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Article

Sustainable energy from the sea: A Comprehensive review of Hybrid Offshore Solar, Wind, and Wave Technologies

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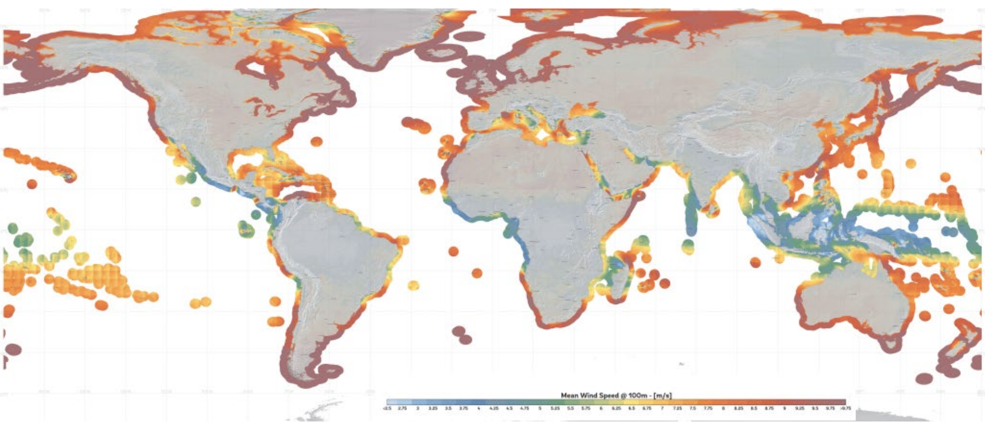
Abstract: The increasing global demand for clean and sustainable energy has intensified research focus on offshore renewable energy systems, particularly those integrating wind, solar, and wave resources. Offshore hybrid renewable energy systems represent a transformative opportunity to harness diverse marine energy sources, aiming to improve energy yield, capacity factor, and reliability compared to single-technology solutions. Evaluation of past literature reveals a critical gap in comprehensive evaluations of fully integrated hybrid offshore platforms that simultaneously deploy floating solar photovoltaic (FPV), offshore wind turbines, and wave energy converters (WECs), including their techno-economic performance and environmental impacts. This study addresses this gap by systematically reviewing the current state-of-the-art offshore floating solar, wind, and wave energy technologies and analyzing key commercial pilot hybrid projects such as Hollandse Kust Noord, W2POWER, and the Hybrid Floating POSEIDON system. A mixed-methods approach combining qualitative literature review, multi-criteria technical, economic, and environmental evaluation, and case study analysis was employed to assess the design innovations, integration strategies, and deployment challenges. Results demonstrate that hybrid offshore systems leveraging synergies between solar, wind, and wave resources can achieve up to five times higher energy output than single-source systems, with floating wind currently leading in maturity and energy production scale, complemented effectively by floating solar and wave converters to enhance seasonal and operational stability. Novel modular floating platforms and advanced mooring systems enable scalable, durable solutions capable of withstanding harsh marine environments. Environmental considerations, including biofouling, corrosion, and ecosystem impacts, can be addressed via mitigation strategies and adaptive site selection.

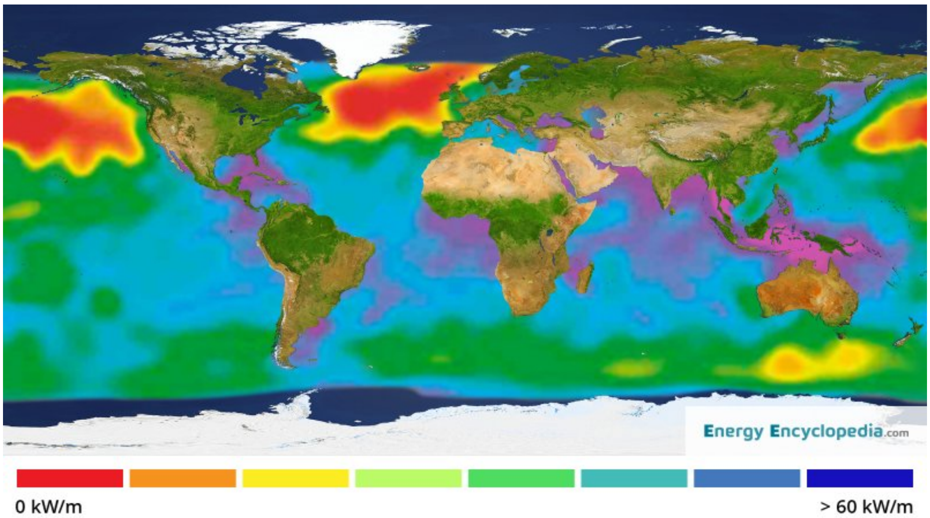
Keywords: Renewable energy integration; Land conservation; Sustainable energy; Climate change mitigation; Marine energy systems; Environmental impact

1. Introduction

In recent years, the global demand for clean and sustainable energy has surged, powered by rapid technological progress and mounting environmental concerns. Researchers and industry leaders are increasingly harnessing renewable energy from natural sources such as the sun, wind, and oceans (Derakhshan et al., 2018), (Díaz et al., 2022). Among marine resources, tidal power, wave energy, offshore wind, and ocean thermal gradients have emerged as promising options for large-scale electricity generation (See Figure 1(a), (b),(c) (The World Bank Group, 2019), ("Economics of wave energy," n.d.; "World_PVOUT_mid-size-map_160x95mm-300dpi_v20250430," n.d.). Offshore floating wind systems, typically deployed in deep waters with high and consistent wind speeds, have shown significant potential for efficient power production, anchored to the seabed with mooring lines and transmitting electricity to shore via undersea cables (Soleimani et al., 2015). Onshore floating systems are installed in shallower waters near coastlines where fixed-bottom turbines are impractical, aiming to capture stronger and more consistent winds and reduce reliance on fossil fuels. Both offshore and onshore floating systems offer advantages such as easier installation and maintenance compared to traditional wind turbines, and their design is critical for optimizing energy capture and ensuring durability under harsh marine conditions. Factors like local topography, wind speed, and noise reduction through acoustic insulation are carefully considered. Europe's offshore energy sector demonstrates this growth, with ocean energy systems projected to reach 40 GW installed capacity and offshore wind systems achieving 3.6 GW by 2020 (Figure 1) (Prässler and Schaechtele, 2012). The design of wind turbines is critical to optimizing energy capture and ensuring durability under harsh marine conditions. Factors such as local topography, wind speed, and noise reduction must be carefully considered (Pérez-Collazo et al., 2015), (Han et al., 2019). It should also reduce noise as much as possible by incorporating adequate acoustic insulation (Wang et al., 2023). The utilization of renewable wind energy has gained popularity worldwide due to its cost-effectiveness, availability, and eco-friendliness (Murray, 2019). The utilization of wind energy has grown worldwide due to its cost-effectiveness, availability, and eco-friendliness, with wind speeds in most regions ranging from 10 to 15 m/s, making it ideal for energy harvesting (Ashwindran et al., 2021). By 2025, global wind power capacity reached 1,136 gigawatts (GW), with record-breaking installations in 2024 adding 117 GW, driven largely by China, the United States, Brazil, India, and Germany. Solar energy has also seen unprecedented expansion, with global solar PV capacity reaching 2.2 terawatts (TW) by the end of 2024, and new installations in 2024 total 597 GW, a 33% increase over 2023. Projections for 2025 suggest up to 655 GW of new solar PV capacity, with favourable conditions potentially pushing this to 774 GW. For example, Western Europe experienced one of its sunniest springs on record in 2025, with certain areas recording up to 50% more GHI than long-term averages, while the UK saw a 42% year-on-year rise in solar output. Wave energy, while less mature than wind and solar, remains promising, with the highest potential in regions like the North Atlantic and Pacific Northwest, where strong and consistent ocean swells prevail. Together, these advances underline a global shift toward renewable energy, driven by robust wind and solar markets, enhanced resource mapping, and the increasing viability of both offshore and onshore floating wind and solar technologies (GWEC, 2014; "Wind Energy Report_ Global Expansion Lags Behind Net-Zero Goals by 2030," n.d.; "Wind industry installs record capacity in 2024 despite policy instability," n.d.).



