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Offshore hybrid renewable energy: insights from real-world implementations

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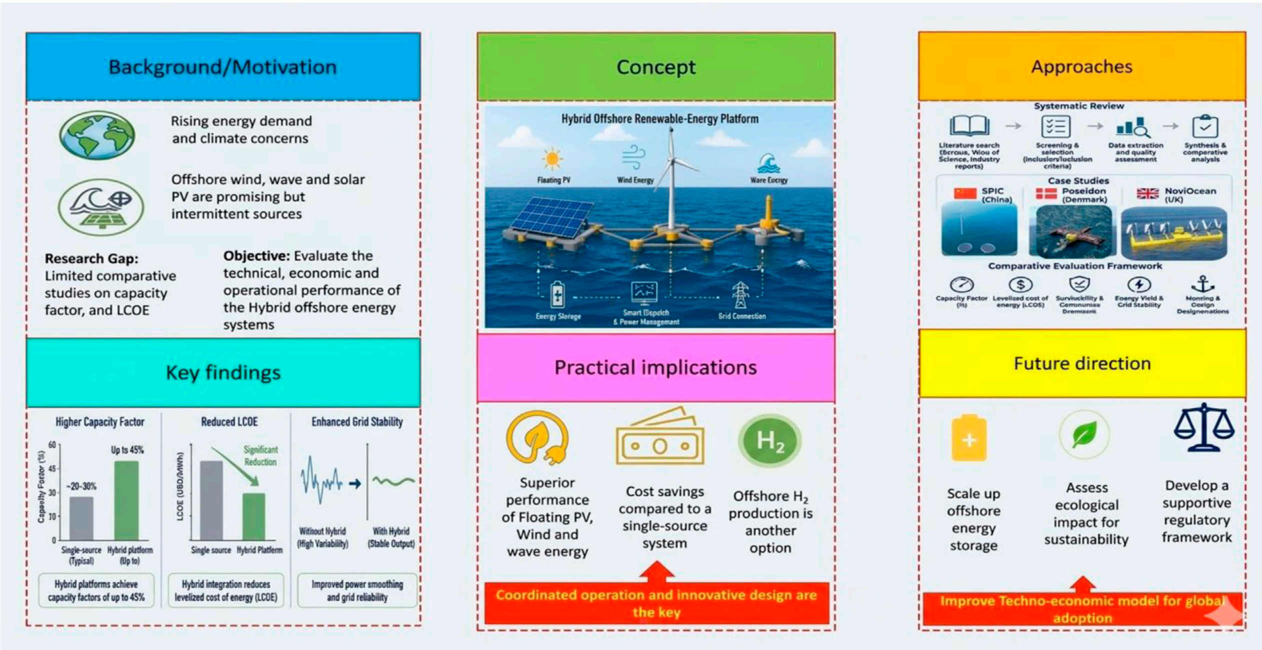
Global energy demand and climate concerns are accelerating the adoption of marine renewable resources, with offshore wind, wave, and solar technologies emerging as key solutions. Hybrid offshore platforms that integrate floating photovoltaic (FPV), wind, and wave systems offer the potential for higher energy yields and greater resource complementarity than standalone installations. This study aims to evaluate the technical, economic, and operational performance of hybrid offshore renewable-energy platforms and identify critical design considerations for large-scale installations. Although research interest is rising, comprehensive comparative analyses of hybrid *versus* single-source systems in terms of capacity factor, levelized cost of energy (LCOE), and survivability remain scarce. To address this gap, a systematic review of literature and industry data was conducted, supported by three detailed case studies SPIC (China), Poseidon (Denmark), and NoviOcean (UK). Results show that hybrid platforms can achieve capacity factors of up to 45%, reduce LCOE, and enhance grid stability through innovations in mooring, energy dispatch, and multi-resource integration. Findings highlight that coordinated operation of wind, wave, and FPV systems significantly increases annual energy yield while mitigating intermittency and minimising spatial footprint. Future research should focus on scaling energy storage, offshore hydrogen production, and assessing regulatory and environmental challenges to enable the commercial viability and global adoption of hybrid marine renewable systems.

