
Hybrid Marine Renewable Energy: Integration of Waves, Currents, and Wind

Abstract

The development of marine renewable energy is a strategic solution to support the global energy transition towards a low-carbon energy system. However, the utilization of single marine energy sources, such as wave energy, ocean currents, and offshore wind, still faces challenges in the form of intermittency and power fluctuations that can affect system reliability. This perspective article discusses the concept of a hybrid marine renewable energy system that integrates wave, current, and wind energy in a single integrated system with a focus on increasing reliability. The discussion focuses on the system integration architecture, reliability aspects, and the role of modern control and monitoring technologies. Based on a literature review and conceptual analysis, the hybrid system is considered capable of increasing capacity factors, reducing power fluctuations, and increasing system availability compared to single-source marine energy systems. The integration of multiple marine energy sources supported by energy storage systems and intelligent power management is seen as an important approach in realizing a reliable and sustainable marine energy system in the future.

Muh. Asyhari Ramadhan*

Department of Ocean Engineering,
Hasanuddin University, Indonesia.

*Correspondence author:

asyhariramadhan17@gmail.com

Keywords: Hybrid Marine Renewable Energy, Wave Energy, Ocean Currents, Offshore Wind, Integrated Systems, Reliability, Energy Sustainability.

1. Introduction

Renewable energy sea own an increasing role important in support system energy sustainable, especially for coastal and island areas that have potential source Power Large oceans. Energy sources such as ocean waves, ocean currents, and offshore wind offer significant energy potential and relatively continuous availability compared to some land - based renewable energy sources. However, utilizing each of these energy sources separately still faces various technical challenges, particularly related to power fluctuations and system reliability.

Each type of marine energy source has distinct characteristics. Wave energy is heavily influenced by wind conditions and seasonal variations, while offshore wind energy fluctuates over short timescales, while ocean currents tend to be more stable and predictable but are limited to specific locations. Reliance on a single marine energy source has the potential to cause unstable energy supplies and reduce system reliability.

To address these issues, the concept of hybrid marine renewable energy has been developed as an alternative approach. Hybrid systems integrate two or more marine energy sources into a single system, leveraging their complementary properties. By combining wave, current, and wind

energy, hybrid systems are expected to improve energy supply continuity and system resilience to marine environmental variability.

With the increasing intensity of climate change and the need for reliable clean energy, studies on system integration and reliability in hybrid marine renewable energy systems have become highly relevant. Therefore, this article presents a perspective on the concept, benefits, and challenges of hybrid marine energy systems, with a primary focus on system reliability.

In the context of marine energy, conventional approaches that utilize a single source of energy (single-source systems) have proven suboptimal (World Energy Council, 2016). Therefore, the Hybrid Marine Renewable Energy (HMRE) approach has emerged, emphasizing the integration of wave, current, and wind energy into a single integrated system.

2. Basic Concept of Hybrid Marine Renewable Energy

Hybrid Marine Renewable Energy is a marine energy generation system that combines two or more marine energy sources within a single integrated infrastructure or network. This integration can be achieved physically (co-location) or through an integrated electrical system.

Wave energy has significant potential, especially in open ocean areas, but is heavily influenced by weather and seasonal conditions. Ocean current energy is relatively stable and predictable, but limited to specific locations with relatively high current speeds. Meanwhile, offshore wind offers significant power capacity but is subject to daily and seasonal fluctuations.

Combining these three energy sources allows for mutual complementarity. When wind power declines, wave energy or ocean currents can still contribute, thus minimizing total power fluctuations. This principle makes hybrid systems superior in terms of reliability compared to single systems.

Energy-wise, hybrid systems benefit from the low correlation between energy sources. When wind power production declines, wave energy remains available due to residual ocean wave energy, while ocean currents can provide a relatively stable power supply. This complementarity is the primary basis for increasing the reliability of hybrid marine energy systems.

Hybrid Marine Renewable Energy is an energy system approach that combines two or more marine energy sources into a single integrated platform or network. The main objectives of this approach are:

- Increase continuity energy
- Reduce fluctuations in electrical output
- Maximizing utilization source Power sea
- Reduce cost infrastructure

3. Integrated Ocean Energy System Architecture

A hybrid ocean energy system consists of several main components: a marine energy converter, a power transmission system, an energy storage system, and an integrated control system. The marine energy converter converts mechanical energy from waves, currents, and wind into electrical energy.