(a)



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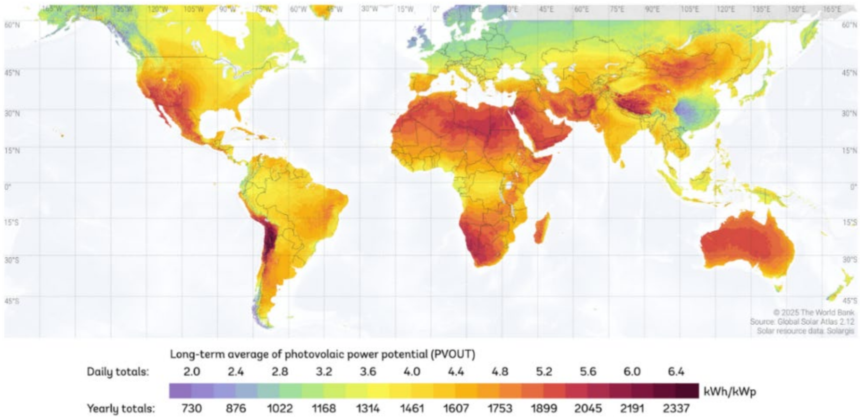
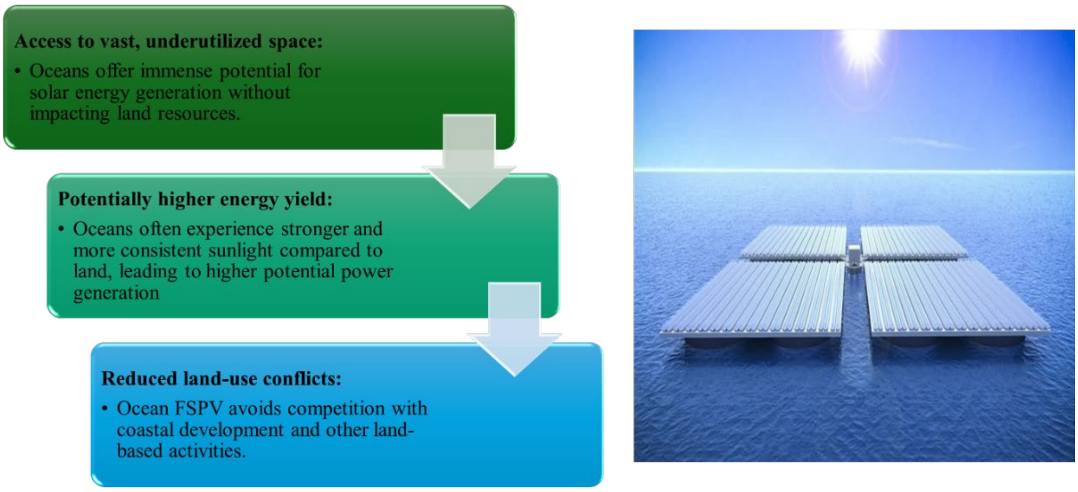


(**c**)

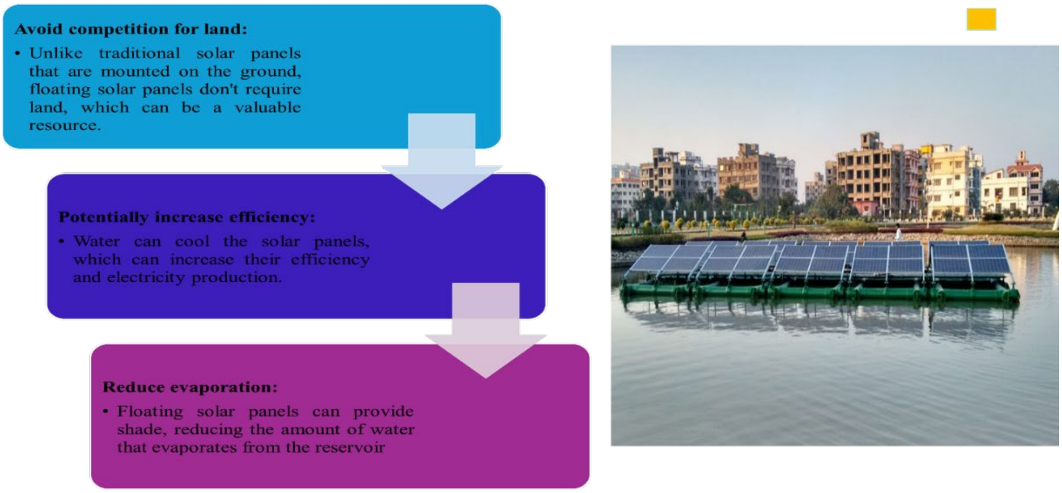
Figure 1. **(a)** Global offshore wind potential, showing key high-wind resource-intensive regions. **(b)** Global wave energy potential highlighting coastal regions with high wave activity. **(c)** Global Solar Irradiation map showing the regions of highest and lowest solar energy.

1.1. Overview of onshore, offshore, and hybrid renewable technologies

Onshore, offshore, and hybrid floating renewable energy systems each have distinct characteristics shaped by their location and environmental conditions. Onshore systems, such as wind turbines or solar panels installed on land, benefit from easier and quicker installation, lower maintenance costs, and cost-effectiveness due to simpler infrastructure. They are typically located in less-populated or rural areas to avoid obstacles that could disrupt energy capture. However, onshore systems may face limitations in available space and lower wind speeds or solar irradiance compared to water-based systems (Kaur et al., 2025a). Offshore systems, including wind turbines and floating solar PV arrays, are installed in bodies of water such as oceans or large lakes (Garrod et al., 2024). Offshore wind turbines take advantage of higher and more consistent wind speeds over water, resulting in greater energy output (Kusuma et al., 2024). Similarly, offshore floating solar systems benefit from increased solar irradiance and the cooling effect of water, which reduces the temperature of photovoltaic cells and enhances their efficiency (Dörenkämper et al., 2021). Studies have shown that offshore floating PV systems can generate approximately 1.99% to 13% more energy than equivalent onshore systems due to these factors (Chayma et al., 2024). However, offshore installations face challenges such as higher installation complexity due to harsh marine conditions, increased operational and maintenance costs, and potential impacts on marine ecosystems (Figure 2(a),(b)). Hybrid floating renewable energy systems combine multiple technologies, such as floating solar with offshore wind turbines, to optimize energy generation while minimizing land use (Kaur et al., 2025b). These systems leverage the advantages of water-based installations and can be deployed in large-scale water bodies without competing for land resources (Solomin et al., 2021). Hybrid systems also benefit from technological advancements in floating platforms and anchoring systems, improving their stability and durability in dynamic water environments. Table 1 shows the comparison (offshore and onshore floating technologies). Onshore renewable energy systems offer cost-effective and easier deployment but are limited by land availability and environmental conditions. Offshore systems provide higher energy yields due to better wind and solar conditions but come with increased complexity and costs, (IREA, 2020),(Lee et al., 2020). Hybrid floating systems represent an emerging approach that integrates the benefits of both, maximizing renewable energy production while addressing land use constraints.



(a) Offshore Floating solar



(b) Onshore floating solar

Figure 2. Schematic of floating solar PV systems: (a) Offshore; (b) Onshore.

Table 1. Comparison of Onshore, Offshore, and Hybrid Floating Systems.