KEYWORDS
floating solar energy, hybrid floating, ocean wind, oceanic energy, sustainable power generation, wave energy

1 Introduction

The leading cause of global warming is dependence on fossil fuels for energy generation. In recent years, climate change has become a major environmental challenge, driving global temperatures higher. The ocean energy sector in Europe has set goals, aiming to install 100 GW of capacity by 2050. According to assessments reported by Ocean Energy Europe, the long-term technical potential of ocean energy in Europe could reach up to 100 GW by 2050, which, under favourable deployment and policy scenarios, could contribute



GRAPHICAL ABSTRACT

approximately 10% of Europe's electricity demand and supply power to around 94 million households. These figures represent estimated potential rather than the objective of a specific project (Ocean Energy Europe). The primary energy sources in the offshore industry include wave energy, tidal energy, ocean thermal energy conversion (OTEC), offshore wind energy, and floating solar energy (Figure 1) (Santhakumar et al., 20243; Zhou et al., 2023). Ocean-based technologies harness the abundant energy resources of the seas, providing a sustainable alternative to land-based energy generation. Offshore floating solar systems have utilised the wide surface area of oceans and large bodies of water, avoided land-use conflicts, and benefited from higher energy yields (Nicholls-Lee and Turnock, 2008). Offshore wind farms harness strong, consistent ocean winds to generate significant electricity (Zhou et al., 2023). Wave and tidal energy systems capture kinetic and potential energy from ocean waves and tidal movements (Nicholls-Lee and Turnock, 2008). OTEC systems convert the thermal gradient between warm surface water and cold deep water into electricity, providing continuous and consistent energy (Petracca et al., 2022). These wave and tidal energy technologies are now integral to hybrid offshore energy concepts (Nicholls-Lee and Turnock, 2008). Wind energy has experienced significant growth due to its cost-effectiveness and low greenhouse gas emissions (Waewsak et al., 2015; Wagner et al., 2011). According to the most recent industry statistics, total global installed wind energy capacity grew strongly in 2024, reaching approximately 1,136 GW by the end of the year, following the addition of around 117 GW of new installations. This growth was driven predominantly by onshore wind, accompanied by continued but smaller gains in offshore wind capacity (Windtech International, 2024). In Europe alone, approximately 285 GW of wind power capacity was operational at the end of 2024, including around 37 GW of offshore wind capacity, with a net increase of about 16.4 GW added during the year (Wind energy in Europe, 2025). These figures reflect ongoing growth in global and regional wind installation as the technology continues to scale (Chen, 2013). Hybrid renewable energy systems offer a potential solution for ensuring continuous power generation and reducing energy costs (Li et al., 2022a). Despite growing interest, hybrid offshore systems remain less developed than their onshore counterparts (Faria et al., 2023). Floating photovoltaic (FPV) systems have emerged as an innovative solar power generation technology, effectively addressing the land-use constraints often associated with conventional ground-mounted photovoltaic (GPV) installations (Ghosh, 2023). The concept was first introduced in Japan in 2007 with a 20-kW prototype developed by the National Institute of Advanced Industrial Science and Technology (Rebecca Williams, 2022). Commercialisation began in 2008 with a 175-kW installation on a winery's irrigation pond in California (Trapani and Redón Santafé, 2015). Since then, FPV technology has grown rapidly, reaching a global installed capacity of 13 GW by 2022, primarily driven by installations in Asia. FPV systems offer several advantages over land-based photovoltaics, including reduced land use, improved panel efficiency from water cooling, and reduced evaporation from water bodies. However, challenges such as higher installation costs (10%–25% more than ground-mounted systems) and the need for robust anchoring systems remain significant barriers to widespread adoption. Despite these challenges, the potential for FPV is immense, with studies estimating that covering just 10% of suitable global water surfaces could yield over 4,000 GW of solar capacity (PUB Singapore's National Water Agency, 2016; Geyer, 2024). The system operates in challenging conditions, including a water depth of one hundred meters and considerable water level variations. Countries facing land insufficiency, such as

