C.). Inverters are specialized devices that efficiently convert D.C. into A.C., facilitating the transition from D.C. to A.C. power [14]. The voltage and frequency of the A.C. can be adjusted to specific requirements through appropriate transformers, switches, and control circuits.

The majority of inverters developed for solar applications are designed to allow parallel connection, thus enhancing the adaptability and scalability of solar systems. For instance, to meet a 60 kW requirement, the outputs of three 20 kW inverters can be integrated in parallel. This provides flexibility in adjusting the capacity of the photovoltaic system according to specific power supply system requirements. Concerning power output, inverters can generate single-phase or three-phase A.C. at any voltage or current capacity needed. Typically, standard outputs include single-phase supply at 120 V A.C. and three-phase supply at levels such as 120/208 and 277/480 V A.C. [14].

To ensure proper protection of inverters against high-intensity energy surges, the D.C. input ports of photovoltaic systems are commonly equipped with fuses. These fuses are integrated into a distribution box located near the inverters. Additionally, the DC input ports of inverters are equipped with various types of semiconductor devices designed to limit excessive voltages and voltage spikes [14].

To prevent damage caused by voltage reversal, each positive (+) output cable from the photovoltaic cells is connected to a rectifier, which functions as a unidirectional device (polarized forward). The energy produced in the form of AC by the inverters is then distributed to consuming devices through circuit breakers, either electronic or magnetic. These circuit breakers serve to protect the inverters from overloads and external short circuits [14].

Power overvoltage's can occur in various circumstances, such as during the switching of capacitor banks used for power factor correction or during load reduction and switching. Excess power generated, in the absence of proper grounding, can cause significant damage to inverters by destroying the insulation of conductors and electronic components [14].

## 5. Automatic identification system (A.I.S.)

Considering its location in the outer harbor areas of ports, this hybrid system must take into account the possibility of unfavorable weather conditions such as dense fog, heavy rainfall, and strong winds with sea states of grade 5 or higher, which can significantly reduce visibility and pose collision risks with other vessels. To minimize these risks, it is essential to integrate into its structure a navigation system known as A.I.S. (Fig. 3.), an abbreviation for Automatic Identification System, a tool used in maritime traffic services. While radar systems installed on ships will play a primary role in identifying the feeding buoy and determining its position, the A.I.S. system represents an additional safety element, contributing to the prevention of any potential collisions that could affect the integrity of the autonomous hybrid system.

**Figure 3**. Automatic Identification System (A.I.S.)

The Automatic Identification System (A.I.S.) is an automatic monitoring technology that provides data about the position, speed, course, and destination of vessels. This system is commonly installed on ships to facilitate their tracking and identification. Regardless of the specific configuration of the underwater buoy, whether it is anchored or designed as a propulsion platform, the fundamental role of the A.I.S. system is to inform other vessels in the vicinity about the presence of the hybrid system. All versions of A.I.S. systems function on alternating current. Within the framework of the hybrid system, they draw electrical power from the distribution panel, as depicted in Fig. 1.

The A.I.S. system can be continuously monitored through the "Marine Traffic" platform, which provides real-time information about maritime traffic in the respective area. It can serve as a warning signal when the A.I.S. system stops transmitting data, indicating a power loss and, consequently, a malfunction in its functionality. In this situation, emergency maintenance intervention becomes necessary to check and remedy the system's operation.

## 6. Structure of the hybrid system

In the early project research, we thoroughly analyzed the metallic structure of the feeding buoy platform. It's mainly influenced by water depth and its efficiency based on the distance from the shoreline. For depths of 30-60 meters, a tripod structure is optimal. For deeper oceanic areas near ports, a floating foundation with seabed anchors is necessary.

Additionally, within this hybrid system, the photovoltaic panels will be anchored using a fastening system connected to the wind turbine's mast. In the northern hemisphere, the orientation of the panels will depend on a 180-degree azimuth angle, necessitating a fixed structure to ensure maximum efficiency of the photovoltaic system, as illustrated in Fig.5.

In the current stage of the project, analyzing the wind system's potential for depths of 30-60 meters, a tripod-type structure can provide an output power of approximately 541 GW, while for depths of 60-900 meters, a floating foundation-type structure can ensure an output power of approximately 1533 GW [18]. Considering these output powers, to achieve maximum efficiency, it is recommended to focus efforts on the development of floating foundations, as illustrated in Fig.4.

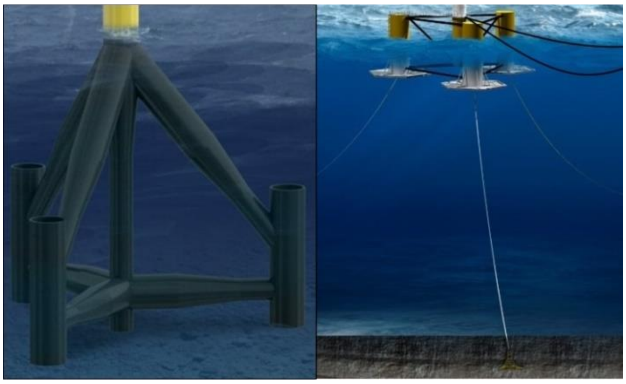

**Figure 4**. The tripod and floating foundation structures of the hybrid autonomous system

## 7. Power supply buoy

To prevent a possible incident or collision with a hybrid system, it is essential to consider an adequate safety distance and analyze optimal solutions that allow the ship to refuel safely without getting too close to the hybrid system itself.