Parameter	Onshore Floating Solar	Offshore Floating Solar	Hybrid Offshore Floating Solar (Solar + Wind/Wave)	Reference
Installation Location	Lakes, reservoirs, irrigation ponds, and other calm	Open seas or coastal zones exposed to waves, tides, and strong winds	Offshore areas where solar platforms are integrated with wind turbines	(Bajc and Kostadinović, 2023; "Marine floating solar plants_ an overview of potential, challenges

	inland water bodies		and/or wave-energy devices	and feasibility _ Proceedings of the Institution of Civil Engineers - Maritime Engineering," n.d.)
Platform Design	Simple modular floating frames, lightweight anchoring systems	Heavy-duty, corrosion-resistant platforms engineered to withstand waves, tides, and storms	Multi-energy platforms combining robust mooring for wind/wave structures with solar arrays, often semi-submersible or hybrid spar designs	(Abhinav et al., 2020)
Environmental Impact	May affect aquatic ecosystems (light penetration, algae growth, dissolved oxygen levels)	Influences marine habitats, hydrodynamics, sediment transport, and local fisheries	Similar to offshore impacts but potentially reduced footprint per unit of energy due to shared infrastructure; careful ecosystem monitoring required	(Ayub et al., 2023; Yousuf et al., 2020)
Maintenance Complexity	Relatively easy access; periodic cleaning and inspection	Higher difficulty and cost due to harsh marine conditions and remote access	Most complex simultaneous upkeep of solar panels, wind turbines, and wave devices requires coordinated offshore operations	(Díaz et al., 2022; Ikhennicheu et al., 2021)
Energy Efficiency	Beneficial water-surface cooling improves PV efficiency over land installations.	Greater cooling effect and higher solar irradiance; typically, 2–13 % higher output than onshore floating systems	Highest overall energy yield by combining continuous solar, wind, and wave resources; improved load-balancing and capacity factor	(Gan et al., 2023; Mannino et al., 2023)
Technical Challenges	Anchoring and stability are relatively simple	Requires advanced mooring, anti-corrosion materials, and wave-motion management	Adds complexity of integrating electrical systems and load management across multiple energy technologies; grid connection and storage are critical	(Kumar et al., 2021; Listianingsih and Susanto, 2023)
Energy Production Potential	Moderate, limited by inland water area and local irradiance	Higher due to stronger, steadier irradiance and cooling	Highest potential: combined solar, wind, and wave resources deliver higher capacity	(Mannino et al., 2023)

		factors and year-round output

1.2. Importance of offshore renewable systems

Offshore renewable energy involves harnessing renewable sources like wind, waves, tides, and currents in the marine environment to produce clean and abundant energy, thereby reducing greenhouse gas emissions and mitigating climate change. Offshore renewable energy is a cornerstone of the emerging blue economy, which promotes sustainable use of marine resources for economic growth while protecting the environment (Zhou et al., 2023). These systems leverage the complementary nature of different energy sources—solar power during daylight, wind power during windy periods, and wave energy from ocean motion—to provide more stable and continuous power generation (Straatman and van Sark, 2008). Hybrid floating platforms can optimize space utilization on the ocean surface, reduce variability in power output, and enhance overall system flexibility. Moreover, they contribute to reducing greenhouse gas emissions and mitigating climate change impacts by providing clean, renewable energy at scale. Despite their promise, hybrid offshore systems face challenges related to environmental impacts, regulatory frameworks, technological integration, and stakeholder engagement. Addressing these challenges is essential for sustainable development and widespread adoption.

1.3. Research Gap and Objective

While offshore renewable energy has attracted significant attention, most studies investigate solar photovoltaics, wind turbines, or wave energy converters as independent systems. This single-technology focus overlooks the potential advantages of integrating multiple resources on a unified offshore platform. Comprehensive evaluations of how solar, wind, and wave systems interact technologically, environmentally, and economically remain limited. In particular, the combined effects on system reliability, energy yield, cost competitiveness, and marine ecosystems are not well understood. This lack of integrated analysis creates a critical knowledge gap in designing and deploying offshore hybrid renewable energy systems. This study addresses that gap by presenting a detailed assessment of hybrid offshore energy systems that simultaneously deploy floating solar PV, wind turbines, and wave energy converters.

This study aims to provide a comprehensive overview of hybrid offshore solar-wind-wave energy systems, focusing on their design, components, benefits, challenges, and potential applications.

- ✓ Discuss the current state of onshore, offshore, and hybrid floating renewable energy technologies.
- ✓ Highlight case studies and recent advancements in hybrid offshore energy projects.
- ✓ Identify gaps in knowledge and propose future research directions to support the sustainable development of offshore renewable energy within the blue economy framework

1.4. Novelty and Unique contribution of the study

Drawing on real-world case studies from diverse coastal regions, it examines the full lifecycle of such systems, including engineering design, installation, maintenance, grid integration, and environmental performance. The research offers a robust analysis, offering guidance for investors and policymakers with clear cost–benefit insights for minimizing ecological disturbance while maximizing energy output. This cross-disciplinary approach not only deepens understanding of hybrid offshore energy potential but also delivers practical design and policy recommendations that support the development of resilient, low-carbon offshore energy infrastructures. By reviewing recent literature and technological developments, this research seeks to inform researchers, policymakers, and industry stakeholders about the opportunities and challenges of hybrid offshore renewable energy systems as sustainable solutions at sea.

2. General description of offshore Wind, Wave, and floating solar systems

2.1. Offshore Wind System Configuration

Offshore wind systems are engineered to harness the stronger and more consistent wind resources available over oceans, enabling higher energy yields compared to onshore installations (Kusuma et al., 2024), (Yan et al., 2022). The design of offshore wind turbines involves addressing complex challenges, such as withstanding harsh marine environments, including waves, currents, and salt corrosion, while ensuring structural integrity and operational reliability (Sickler et al., 2023). Recent advancements focus on optimizing turbine size, layout, and materials to maximize performance and reduce costs (Bilgili and Ünal, 2023). For instance, irregular turbine layouts have been shown to increase annual energy production and improve power output stability relative to wind direction, although they may induce higher fatigue loads on turbine structures, requiring reinforced designs, (Brussa et al., 2023). Additionally, floating offshore wind turbines are gaining attention, with integrated dynamic modelling of hull, mooring, and turbine components essential for their design and performance assessment (Zeng et al., 2024). These systems incorporate coupled hydrodynamic and aerodynamic analyses to ensure stability and efficiency under variable ocean conditions. Continuous innovations, including the application of artificial intelligence in design optimization and the development of robust floating platforms (Figure 3), are driving the evolution of offshore wind technology toward greater reliability and cost-effectiveness (Perez-Collazo et al., 2018).

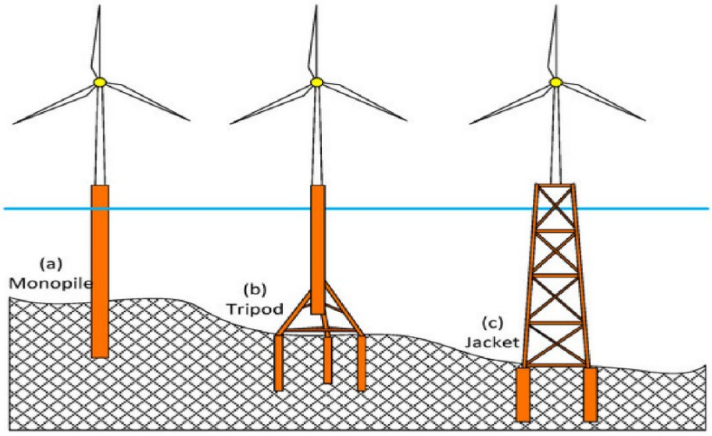


Figure 3. Types of fixed offshore wind turbine foundations: (a) monopile, (b) tripod, and (c) jacket (Ramanan et al., 2024a).