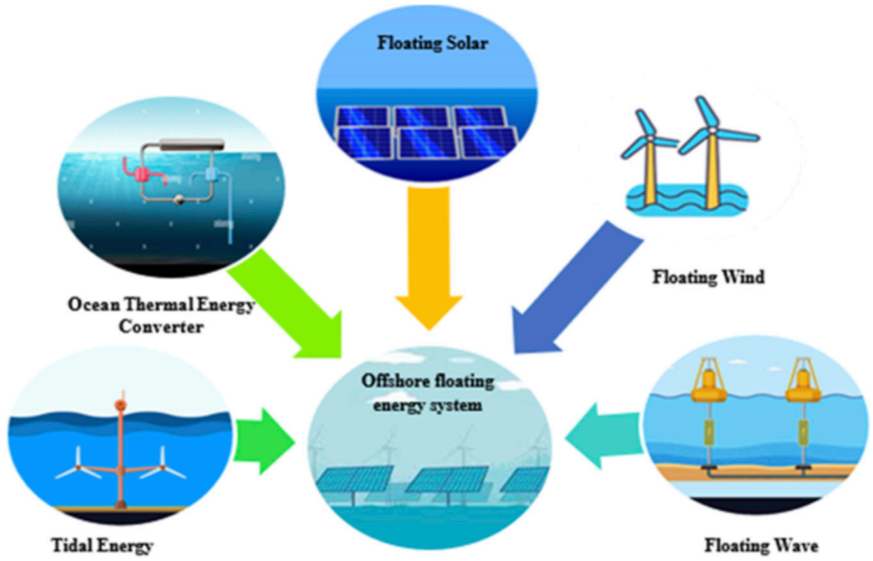


FIGURE 1
Various offshore floating energy systems.

Singapore and South Korea, increasingly demand FPV technology to meet their growing electricity demand while contributing to global efforts in achieving affordable and clean energy, as outlined in the United Nations Sustainable Development Goals (SDG) (Hasan et al., 2024; Gan et al., 2023).

1.1 Current state of offshore hybrid renewable energy

Offshore renewable energy systems are advancing rapidly, particularly those integrating multiple sources like wind, wave, and solar power. The EU is at the forefront, with ambitious targets for offshore wind and ocean energy by 2030 (Rebecca Williams, 2022). Integrating various offshore energy technologies offers a comprehensive approach to energy generation by combining the unique advantages of each, mitigating individual limitations, and improving overall efficiency and reliability. Such integration enhances energy security, reduces greenhouse gas emissions, supports sustainable development by advancing technical innovation, creating employment opportunities, and stimulating economic growth in coastal and island regions. These systems offer significant advantages in increased energy production, optimised space utilisation, and reduced power fluctuations. Projects such as those in China (floating solar and wind projects) (López et al., 2020), the Poseidon project (McTiernan and Sharman, 2020), and the NoviOcean project (NoviOceana, 2024) demonstrate the feasibility and benefits of such integrated approaches, paving the way for future advancements in marine renewable energy technology. Hybrid systems that combine offshore wind with solar power have been shown to significantly increase capacity and energy production per unit surface area, with improvements by factors of ten and seven, respectively (Vo et al., 2021). This combination also results in smoother power output, as evidenced by a novel Power Smoothing (PS) index that can reach up to 63% (López et al., 2020). The advantages of such hybrid systems are not limited to specific regions but apply to several countries that are considering marine renewable energy. The Poseidon project, developed by Poseidon Floating Power, demonstrates the innovative hybrid concept of combining floating wind turbines with wave energy converters (Nassar et al., 2020; Saeidtehrani et al., 2022). This approach has been explored to enhance power production and reduce platform motions (Saeidtehrani et al., 2022; Friel et al., 2019). Studies have shown that integrating wave energy converters with floating wind turbines can increase overall power production by 22%–45%, depending on environmental conditions, and stabilise the power output by reducing platform motions (Zhou et al., 2023; Si et al., 2021). The Poseidon project, specifically, has been analysed for its cost-effectiveness, with manufacturing costs being a significant factor in its economic viability (Castro-Santos et al., 2016). The NoviOcean project by Novige represents a multi-energy offshore power solution that combines wave, wind, and solar energy. This innovative approach aims to deliver a total output of 1 MW by leveraging the complementary nature of these renewable sources. Hybrid systems like NoviOcean are designed to reduce power fluctuations and investment costs, offering a promising solution for the future of marine energy. Integrating multiple energy sources into a single platform can improve hydrodynamic stability and lower the Levelized Cost of Energy (LCOE) compared to traditional systems (NoviOceana, Technology – NoviOcean, NoviOceanc).