In an integrated system, multiple converter types can be installed on a single platform or in the same sea area. Sharing infrastructure, such as foundations, submarine cables, and mooring systems, can improve cost efficiency and operational ease.

Power transmission and management systems play a crucial role in maintaining the quality and stability of generated electricity. Power electronics devices are used to adjust the voltage and frequency from various sources to safely distribute it to the grid or loads. Energy storage systems, such as batteries or hybrid storage systems, serve as a buffer against short-term power fluctuations.

Energy storage systems play a crucial role in hybrid systems as a buffer against short-term power fluctuations. The use of batteries, supercapacitors, or hybrid storage systems allows for stable power supply even when there are fluctuations in one of the energy sources.

Additionally, a sensor-based control and monitoring system with real-time data enables more optimal power management. The integration of marine environmental data and energy prediction

models supports more accurate and adaptive operational decision-making.

4. The Concept of Reliability in Marine Hybrid Energy Systems

Reliability is a critical parameter in energy systems, particularly for marine applications operating in extreme environments. Reliability reflects a system's ability to operate continuously without interruption for a specified period.

In hybrid systems, reliability is enhanced through diversified energy sources and system redundancy. Failure of one energy source does not necessarily cause the entire system to stop operating. This significantly increases system availability.

Reliability is a key parameter in evaluating the performance of marine renewable energy systems, particularly as they operate in dynamic and extreme marine environments. In hybrid systems, reliability is enhanced through diversified energy sources, system redundancy, and the implementation of intelligent power management.

System reliability can be assessed in terms of system availability, fault tolerance, and power supply continuity. Integrating multiple energy sources reduces the risk of total system failure, as a disruption to one source does not immediately halt all energy production. This increases overall system availability.

Additionally, the use of condition monitoring systems and predictive maintenance allows for early detection of potential component failures. This contributes to increased system lifespan and reduced operational downtime.

5. Integration as the Core of Hybrid Marine Renewable Energy

a. Synergy of Energy Characteristics

The main key to HMRE lies in the differences in the characteristics of each energy source:

- Ocean current energy is very stable and predictable
- Wave energy has moderate variability but is relatively consistent
- Wind energy has a large capacity but is volatile

This difference creates a complementarity effect, where one energy source can cover the weaknesses of another source (Lewis et al., 2011).

As an example:

- When the wind blows weaken → wave Still bring energy
- When the condition surface sea calm → current still Work

Thus, integration results in a more stable energy profile than a single system.

b. Infrastructure and System Integration

Apart from energy sources, integration also occurs at the system level, including:

- Integrated Platform
Wind turbines can be installed together with wave converters in one floating structure
- Joint Transmission System
The output from various energy sources is combined in one cable network.
- Centralized Energy Management
The control system regulates energy distribution optimally.

This approach has been proven to reduce infrastructure costs and increase system efficiency (IRENA, 2020).

6. Wave, Current, and Wind Energy Integration Model

In its implementation, HMRE can be developed in several main models:

a. Co-located Hybrid System

Various technologies are placed in the same sea area.

b. Physically Integrated System

Energy devices are combined in one physical structure, such as:

Wind turbine + wave energy converter in one platform

c. Electrically Integrated System

Separate energy sources but connected in one electricity network.

These models demonstrate that integration is not only conceptual, but can be implemented technically in a variety of configurations.

7. Integration Advantages in HMRE

The integration approach provides several key advantages:

a. Energy Output Stability

The combination of three energy sources reduces power fluctuations significantly (Falnes, 2007).

b. Economic Efficiency

The use of shared infrastructure reduces investment and operational costs (IRENA, 2020).

c. Capacity Factor Increase

Hybrid systems have a higher energy utilization rate than single systems.

d. Energy Resilience

The system continues to operate even if one of the energy sources experiences a decrease.