2.2. Offshore floating solar system configuration

Offshore floating solar photovoltaic (FPV) systems represent an innovative approach to harness solar energy by installing solar panels on buoyant platforms designed to withstand harsh marine environments (Kaur et al., 2025a), (Abdelal, 2021). These systems are engineered to endure complex hydrodynamic and aerodynamic forces, including nonlinear wave loads and stochastic sea conditions, which are critical design considerations to ensure structural integrity and operational consistency, (Emami and Karimirad, 2025),(Zeng et al., 2024). The floating platforms are anchored to the seabed, allowing them to remain stable despite waves and wind, while the surrounding water provides a natural cooling effect that enhances the efficiency of photovoltaic cells. Offshore solar systems can use monocrystalline panels for the highest efficiency and durability, polycrystalline panels for lower cost but moderate performance, thin-film panels for lightweight, flexible installation with lower efficiency, and bifacial panels to capture sunlight from both sides and boost output over reflective seawater (Figure 4) (Ghigo et al., 2022),(Akrouch et al., 2023), (Kaur et al., 2025a). Recent studies have developed advanced numerical models and multi-physics frameworks to analyse the interaction between fluid dynamics and structural responses, optimizing platform configurations to minimize power losses caused by platform motion and structural deformation (Nassar et al., 2020), (Sapti et al., 2019). Additionally, offshore FPV systems have demonstrated resilience in extreme weather, such as enduring waves over 10 meters and high wind speeds exceeding 100 km/h, as evidenced by installations like the North Sea solar farm ("Dutch floating solar unit weathers through major North Sea storms intact - Offshore Energy," n.d.; Ramanan et al., 2024a, 2024b). The integration of these systems with optimized electrical grid layouts, including AC and DC networks, further improves energy yield and commercial feasibility(Gustavo and Enrique, 2011). Despite their promise, ongoing research addresses challenges such as corrosion, biofouling, mooring design, and large-scale arrangement logistics to ensure long-term sustainability and cost-effectiveness.

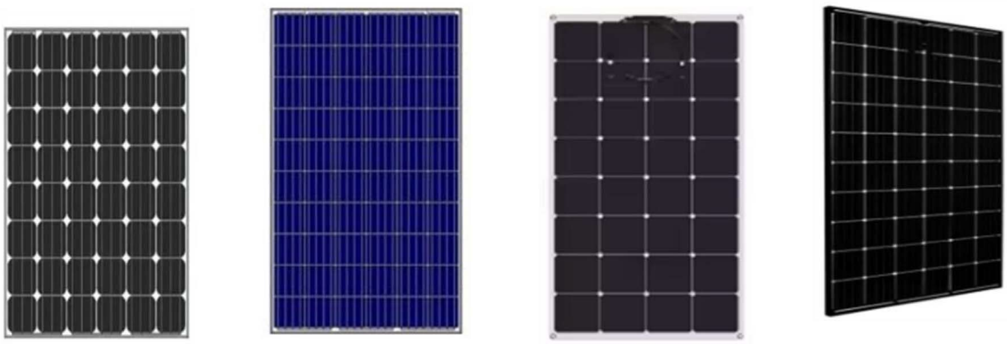


Figure 4. Typical solar PV panel types: (a) Monocrystalline, (b) Polycrystalline, (c) Thin-film, and (d) Bifacial.

2.3. Offshore wave energy system configuration

Offshore wave energy systems can be broadly categorized by their design types and performance characteristics. Design-wise, these systems typically include point absorbers, oscillating water columns, attenuators, overtopping devices, and terminators. Point absorbers are buoy-like structures that move with the waves, converting the motion into energy (Alsebai et al., 2023). Oscillating water columns capture waves in a chamber where the rising and falling water level drives an air turbine (Li et al., 2022). Attenuators are long, multi-segmented floating structures aligned parallel to the wave direction, flexing with wave motion to generate power (Mohsan et al., 2022). Overtopping devices capture water in a reservoir above sea level and release it to drive turbines (Zhang et al., 2021). Systems are assessed based on power output, efficiency, survivability in harsh offshore conditions, and dependability. Offshore wave energy systems are designed to maximize energy capture from wave motion while maintaining durability and economic viability. Some designs focus on maximizing energy from irregular wave patterns, while others emphasize robustness against storm conditions (Abanades et al., 2018; Iglesias and Carballo, 2010). The trade-off between efficient energy conversion and survivability is a major consideration in design and performance evaluation. Offshore wave energy system designs range from buoyant absorbers to sophisticated chambers and reservoirs, each with distinct performance metrics centred on efficiency, durability, and energy reliability in offshore environments (Emami and Karimirad, 2025).

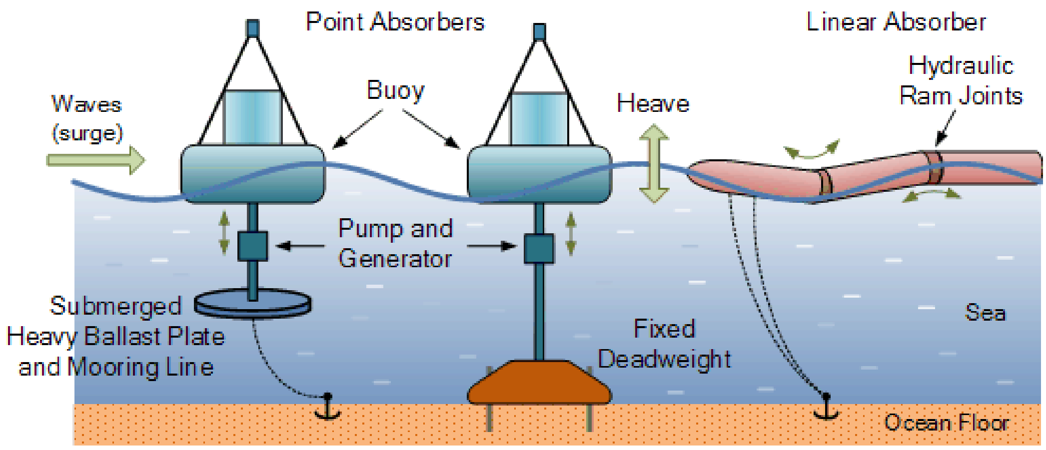


Figure 5. Wave-energy converters illustrating power generation from buoy-heave and articulated absorbers (Alternative Energy Tutorials, n.d.).

3. Methodology

A survey of offshore floating renewable energy technologies was carried out to identify the key trends, challenges, and opportunities within floating offshore hybrid energy systems. This research employed a range of methods to ensure a comprehensive understanding of the field, as illustrated in the Flowchart (Figure 6).