1.2 Gap in existing literature and research problem

Despite notable progress in Offshore hybrid renewable energy (OHRE) systems, as evidenced by projects such as China's wind-solar hybrids, the Poseidon offshore platform, and the Novi Ocean initiative, critical research gaps remain. Current designs prioritise technical feasibility and energy output but lack integrated techno-economic-environmental assessments, including life-cycle costs, ecological footprints, and socio-political trade-offs. Long-term performance data are scarce, with most case studies (such as North Sea wind-hydrogen systems) offering only short-term insights, leaving uncertainties about decades-long reliability, maintenance needs, and component degradation. Grid integration challenges—particularly those related to energy storage and transmission optimisation—remain insufficiently explored. Similarly, adaptive artificial intelligence approaches for balancing cost, reliability, and environmental impacts have rarely been studied in this context. Additionally, synergies with emerging technologies, such as subsea hydrogen storage or carbon capture, lack systematic analysis, despite their potential to enhance system efficiency.

1.3 Contribution and novelty of this paper

This paper provides a comprehensive assessment of OHRE systems by analysing their technological, economic, and environmental dimensions, with particular emphasis on integrated platforms combining floating solar photovoltaics, offshore wind turbines, and wave energy converters. The novelty of this research lies in its system-level evaluation of the synergistic benefits of multi-source offshore integration, demonstrating how combined solar–wind–wave platforms can enhance energy reliability, improve resource utilization, and reduce greenhouse gas emissions relative to single-source offshore installations. The study further contributes by analysing real-world case studies from different geographical regions, providing insights on solar efficiency, turbine design, and wave energy output, to establish the conditions under which multi-source hybridization becomes cost competitive. In addition, recent technological advancements in floating structures, energy storage solutions and smart grid control are synthesized to highlight pathways for performance optimisation. Finally, it translates these findings into a practical implementation roadmap, grounded in three real-world case studies (SPIC, Poseidon, and NoviOcean), and offers targeted recommendations for policymakers, engineers, and industry stakeholders on permitting, R&D investment, and environmental impact assessment.

1.4 Objective of the study

- This review overviews the various offshore energy systems, including solar, wind, and wave technologies for sustainable energy production.
- The study analyses the various case studies from Spain (solar and wind), Denmark (wind and wave), and the UK (solar, wind, and wave) to provide insights into offshore hybrid energy technologies.
- The study also explores the benefits, challenges, risks, and applications of various hybrid configurations for practical implementation.

The paper has been structured into three primary sections. Section 2 overviews offshore renewable energy sources, including solar, wind, wave, OTEC, and tidal systems. It examines the design principles and components while comparing their advantages and limitations. Section 3 focuses on the case studies of offshore hybrid floating systems; Section 4 discusses future research directions and recommendations; and Section 5 provides the conclusion.

2 Overview of offshore renewable energy system

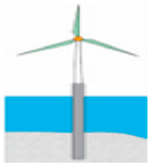
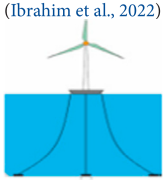
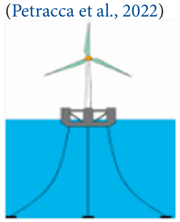
2.1 Offshore floating wind

Offshore wind energy has developed as an important and scalable alternative to fossil fuels, capable of delivering base-load equivalent with considerably lower greenhouse gas emissions than conventional fossil fuels (Islam et al., 2024). However, its environmental footprint is not without concern, as cumulative effects, including marine habitat modification, underwater noise during construction, and barrier effects on bird and bat migration, remain active areas of ecological research and monitoring (Pouran et al., 2022; Skov, 2023). The industry has grown rapidly due to technological advancements, supportive policies, and the increasing demand for clean energy solutions (Prasad et al., 2024). The energy conversion process in a wind turbine involves capturing wind energy using the blades, transmitting it to the generator *via* the gearbox, and generating electricity (Wind). The electricity is then delivered to the grid or directly to the load. Wind turbine designs varied in terms of axis adjustment, rotor size, power regulation, blade number, yaw control, and speed operation (Gustavo and Enrique, 2011). Various foundation types were developed for offshore wind turbines, including fixed and floating structures. Fixed structures were suitable for shallow waters, while floating structures were more appropriate for deepwater locations (Capanoglu, 2005). The choice of wind turbine structure type depends on factors such as water depth, seabed conditions, and environmental considerations. Table 1 provides a comprehensive overview of different foundation types, outlining their advantages and disadvantages. Foundations are crucial in anchoring wind turbines to the seabed, ensuring their stability and operational efficiency.