In this regard, a "monobuoy" type can provide a suitable solution. This buoy allows the ship to anchor at a safe distance of at least 100-200 meters from the hybrid system. When the wind blows from a certain direction, the wind turbine rotor will orient itself perpendicular to the wind direction, and the buoy will be positioned behind the wind turbine mast, in the opposite direction of the rotor's orientation (as shown in Fig.5.), ensuring an efficient and safe interaction between the ship and the hybrid system.

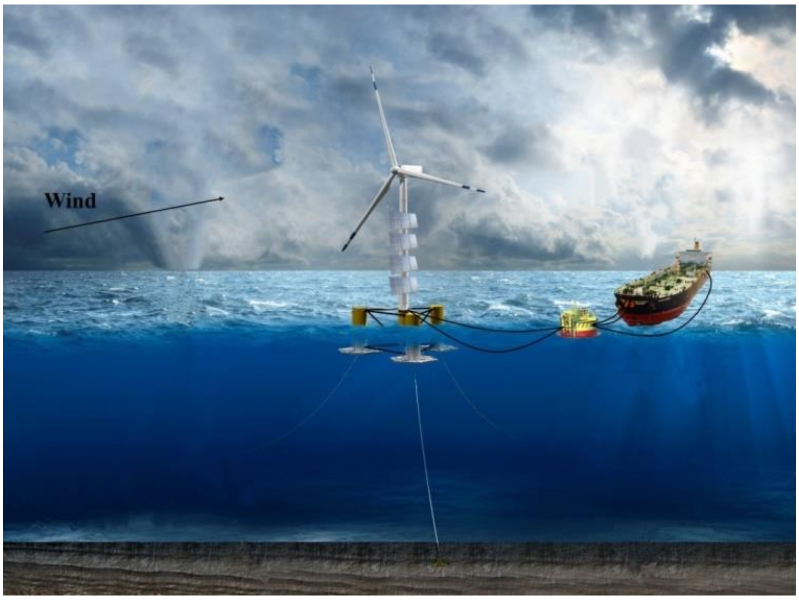

**Figure 5**. Power supply buoy interconnecting the hybrid system and the ship

When a ship is anchored, it can position itself based on its maneuvering characteristics and the influences of the surrounding environment, such as current and wind direction. This orientation tendency may vary depending on the superstructure configuration, which can be located either at the front of the ship (bow) or at the rear (stern). After the anchoring process is completed, the ship will usually align itself in the direction of the buoy, orienting itself in opposition to the wind direction.

## 8. Conclusion

In protected natural areas where marine ecosystems, including coral reefs and endangered species, are found, this hybrid system emerges as a vital solution for ships that are restricted from anchoring in the outer anchorages of ports due to the environmental impact of pollution on the maritime environment. Ships can anchor and connect to renewable energy supply points, similar to connecting to onshore power sources upon docking in ports. With this transition to renewable energy, the operation of onboard diesel generators is halted, thus preventing pollution in the port's anchorage area while awaiting clearance from the Port Authority.

Combining solar and wind energy in a hybrid system can compensate for the intermittency of each source, resulting in a reliable and cost-effective solution for regions with inconsistent traditional grid electricity, especially in remote regions.

Detailing the crucial role of battery storage in compensating for intermittent energy sources. The autonomy period and careful battery selection, particularly lead-acid batteries, are explored, along with discharge levels and the impact of variables like temperature on battery voltage.

A comprehensive overview of charge controllers and their essential role in protecting batteries from overcharging and deep discharging. The diversion charge controller's function and criteria for its efficient operation are highlighted.

Exploring the role of inverters in converting DC electricity into AC, essential for compatibility with standard electrical systems. Attention is given to parallel connections, power outputs, protection against energy surges, and potential damages caused by voltage reversal.

The A.I.S. monitoring system provides continuous real-time monitoring of the wind-photovoltaic hybrid autonomous system's performance. By transmitting alarm signals, it promptly notifies maintenance and repair teams, who can intervene rapidly in emergency situations. In maritime applications, integrating A.I.S. systems into hybrid systems is indispensable for enhancing safety.

A.I.S. provides valuable data regarding vessel position, speed, course, and destination, thereby contributing to collision prevention.

Analyzing the metallic structure of the feeding buoy platform based on water depth and efficiency considerations. Recommending tripod and floating foundation structures for different scenarios, with a focus on maximizing output power.

Introducing the concept of a "monobuoy" type for safe ship anchoring and refueling. Emphasizing the importance of maintaining a safe distance between ships and hybrid systems and explaining how wind direction influences the arrangement.