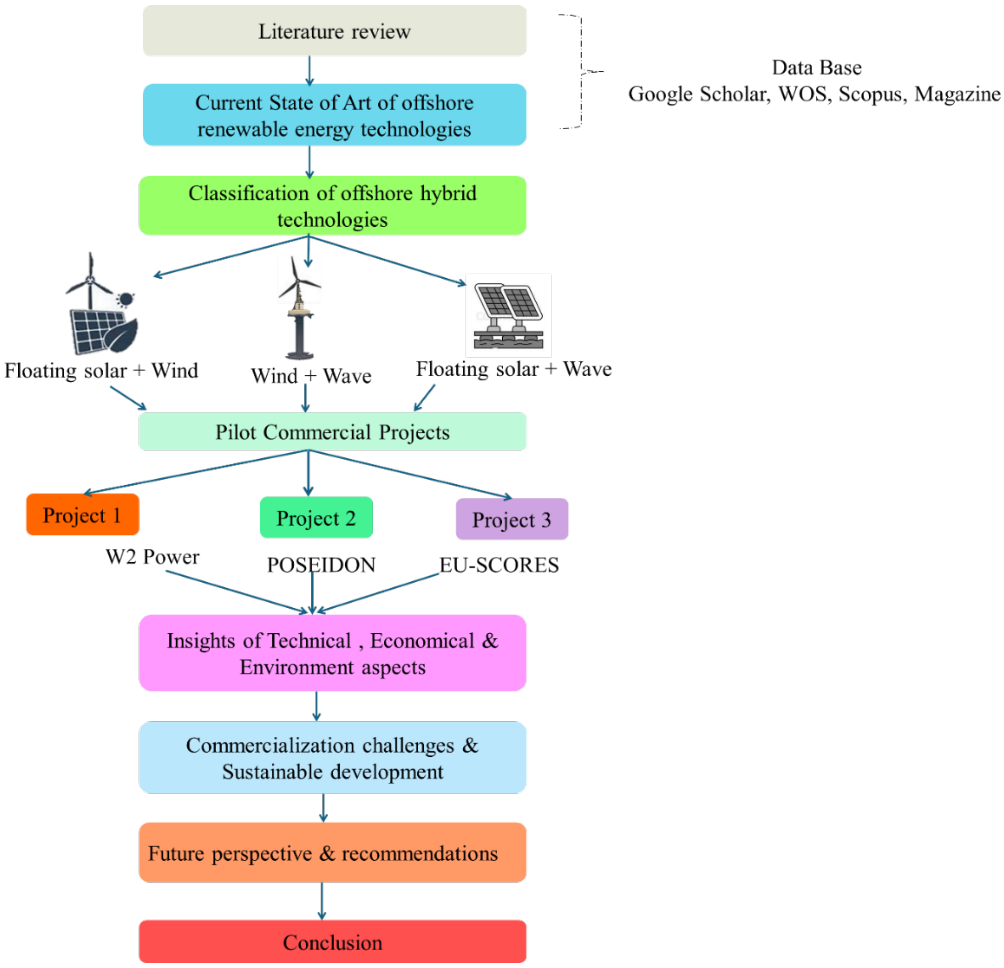


Figure 6. Flowchart highlighting the Methodology framework of the study.

3.1. Research Design and Framework

The study utilized a systematic, mixed-methods approach that combined a comprehensive qualitative literature review with a detailed multi-criteria analysis of existing pilot and commercial projects. This framework was selected to provide a holistic understanding of the subject, moving beyond theoretical models to address practical, real-world applications. The initial phase focused on building a deep technical and conceptual foundation, while the subsequent phases applied this knowledge to evaluate specific projects, allowing for the identification of key trends, challenges, and opportunities. The research followed a logical progression from broad foundational knowledge to specific applications, as depicted in the project's conceptual flowchart, ensuring a rigorous and verifiable research process.

3.2. State-of-the-Art survey

The foundational phase of this research involved a comprehensive and systematic review of existing literature to establish a robust knowledge base and identify the current state of offshore renewable energy technologies. A systematic review process was initiated with an exhaustive search across leading academic databases, including Scopus, Web of Science, and IEEE Xplore. These databases were chosen for their extensive indexing of peer-reviewed journal articles, conference papers, and technical reports, which are considered the primary sources of validated scientific and technical information in this domain. A meticulous search strategy was implemented using a combination of targeted keywords, such as "floating solar," "offshore wind," "wave energy," "hybrid renewable systems," "semi-submersible platform," and "wave energy converters." This methodical approach ensured the capture of relevant and high-quality information, establishing a strong foundation for subsequent analysis. The review also incorporated industry white papers and project reports to provide a practical, industry-facing perspective on technology readiness and commercialization efforts, supplementing the academic data with real-world context. The review critically analysed current developments in offshore solar photovoltaics, wind turbines, and wave-energy converters to capture the state of the art. The analysis considered the operational performance, design variations, and engineering solutions required to ensure the robustness of these systems against harsh marine conditions, including strong winds, corrosive saltwater, and dynamic wave forces.

3.3. Combination of Offshore Hybrid Technologies and Selection of Commercial Project

Next, the study classified offshore hybrid renewable systems based on the combination of energy sources they utilize:

- Wind–Solar hybrids
- Wind–Wave hybrids
- Tri-generation systems (wind, wave, and solar)

Following the foundational literature review, three representative pilot and commercial projects were selected to provide practical, real-world context and insights that extend beyond theoretical designs and concepts. The rationale for the case selection was based on the projects' ability to showcase diverse engineering strategies and commercialization pathways, as shown in Table 2.

Table 2. Comparative Analysis of Key Hybrid Offshore Projects.

Project	Hybrid Type	Selection rationale	Data sources	Aspects analysed
Hollandse Kust Noord	Wind–Solar	First large-scale offshore wind farm integrating floating solar in high-wave conditions.	Project reports, academic publications, government/EU databases	Technology integration Spatial design Policy and funding mechanisms
W2Power	Wind–Wave	Innovative floating platform combining dual wind turbines and wave energy converters.	Developer reports, technical white papers, GIS analysis data	Platform design and mooring system Site selection criteria: Hybrid power management
EU-SCORES	Multi-source (Wind, Wave, Solar)	EU-funded demonstration of hybrid energy parks combining multiple sources in various locations.	EU project documentation, technical consortium publications	Modular platform potential Environmental adaptability Scalability and deployment strategy

3.4. Evaluation of Technical, Economic, and Environmental Parameters

Each case study selected for this research was examined through a detailed multi-criteria evaluation to provide a well-rounded understanding of hybrid offshore renewable energy systems. The analysis considered three main dimensions: technical, economic, and environmental. From a technical perspective, the evaluation looked at platform stability, mooring system design, energy conversion efficiency, and strategies for grid integration. In terms of economic performance, the study assessed cost-effectiveness, scalability, and financing models. Emphasis was placed on how innovations like towable platforms can streamline installation and reduce operational costs. The analysis also addressed the financing barriers that often arise in the development of pilot and demonstrator projects, which are critical steps toward commercialization. For the environmental dimension, the assessment focused on the potential impacts on marine ecosystems, habitats, and biodiversity. Consideration was given to the importance of mitigation strategies to minimize ecological disruption and support the long-term sustainability of offshore hybrid systems.

4. Results and Discussion

This multi-faceted evaluation provided a holistic framework for comparing different case studies and identifying both the opportunities and challenges associated with hybrid offshore renewable technologies. The integration of offshore solar, wind, and wave energy technologies presents a transformative opportunity to harness the vast renewable energy potential of marine environments. Each technology brings unique advantages and challenges, and their combination in hybrid systems offers significant synergies for sustainable energy generation.

4.1. Wind and Wave converters (Design and performance parameters)

Research into hybrid wind and wave systems has examined both ballast-stabilized and buoyancy-stabilized platform designs, aiming to optimize stability and energy capture in offshore environments (Karimirad, 2014a)(Roy et al., 2018). This innovative system builds upon WindFloat technology, a semi-submersible floating platform specifically engineered to support large offshore wind turbines in deep waters up to 1,000 meters (approximately 3,280 feet) (van Niekerk and van der Pot, 1985). The WindFloat platform (see Figure 7) utilizes a patented floating foundation system that streamlines deployment by eliminating the need for costly and complex fixed-bottom foundations. Instead, the platform can be towed to its designated site and positioned for installation, simplifying logistics and reducing overall costs (Salter, 2016). The Wind Float is designed to minimize turbine motion in response to waves, thereby enhancing energy production efficiency. It supports a single three-bladed, horizontal-axis wind turbine with a rated capacity of 6 MW. The platform structure, constructed from steel and concrete, not only improves durability and reduces installation expenses but also lowers ongoing maintenance requirements. Principle Power has conducted extensive numerical and experimental research to evaluate various wave energy converter designs for integration with the WindFloat, aiming to further boost energy output and system dependability (Zhou et al., 2023). Currently, the field of wave energy converters remains highly diverse, with numerous technological approaches under development and no single dominant solution. This variety presents a broad design landscape for future hybrid wind and wave systems, allowing for continued innovation and adaptation to the unique challenges of offshore renewable energy. The Wind Wave Float and Wind Float platforms exemplify the potential of hybrid systems to provide robust, efficient, and cost-effective solutions for deep-water renewable energy generation.

Figure 7. Offshore Floating wind turbine and Wave converter platform (Otter et al., 2022).