2.2 Offshore wave converter

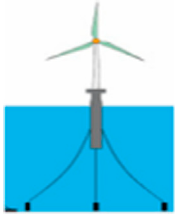
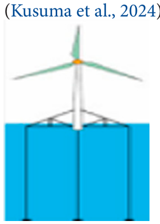
Wave energy, derived from ocean waves, has great potential as a renewable source of sustainable electricity (Arguilé-Pérez et al., 2022). Although wind and solar power have historically led the renewable energy industry, wave energy has increasingly been endorsed as a reliable and eco-friendly option, particularly for coastal areas (). Wave energy converters (WECs) are innovative devices that convert the kinetic and potential energy of ocean waves into electricity (Oliveira-Pinto and Stokkermans, 2020b). These devices typically comprise an energy capture component and a power take-off (PTO) system. The energy capture component harnesses wave motion to generate mechanical energy, which is then transferred to the PTO system for further conversion to electrical energy (Ahamed et al., 2020). Table 2 provides a comprehensive overview of various Wave Energy Converters (WECs), highlighting their unique characteristics and advantages. The critical role of Power Take-Off (PTO) systems in extracting energy from wave motion and converting it into electricity was emphasised, along with the factors influencing PTO system selection

TABLE 1 Offshore wind turbine, along with advantages and disadvantages (Bostan et al., 2019; Jallad et al., 2017).

Structure type	Description	Depth suitability	Stability	Advantages	Disadvantages	Installation complexity	Cost
Monopile (Lee et al., 2014) 	A single large-diameter steel tube was driven into the seabed.	Up to 30 m (shallow water)	High in shallow waters	Simple design, cost-effective, widely used.	Limited to shallow waters, unsuitable for hard seabeds.	Moderate	Low to moderate
Jacket/Lattice structure (Rebecca Williams, 2022) 	Steel lattice framework anchored with piles.	20–80 m	Very stable	Suitable for deeper waters, proven in the oil and gas industry.	High construction and installation costs.	High	High
Tripod (Bashetty and Ozcelik, 2021) 	A joint at the top connects three monopiles.	20–60 m	Stable	A broader base increases stability and simplifies installation.	Limited to moderate depths, more material is required than monopile.	Moderate	Moderate
Spar-Buoy (Ibrahim et al., 2022) 	Floating cylindrical structure anchored by mooring lines.	>60 m (deep water)	Stable in deep waters	Excellent for very deep waters, minimal seabed impact.	Complex installation requires specialized vessels.	High	Very high
Semi-submersible (Petracca et al., 2022) 	A frame connects a floating platform with multiple buoyant columns.	>60 m (deep water)	Stable under wave motion	Flexible design, suitable for various depths and seabed conditions.	Requires large anchoring systems and a complex installation process.	Very high	Very high

(*Continued*)

TABLE 1 Continued

Structure type	Description	Depth suitability	Stability	Advantages	Disadvantages	Installation complexity	Cost
Tension leg platform (TLP) (Kusuma et al., 2024) 	The floating structure is tethered to the seabed with tensioned mooring lines.	>60 m (deep water)	Extremely stable	Minimal vertical movement, highly efficient in energy transfer to the turbine.	Requires precise installation and advanced anchoring systems.	Very high	Very high
Tri-Floater (Barge) (Kusuma et al., 2024) 	Mooring lines anchor a floating barge with a wide base for stability.	>60 m (deep water)	Moderate	Simple design, cost-effective for floating structures.	Less stable compared to spar or TLP in harsh weather conditions.	Moderate	Moderate to high

(Li et al., 2022b). The discussion also covered the importance of mooring systems for ensuring WEC stability and the use of submarine cables for reliable electricity transmission to the onshore grid. It emphasised the significant potential of wave energy as a clean and sustainable energy source, highlighting the ongoing progress in WEC technologies and accelerating its path toward commercialisation (Abaei et al., 2025; Claus and López, 2022).

2.3 Offshore floating solar

Floating solar systems, also known as Floating Photovoltaic (FPV) systems, have emerged as a promising renewable energy technology (López et al., 2020). FPV systems offered several advantages over traditional land-based solar installations by installing solar panels on water bodies, including optimal land use, improved solar panel cooling, and reduced water evaporation. Underwater cabling connected the solar panels to the onshore grid, ensuring reliable power transmission (Huang et al., 2019). A mooring system was essential to anchor the floating structure and prevent it from drifting. Table 3 compares several PV module types suitable for FPV applications. Floating solar power offers a sustainable, efficient way to generate solar energy. Using ocean water bodies, FPV systems maximise land use, enhance solar panel performance, and contribute to environmental sustainability. As the technology evolves, offshore floating solar is poised to play a significant role in meeting the growing demand for renewable energy.