8. Challenges of Hybrid System Integration

Despite its promise, the integration of wave, current and wind energy faces complex challenges:

a. Multi-Energy System Design

Integration requires a cross-disciplinary engineering approach (Khan et al., 2009).

b. Interaction Between Devices

Waves and currents can affect the performance of wind turbines and vice versa.

c. High Cost

Hybrid technology is still in the development stage.

d. Extreme Marine Environment

Corrosion, biofouling, and large waves affect the lifespan of the system (Lewis et al., 2011).

e. Regulation

There is no specific policy framework for hybrid systems.

Indonesia and Potential Implementation of HMRE

Indonesia has ideal conditions for HMRE development because:

- Has many straits with strong currents
- Wave high in the southern region
- Potential wind off beaches in the area east

The integration of these three energy sources is very relevant for:

- remote island
- Microgrid system
- Resilience energy national

From this perspective, Indonesia is not only a technology user, but has the potential to become a center for hybrid marine energy innovation.

9. Discussion

From a sustainability perspective, hybrid ocean energy systems offer a more efficient and environmentally friendly approach than utilizing a single energy source. System integration allows for optimal utilization of ocean energy with a more manageable environmental impact.

Furthermore, the hybrid approach also improves energy security, especially for remote areas and small islands that are difficult to reach from the main electricity grid. This system can serve as a reliable and sustainable independent energy solution.

10. Conclusions

Hybrid Marine Renewable Energy places the integration of wave, current, and wind energy at the heart of future marine energy systems. This approach has been proven to improve stability, efficiency, and energy resilience compared to single systems (IRENA, 2020).

Although it still faces technical and economic challenges, the huge potential, especially in Indonesia, makes HMRE a strategic solution in the global energy transition.

With the right technology and policy development, this integration can become the foundation of a sustainable and resilient energy system.

References

- Samsó, R., Crespín, J., García-Olivares, A., & Solé, J. (2023). Examining the Potential of Marine Renewable Energy: A Net Energy Perspective. *Sustainability*. <https://doi.org/10.3390/su15108050>
- Gao, Q., Yuan, R., Ertugrul, N., Ding, B., Hayward, J., & Li, Y. (2023). Analysis of energy variability and costs for offshore wind and hybrid power units with equivalent energy storage systems. *Applied Energy*. <https://doi.org/10.1016/j.apenergy.2023.121192>
- Hu, J., Zhou, B., Vogel, C., Liu, P., Willden, R., Sun, K., Zang, J., Geng, J., Jin, P., Cui, L., Jiang, B., & Collu, M. (2020). Optimal design and performance analysis of a hybrid system combining a floating wind platform and wave energy converters. *Applied Energy*. <https://doi.org/10.1016/j.apenergy.2020.114998>
- Xu, Y., Shi, Y., Xiong, Z., & Yang, H. (2023). Multi-state reliability assessment for shipboard hybrid turbine-diesel generation system with redundancy and aging effects. *Quality and Reliability Engineering International*, 39, 1001 - 1023. <https://doi.org/10.1002/qre.3276>
- Liu, H., Fan, A., Li, Y., Bucknall, R., & Vladimir, N. (2025). Multi-objective hierarchical energy management strategy for fuel cell/battery hybrid power ships. *Applied Energy*. <https://doi.org/10.1016/j.apenergy.2024.124981>
- Kangaji, L., Raji, A., & Orumwense, E. (2024). Optimizing Sustainability Offshore Hybrid Tidal-Wind Energy Storage Systems for an Off-Grid Coastal City in South Africa. *Sustainability*. <https://doi.org/10.3390/su16219139>
- Kangaji, L., Raji, A., & Orumwense, E. (2025). Cutting-edge progress in offshore wind and tidal stream power technology—State-of-the-Art. *AIMS Energy*. <https://doi.org/10.3934/energy.2025007>
- Pelosi, D., Gallorini, F., Alessandri, G., & Barelli, L. (2024). A Hybrid Energy Storage System Integrated with a Wave Energy Converter: Data-Driven Stochastic Power Management for Output Power Smoothing. *Energies*. <https://doi.org/10.3390/en17051167>
- Liu, Y., Tian, Z., Yang, J., & Lin, Z. (2025). Data-Driven Evolutionary Game-Based Model Predictive Control for Hybrid Renewable Energy Dispatch in Autonomous Ships. *2025 4th International Conference on New Energy Systems and Power Engineering (NESP)*, 482-490. <https://doi.org/10.1109/nesp65198.2025.11041353>