The Hybrid Floating POSEIDON project is a cutting-edge renewable energy initiative that aims to combine wind and solar energy generation on floating platforms in offshore locations. The project was initiated by a consortium of renewable energy companies, engineering firms, and research institutions to develop an innovative and sustainable approach to renewable energy production (Karimirad, 2014b). The Poseidon Wave and Wind system produced by Floating Power Plant includes a buoyancy-stabilized platform with three wind turbines and multiple wave energy converters (WECs) (Perez-Collazo et al., 2018). Floating Power Plant, a Denmark-based company, created the Poseidon system. A 37-meter-scale model of the Poseidon system was tested offshore of Denmark, as shown in Figure 13(Roy et al., 2018)(Bashetty and Ozcelik, 2021). The full-scale version of the Poseidon system can range from 80 to 150 meters (about 492.13 ft), depending on the location(Yuan et al., 2021). The 37-meter-scale model included 10 WECs with a capacity of 3 kW each and 3 wind turbines with 11 kW each. The Poseidon system oscillates body WECs and water column WECs(Jaax, 2016). The oscillating water columns are expected to generate 2.6 MW, while the wind turbines will generate 2.3-5 MW in the complete Poseidon system. The Hybrid Floating POSEIDON project aimed to address these challenges by integrating wind and solar energy on floating platforms to optimize energy production, reduce costs, and minimize environmental impacts (Karimirad, 2014a).

Figure 8. Poseidon hybrid floating system combining wind turbines and wave energy converters (Tomey-Bozo et al., 2015).

Case study Project 1: W2POWER

W2POWER, founded in 2015, is a renewable energy company specializing in hybrid floating offshore energy systems that integrate wind and wave power. The W2Power platform couples two floating wind turbines, each rated at 3.6 MW, with oscillating-body wave energy converters (WECs) capable of generating an additional 2 to 3 MW, generate up to 10 MW of combined renewable energy (Hanssen et al., 2015b), (Hanssen et al., 2015a). This innovative system has undergone advanced GIS-based site selection and ocean demonstration campaigns, including a 1:6 scale test near the Canary Islands, confirming its viability for deep-water deployment in challenging marine environments. The platform comprises a semi-submersible structure supporting the dual wind turbines and an array of wave energy converters arranged symmetrically to capture wave energy omnidirectionally. Energy from both wind and waves is harnessed and managed through an integrated power management system that optimizes the hybrid energy inputs for maximum electricity generation, with surplus energy stored in onboard batteries for reliability (Karimirad, 2014a)(Roy et al., 2018). The wave energy converters utilize hydraulic power take-off systems and are integrated with a turret-type mooring system that allows the platform to weathervane and minimize structural loads. W2POWER employs a systematic approach to site selection using Geographic Information System (GIS) technology that considers wind availability, oceanographic data, grid proximity, environmental impacts, and logistical factors to identify optimal locations (Hanssen et al., 2015b), (Legaz et al., 2018). This ensures efficient resource utilization while minimizing ecological and operational risks. The key advantages of the W2Power system include its ability to generate stable, high-capacity renewable energy by combining complementary wind and wave resources; its innovative semi-submersible design that reduces costs and improves maintenance accessibility; and its potential to exploit deep-water sites where traditional fixed foundations are infeasible. Challenges include the technical complexity of integrating two energy harvesting systems, managing dynamic environmental loads, and ensuring cost-effectiveness at scale. W2Power represents a significant step toward multi-use offshore renewable energy solutions, offering enhanced capacity factors, improved energy reliability, and efficient use of marine spaces. The concept has the potential to transform offshore energy landscapes, particularly for deep-water regions globally, and is supported by extensive numerical modelling, tank testing, and real-sea demonstrations (Haji et al., 2018). W2Power represents a significant step toward multi-use offshore renewable energy solutions, offering enhanced capacity factors, improved energy reliability, and efficient use of marine spaces. The concept has the potential to transform offshore energy landscapes, particularly for deep-water regions globally, and is supported by extensive numerical modelling, tank testing, and real-sea demonstrations.

Figure 9. Wind Float semi-submersible floating wind turbine and wave converter.

4.2. Offshore floating solar and wave converter (Design and performance parameters)

A wave and solar hybrid offshore system is a form of renewable energy that combines the power generation capabilities of wave energy and solar energy technologies (Figure 10). Integration of two complementary renewable energy technologies, each leveraging different aspects of the marine environment for efficient energy generation. Wave energy converters (WECs) capture the kinetic and potential energy of ocean waves through various mechanisms, such as oscillating water columns, point absorbers, or submerged rotors, converting this motion into electricity (Fusco and Ringwood, 2013; Petracca et al., 2022). Solar converters, meanwhile, utilize photovoltaic panels often mounted on floating platforms to harness abundant solar radiation over water surfaces. The wave energy component of the hybrid system involves capturing the kinetic energy from ocean waves and converting it into electrical power using devices such as floating buoys, oscillating water columns, or submerged devices (Pérez-Collazo et al., 2015)(European Commission, 2019). These devices harness the motion of the waves and convert it into electricity. On the other hand, the solar energy component of the hybrid system captures energy from sunlight using solar panels or photovoltaic (PV) cells, which convert sunlight into direct current (DC) electricity(Wang and Lund, 2022). This DC electricity can then be converted into alternating current (AC) electricity using inverters and integrated into the overall power generation system. Typically, offshore solar systems use fixed PV modules mounted on floating platforms at a predetermined angle, referred to as fixed-type floating solar. Nevertheless, there has been an increasing interest in pilotless tracking solar systems, which adjust the position of the PV modules based on the time of day to track the sun's movement (Jee et al., 2022). Designing, implementing, and operating a hybrid offshore system requires careful consideration of various factors, including assessing the availability of wave and solar resources, ensuring the technical feasibility of combining the two energy sources, evaluating economic viability, addressing potential environmental impacts, and navigating regulatory considerations (Salter, 2016).

Figure 10. Offshore floating platform integrating solar PV panels with wave-energy converters (Bellini, 2021a).

Integrating wave and solar energy in a hybrid offshore system can synergistically optimize power generation. For instance, the solar component can continue generating electricity from sunlight during low or no waves, and vice versa (Karimirad, 2014b). Energy storage technologies like batteries can also be combined into the system to store extra energy during limited resource availability. While PV solar battery storage stores electrical energy for later use, thermal heat storage retains solar energy in the form of heat, which can be converted to electricity or used directly for thermal applications, offering greater flexibility in energy management (Aydin et al., 2025). Shifting toward renewable energy sources like solar and wind is crucial in combating climate change. However, these energy sources have limitations, such as intermittency and low capacity factors, which can affect their reliability. To tackle these limitations, a potential solution is to leverage a hybrid offshore system that combines wave and solar energy. Wave and solar energy can complement each other in a hybrid system, as they often exhibit opposite availability patterns. For example, wave energy tends to be more consistent during winter, while solar energy is more abundant during summer. By harnessing the combined power of these two energy sources, a hybrid offshore system could potentially provide a more renewable energy supply throughout the year (Hanssen et al., 2015b). Environmental impacts are significant, as any offshore energy system can potentially affect marine life, ecosystems, and habitats. Mitigation measures should be implemented to minimize these impacts and ensure the sustainability of the hybrid offshore system. Financing is another challenge; developing a demonstrator for a hybrid offshore system without adequate funding may be difficult (Hanssen et al., 2015a).

4.3. Offshore floating solar and wind converters (Design and performance parameters)

A floating solar system is a renewable energy system that generates electricity using solar panels while floating on a body of water. Combining solar and wind converters in hybrid systems offers significant advantages. These integrated setups can smooth out energy production variability, as wind and solar resources often complement each other temporally and spatially. These systems use photovoltaic panels, which convert sunlight into electrical energy using the photovoltaic effect. Solar panels in a floating system work similarly to those on land, but with the added advantage of water's cooling effect (López et al., 2020a). A straightforward configuration involves filling the open space between offshore wind turbines with FPV panels(Bi and Law, 2023). This approach prevents any interference between producing renewable energy from both sources. Combining offshore wind turbines and FPV panels to formulate a hybrid renewable energy system increases the power output per unit surface area of marine space and reduces temporal variability (see Figure 10)(López et al., 2020b). It is crucial to conduct a comprehensive assessment of various factors, such as resource availability, technological capabilities, economic feasibility, and environmental impacts, to determine the viability of a renewable energy system (Kalogirou and Tripanagnostopoulos, 2006). This leads to a higher energy output than land-based systems and the ability to use bodies of water not otherwise used (Perez-Collazo et al., 2018).