2.4 OTEC (ocean thermal energy conversion)

Ocean Thermal Energy Conversion (OTEC) is a renewable energy technology that harnesses the temperature difference between the warm surface waters and the cold deep waters of the ocean, 20 °C to generate electricity (Zumerchik, 2009). This temperature gradient, typically found in tropical and subtropical regions, provided a reliable and sustainable energy source. Three main types of OTEC systems were developed in Table 4. (a) Closed-cycle OTEC in this system uses a working fluid, such as ammonia, to transfer heat between the warm surface water and the cold deep water. The working fluid evaporated in the heat exchanger, driving a turbine to generate electricity. The condensed vapour is then pumped back into the evaporator, completing the cycle. (b) Open-cycle OTEC in Warm surface water was directly flashed into vapour, which drove a turbine. The condensed vapour is then returned to the ocean. (c) Hybrid OTEC in this system combines elements of both closed-cycle and open-cycle systems, offering potential advantages in efficiency and cost-effectiveness. An OTEC system requires several essential components to function effectively. Warm surface water is drawn in through a dedicated intake pipe and delivered to a heat exchanger. Simultaneously, cold deep water was also channelled into the heat exchanger through another intake pipe. These heat exchangers facilitate heat transfer between the warm and cold water by using a working fluid in closed-cycle systems or directly flashing the water into vapour in open-cycle systems. The resulting energy is harnessed by a turbine, which converts it into mechanical energy. This mechanical energy is then transformed into electricity by a generator. Closed-cycle systems utilise a condenser to cool and condense the vaporised working fluid back into a liquid for recirculation (Yamada et al., 2009). Pumps were strategically placed to ensure the efficient circulation of the working fluid and water throughout the system (Science, 2005). OTEC presents a promising renewable energy solution with the potential to support sustainable power generation (Zumerchik, 2009). Especially in regions with favourable oceanographic conditions. In contrast, the technology faces challenges related to cost, environmental impacts, and a lack of technological advancements. Ongoing research and development efforts aim to address these issues and realise the full potential of OTEC.

2.5 Comparison between onshore and offshore floating installations

Onshore and offshore floating PV systems offer unique advantages; they differ significantly in terms of environmental conditions, technical requirements, costs, and integration potential. Despite their challenges, offshore systems present a promising future for renewable energy expansion, especially in land-constrained regions (Table 5).

2.6 Summary of offshore renewable energy technologies

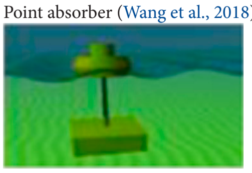
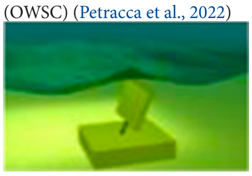
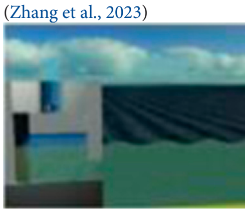
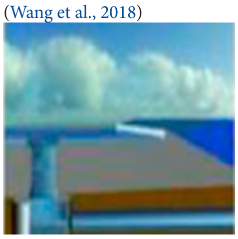
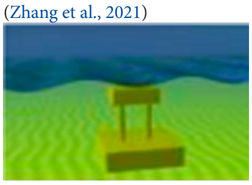
Offshore renewable energy sources, including wind, wave, solar, and OTEC, offer a sustainable pathway to large-scale electricity generation while minimising environmental impact. Deploying floating platforms in deep-sea locations significantly expands the potential for energy production and reduces reliance on land-based installations. However, developing and implementing these technologies poses challenges, including high capital costs, complex installation procedures, and ongoing maintenance requirements. Despite these hurdles, continuous technological advancements and research efforts are steadily improving the feasibility and cost-effectiveness of offshore renewables. Furthermore, integrating hybrid solutions that combine various renewable sources, such as solar, wind, and wave power, holds immense promise for enhancing the efficiency and reliability of offshore energy generation (Figure 2).

3 Integration of multi-source offshore energy system

Integrating floating solar, wind, and wave technologies presents a promising solution to energy production and climate change challenges. Integrating offshore wind, waves, and floating photovoltaic systems on a shared platform enhances overall capacity factors, reduces the levelized cost, and supports the development of more sustainable offshore energy systems. This integration is achieved through various configurations, including hybrid power plants, energy storage systems, and innovative grid technologies, which enhance system reliability and efficiency.