Highlighting the hybrid system's significance in protected natural areas, offering a sustainable solution for ships while preventing pollution in outside port anchorage areas. Summarizing key components' roles and stressing the system's adaptability and safety features in adverse weather conditions. Emphasizes the developments in offshore hybrid systems, specifically tailored to address the challenges faced in maritime zones, showcasing the integration of solar and wind energy for a reliable and sustainable power supply.

**References**

[1] O. Cristea, "Testing of PV module efficiency in naval conditions," *2013 - 8th Int. Symp. Adv. Top. Electr. Eng. ATEE 2013*, 2013, doi: 10.1109/ATEE.2013.6563534.
[2] I. A. Adejumobi, S. G. Oyagbinrin, F. G. Akinboro, M. B. Olajide, and O. State, "Hybrid Solar and Wind Power: an Essential for Information Communication Technology Infrastructure and People in Rural Communities," *Int. J. Res. Rev. Appl. Sci.*, vol. 9, no. October, pp. 130–138, 2011, [Online]. Available: https://pdfs.semanticscholar.org/bf99/c332bcdcd9e2fa23a875c819b1500e046361.pdf.
[3] B. Jia, H. Wu, and Y. Li, "Flexible On-grid and Off-grid Control Strategy of Photovoltaic Energy Storage System Based on VSG Technology," *5th IEEE Conf. Energy Internet Energy Syst. Integr. Energy Internet Carbon Neutrality, EI2 2021*, pp. 1978–1985, 2021, doi: 10.1109/EI252483.2021.9712963.
[4] O. Cristea, M.-O. Popescu, F. Deliu, and A. S. Calinciuc, "Dynamic performances of a wind power system," in *2014 International Symposium on Fundamentals of Electrical Engineering (ISFEE)*, Nov. 2014, pp. 1–5, doi: 10.1109/ISFEE.2014.7050635.
[5] P. Popov, F. Deliu, V. Dobref, and P. Burlacu, "Study on the efficiency of a low-power vertical wind turbine.," *Sci. Bull. cel Batran'Naval Acad.*, vol. 22, no. 2, 2019.
[6] F. DELIU, P. POPOV, P. Burlacu, and V. Dobref, "IMPLEMENTATION PHOTOVOLTAIC PANELS IN LIGHTING SYSTEM OF A SHIP," 2015.
[7] O. Cristea, M. O. Popescu, and A. S. Calinciuc, "A correlation between simulated and real PV system in naval conditions," *2014 Int. Symp. Fundam. Electr. Eng. ISFEE 2014*, Feb. 2015, doi: 10.1109/ISFEE.2014.7050571.
[8] A. Wasonga, M. Saulo, and V. Odhiambo, "Solar-Wind Hybrid Energy System for New Engineering Complex- Technical University of Mombasa," *Http://Www.Sciencepublishinggroup.Com*, vol. 4, no. 2, p. 80, 2014, doi: 10.11648/j.ijepe.s.2015040201.17.
[9] F. DELIU and P. BURLACU, "USE OF RENEWABLE ENERGY SOURCES," *Nat. gas*, vol. 135, no. 2, p. 2.
[10] O. Cristea, M. Bălăceanu, M.-O. Popescu, and A. S. Calinciuc, "Embarked PV module's mathematical model: Simulation, experiment and validation," *UPB Sci. Bull. Ser. C Electr. Eng. Comput. Sci.*, vol. 78, no. 3, 2016.
[11] H. K. V Lotsch *et al.*, *Optical Sciences*. 2007.

[12] J. F. Manwell, “Hybrid Energy Systems,” *Encycl. Energy*, pp. 215–229, 2004, doi: 10.1016/B0-12-176480-X/00360-0.

[13] D. Rekioua, “Energy Storage Systems for Photovoltaic and Wind Systems: A Review,” *Energies 2023, Vol. 16, Page 3893*, vol. 16, no. 9, p. 3893, May 2023, doi: 10.3390/EN16093893.

[14] P. Gevorkian, “Solar Power in Building Design,” p. 506, 2008.

[15] F. Deliu, P. Popov, and P. Burlacu, “The Impact of the Wind Speed on the Dynamics of the Wind Energy System,” in *International conference KNOWLEDGE-BASED ORGANIZATION*, 2016, vol. 22, no. 3, pp. 628–633.

[16] S. Kitaronka, “Lead-Acİ D Battery,” no. January, 2022, doi: 10.6084/m9.figshare.19115057.

[17] R. Perez, “Lead-Acid Battery State of Charge vs. Voltage,” no. September, pp. 66–70, 1993.

[18] L. Li and J. Ren, “Offshore wind turbines and their installation,” *CICC-ITOE 2010 - 2010 Int. Conf. Innov. Comput. Commun. 2010 Asia-Pacific Conf. Inf. Technol. Ocean Eng.*, pp. 248–251, 2010, doi: 10.1109/CICC-ITOE.2010.69.