Figure 11. Offshore floating platform integrating solar photovoltaic panels with a wind turbine for hybrid energy generation ("Tadek Ocean Engineering Expands UK Office," n.d.).

Case study Project 2: Hollandse Kust Noord Offshore Wind–Solar Hybrid

The Hollandse Kust Noord offshore wind park, operated by CrossWind, a joint venture between Shell and Eneco, is pioneering the integration of offshore floating solar within an operational wind farm, marking the first such hybrid project in the world in high-wave North Sea conditions. Fully commissioned in late 2023 with a capacity of 759 MW from 69 Siemens Gamesa turbines, the wind farm is situated approximately 18.5 km off the Dutch coast near Egmond aan Zee. In 2025, Oceans of Energy installed a 0.5 MWp floating solar farm directly between the wind turbines, anchored securely to withstand harsh offshore marine conditions and connected electrically to nearby turbine foundations for seamless energy transfer. This innovative design utilizes existing sea space efficiently by complementing wind generation with solar power on sunny but less windy days, potentially increasing overall energy output by up to five times while avoiding additional grid congestion. The project also incorporates cutting-edge technologies such as battery storage, green hydrogen production via an electrolyzers, and advanced wake control for enhanced wind turbine efficiency. Despite higher initial costs and operational complexities, the integration promises improved capacity factors, greater grid utilization, and a more continuous power supply, key advantages toward a strong renewable energy future. Supported by a €20 million investment in offshore solar technologies and strong backing from governmental and EU programs, this hybrid installation serves as a globally significant model for future multi-technology offshore renewable energy parks, pushing forward sustainable marine energy integration while addressing ecological and technical challenges unique to offshore environments ("Oceans of Energy offshore solar farm 'Nymphaea Aurora' ready for tow out to Hollandse Kust Noord offshore wind farm - Oceans of Energy," n.d.; of Energy, 2023).

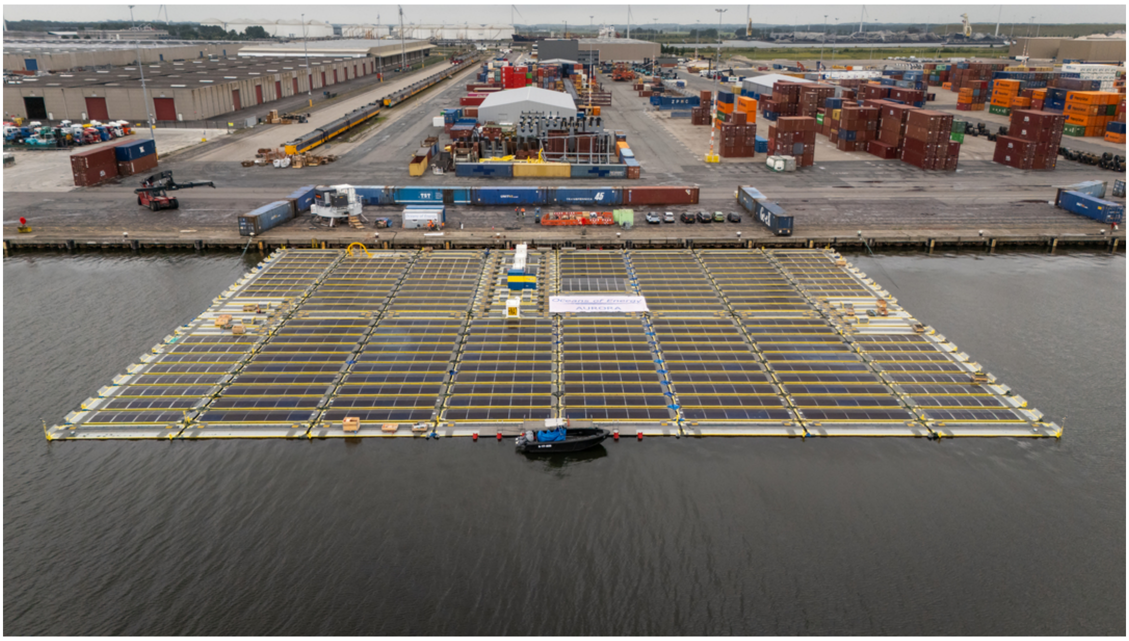


Figure 12. Hollandse Kust Noord Offshore Wind–Solar Hybrid Project ("Oceans of Energy offshore solar farm 'Nymphaea Aurora' ready for tow out to Hollandse Kust Noord offshore wind farm - Oceans of Energy," n.d.).

4.4. Offshore floating solar, wind, and wave converter (Design and performance parameters)

The development of hybrid offshore renewable energy systems integrating wind, solar, and wave power has demonstrated strong potential to accelerate the global transition toward low-carbon energy.

Project 3: EU-SCORES

Sinn Power's Ocean Hybrid Platform (OHP), off Heraklion, Crete, supports 80 kW of solar PV with optional small wind turbines and wave converters. Engineered to withstand 12 m waves and 27 m/s wind speeds, the modular structure can be tailored for nearshore or offshore hybrid parks and is central to the EU-SCORES demonstration sites. The OHP is suitable for both nearshore and offshore applications and is being actively marketed for integration into hybrid renewable parks (see Figure 11)(Bellini, 2021b). On a larger scale, the European Union is supporting the development of hybrid marine energy parks through the EU-SCORES project, led by the Dutch Marine Energy Centre (DMEC). This initiative involves a consortium of 16 leading energy companies and research groups. The project is constructing two demonstration plants, such as the 3 MW offshore solar system developed by Oceans of Energy, which is being co-located with a bottom-fixed wind farm off the Belgian coast. In Portugal, a 1.2 MW wave energy array, developed by CorPower Ocean, is integrated with a floating wind farm. These projects aim to demonstrate the feasibility and benefits of combining wind, solar, and wave energy on an industrial scale, to create bankable, scalable solutions for future offshore renewable energy parks ("Floating into the Future_ Unlocking the Potential of Offshore Wind Energy _ Hitachi Energy," n.d.). Offshore hybrid floating solar, wind, and wave projects represent a significant step forward in the renewable energy sector. By leveraging the complementary nature of these energy sources and innovative platform designs, these projects not only increase energy output but also enhance the reliability and sustainability of offshore renewable energy systems. The ongoing EU-SCORES project and similar initiatives are paving the way for future large-scale, multi-technology marine energy parks.

Figure 13. 80-kW floating energy system created by Sinn Power, located in Heraklion, Greece.

4.5. Comparative analysis

The case studies reviewed in this paper, including the W2Power, Poseidon, and EU-SCORES projects, highlight important lessons and point to several key opportunities and research needs for the next generation of marine energy systems. Combining complementary resources, for instance, the higher solar availability in summer with stronger wave energy in winter, can mitigate intermittency and enhance capacity factors. A clear progression emerged from simple co-located projects, which share electrical infrastructure, to fully integrated platforms like Sinn Power's modular Offshore Hybrid Platform that unites solar, wind, and wave technologies on a single structure. Platform design proved to be the central enabler of this evolution, with robust, towable, and modular foundations exemplified by Hollandse Kust Noord allowing efficient installation, scalability, and stable power generation. Site selection was shown to be a multi-dimensional challenge requiring careful optimization of resource potential, grid proximity, environmental impact, and cost. Modular and scalable designs, such as those seen in the Sinn Power Ocean Hybrid Platform and Poseidon systems, show promise but require further refinement to reduce manufacturing costs and simplify large-scale deployment. Comparative economic analyses across different ocean regions can also identify the most cost-effective deployment sites and inform policy frameworks that encourage private investment. Although hybrid offshore projects reduce intermittency and improve energy yield, high capital expenditures remain a barrier. Streamlined installation techniques, such as towable platforms and integrated cabling solutions, must be optimized to reduce costs. The environmental footprint of hybrid offshore systems remains an important area for investigation. While these projects generally aim to reduce greenhouse gas emissions, their effects on marine biodiversity, benthic habitats, and coastal ecosystems must be carefully assessed. Pilot and demonstration projects, including W2POWER and POSEIDON, were identified as essential for de-risking technology, securing financing, and achieving regulatory approval. While pilot projects such as the EU-SCORES initiative have proven technical feasibility, expanding these efforts to industrial-scale parks will be the next major step. The analysis showed that hybrid offshore systems are driven not only by the goal of higher energy output but also by the need to improve reliability and reduce intermittency by combining complementary resources such as solar and wave energy. The experience of pioneering projects such as Hollandse Kust Noord, W2POWER, Poseidon, and EU-SCORES highlights the importance of pilot demonstrations to validate technology, optimize designs, and build stakeholder confidence.

Table 3. Comparative Overview and Multi-Criteria Evaluation of Key Hybrid Offshore Projects.

Project / Platform	Hybrid Type	Rated / Tested Capacity (MW)	Capacity Factor*	Key Design & Boundary Conditions	Indicative Cost / O&M Notes	Reference
Hollandse Kust Noord (NL)	Bottom-fixed offshore wind + floating solar + green H_2 pilot	759 MW wind + 0.5 MWp FPV (2025 pilot)	Wind ~45 % (Siemens Gamesa SG11), Solar ~18 % est.	North Sea, 18.5 km offshore; mean Hs ~2 m, extreme Hs > 6 m; grid-connected electrolyser & battery	EU-backed €20 M offshore FPV programme; O&M shared with wind farm	(Perez and Iglesias, 2012),(Vo et al., 2021)
W2POWER (ES)	Floating twin-wind + wave	2 × 3.6 MW wind + 2–3 MW wave ≈10 MW	Wind 35–45 % est.; wave add-on up to +10 % annual energy	Canary Islands tests; 1:6 scale; semi-submersible with turret mooring; survival Hs 12 m design	CapEx lower than separate farms due to shared mooring; OPEX TBD from demo	(Karimirad, 2014a),(Roy et al., 2018) (Hanssen et al., 2015b),(Hanssen et al., 2015a)
Poseidon / Floating Power Plant (DK)	Floating wind + wave	Full-scale: 2.3–5 MW wind + 2.6 MW wave	Wind 30–40 % est.; wave +5–10 %	North Sea prototypes; 37 m test platform with 10 WECs; designed for Hs > 10 m	Modular steel pontoon lowers O&M; wave PTO maintenance key	(Zhou et al., 2023), (Karimirad, 2014b)
EU-SCORES / Sinn Power OHP (GR)	Floating solar + optional wind + wave	0.08 MW solar (Crete demo); scalable to multi-MW	Solar 16–20 % (Mediterranean); wave potential site-specific	Engineered for 12 m significant wave height, 27 m s^{-1} wind; modular cubes	Designed for mass production; OPEX goal < €30 k MW^{-1} yr^{-1}	(Bellini, 2021a),(Kalogirou and Tripanagnostopoulos, 2006).
WindFloat (PT/ES reference)	Floating wind (with wave-energy R&D)	6 MW single turbine	40–45 %	Semi-submersible, 1000 m water depth; tow-to-port maintenance	Demonstrated ~20 % installation cost savings vs. fixed	(van Niekerk and van der Pot, 1985),(Salter, 2016)

5. Future perspectives, Recommendations, and research directions

Scaling hybrid offshore renewable energy systems to commercial levels involves overcoming multifaceted challenges spanning technical, economic, environmental, and regulatory domains. Future work should focus on:

- Improving the engineering of floating platforms that can efficiently combine multiple renewable sources while remaining robust in harsh offshore environments. Advances in floating platform designs, such as semi-submersible and towable modular structures, will improve stability, reduce installation costs, and facilitate scalability in deep and challenging marine environments. Logistical challenges in installation and maintenance, especially in deep-water and harsh marine environments, require further development of towable, modular platforms and coordinated offshore operation strategies.

- Research into lightweight yet durable materials, advanced mooring systems, and real-time monitoring technologies will be critical to ensure long-term reliability and adaptability to varying sea states. Emerging technologies in materials, anti-corrosion coatings, biofouling mitigation, and robust mooring systems are critical to prolonging operational life and reducing maintenance complexity in harsh oceanic conditions.
- Artificial intelligence and digital twin models are anticipated to play an increasing role in optimizing system design, operation, and predictive maintenance, fostering resilient and cost-effective hybrid offshore renewable energy infrastructures.
- Evaluate the performance of hybrid arrays under diverse climatic conditions, including extreme weather events, to provide robust operational data for regulators and investors. Site selection must balance resource availability with ecological sensitivity and grid connectivity.
- Furthermore, the incorporation of energy storage solutions such as batteries and thermal storage will enable better load balancing and enhance the continuity of the power supply.
- Demonstrating stable, large-scale grid connectivity will be key to attracting commercial investment and ensuring reliable energy delivery to coastal and island communities. Integration strategies focusing on optimized electrical grid layouts, hybrid power management, and smart control systems will be key enablers for improving overall system efficiency and reliability.
- Research into lightweight yet durable materials, advanced mooring systems, and real-time monitoring technologies will be critical to ensure long-term reliability and adaptability to varying sea states.
- Explore innovative financing models, including public-private partnerships and green investment mechanisms, to support commercial scaling. High capital costs and complex integration of multiple energy conversion devices demand innovative financing models and supportive policy frameworks to de-risk investments and promote early adoption.
- Prioritize long-term ecological monitoring, development of low-impact anchoring solutions, and adaptive management strategies to mitigate potential disturbances to marine life. Environmental impacts on marine ecosystems necessitate rigorous monitoring and implementation of mitigation measures to preserve biodiversity and ecosystem health, which in turn support sustainable development goals.
- Finally, supportive policy frameworks are essential to accelerate the deployment of hybrid offshore systems. Regulatory complexity, including permitting and compliance, must be streamlined to facilitate project approval and deployment. International collaboration is needed to harmonize permitting procedures, create standardized safety protocols, and facilitate cross-border electricity trade. Policies that incentivize multi-technology installations could further enhance the economic competitiveness of hybrid platforms.

The future of offshore hybrid renewable energy systems lies in continued innovation and enhanced integration of floating solar, wind, and wave technologies. Scaling hybrid offshore renewable energy systems to commercial levels involves overcoming multifaceted challenges spanning technical, economic, environmental, and regulatory domains. Collaboration between industry, academia, and governmental entities will be crucial to address these challenges collectively and accelerate the transition towards sustainable, large-scale offshore hybrid renewable energy systems.

6. Conclusion

Hybrid offshore renewable energy systems combining floating solar photovoltaic, wind turbines, and wave energy converters represent a transformative frontier in the pursuit of clean, sustainable, and reliable energy generation. By leveraging the complementary nature of these renewable resources, hybrid platforms can significantly improve capacity factors, energy yield, and grid stability compared to single-technology installations. Continued technological advancements in floating platforms, mooring, energy storage, and smart integration strategies will enhance system performance while reducing costs and environmental impacts. Nevertheless, commercialization and large-scale deployment remain constrained by technical challenges, high investment costs, environmental considerations, and regulatory complexities. Addressing these challenges requires coordinated efforts in innovation, policy support, environmental stewardship, and demonstration projects. The growing portfolio of hybrid offshore projects worldwide illustrates the feasibility and immense potential of these systems to contribute substantially to the global renewable energy transition and the blue economy. Sustained research, technology development, and stakeholder collaboration will pave the way for scalable, resilient, and economically viable offshore hybrid renewable energy infrastructures, marking a pivotal step in combating climate change and achieving sustainable development. With thoughtful investment and strategic development, these systems can become a cornerstone of the world's transition to clean, reliable, and sustainable energy.

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