The various potential configurations for offshore floating energy systems offer distinct advantages, as shown in Figure 3.

TABLE 2 Wave Energy Converters (WEC) along with advantages and disadvantages.

WEC type	Operating principle	Advantages	Disadvantages
Oscillating body converters (Yang et al., 2024; McTiernan and Sharman, 2020)			
Attenuator 	A floating device that operates parallel to the wave direction, capturing energy from the relative motion of its segmented arms.	• Simple design. • Offshore and nearshore installations. • Effective across various wave conditions	• Lower energy efficiency in certain sea states • Requires regular maintenance due to moving parts
Point absorber (Wang et al., 2018) 	A floating structure that absorbs energy from all directions through its heave, surge, or pitch movements at or near the water surface.	• Highly efficient energy capture • Flexible design adaptable to different environments • Suitable for large-scale installations	• Complex design • Higher maintenance
Oscillating wave surge converter (OWSC) (Petracca et al., 2022) 	Extracts energy from wave surges using a pendulum-like flap or arm that oscillates in response to horizontal wave motion.	• Effective at capturing surge energy • Scalable to various wave heights	• Mechanical complexity poses maintenance challenges • Reduced performance in low-energy sea states
Pressure and column devices			
Oscillating water column (OWC) (Zhang et al., 2023) 	A partially submerged structure that uses wave motion to compress and decompress a trapped air column, which in turn drives a turbine.	• Relatively simple design • Adaptable for both onshore and offshore deployment • Compatible with hybrid energy systems	• Lower energy capture efficiency than some alternatives • Potential environmental impact from air compression noise
Submerged pressure differential (Wang et al., 2018) 	A nearshore device that generates electricity by exploiting pressure differentials created by wave-induced changes in sea level above submerged components.	• Effective in shallow coastal waters • Minimal visual impact on the marine environment	• Limited deployment options; requires specific seabed conditions • Underwater components pose maintenance challenges
Overtopping and rotation devices			
Overtopping/Terminator device (Zhang et al., 2021) 	Captures water as waves break over a ramp into an elevated reservoir; the water is then released back through low-head turbines to generate power.	• High energy conversion efficiency in suitable conditions • Robust structure; relatively low maintenance	• Requires specific wave conditions for optimal performance • High construction costs; potential localised environmental impact

(*Continued*)

TABLE 2 Continued

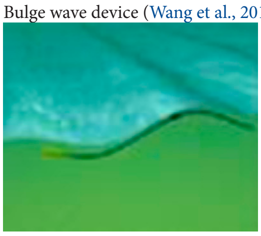
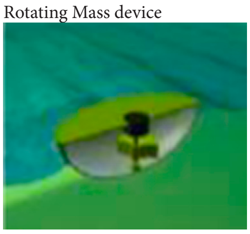
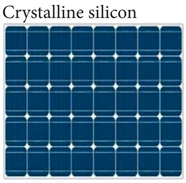
WEC type	Operating principle	Advantages	Disadvantages
Bulge wave device (Wang et al., 2018) 	A flexible rubber tube filled with water; incoming waves create a pressure bulge that travels along the tube and drives a turbine at its end.	• Efficient energy capture across a range of sea states • Simple mechanical components reduce maintenance needs	• Higher initial costs due to design complexity • Susceptible to wear and tear from harsh marine conditions
Rotating Mass device 	Uses the heaving and swaying motion of a floating platform to drive an eccentric weight or gyroscope, converting mechanical rotation directly into electrical energy.	• Converts mechanical motion directly into electricity • Adaptable to various marine environments	• Mechanical complexity leads to high maintenance costs • Energy efficiency varies with wave conditions

TABLE 3 PV module for offshore applications (Yamada et al., 2009; Gan et al., 2023; Garrod et al., 2024).

Type	Support structure	Weight	Efficiency	Advantages	Disadvantages
Crystalline silicon 	Fixed or floating	Heavy	High efficiency (18%–22%)	High power output, reliable, long life span.	High-cost, brittle
Flexible thin Film PV 	Flexible floating platforms	Light 300–500 g/m^2	10%–15% lower than silicon-based PV	Easy to deploy, good in low-light and high-temperature conditions.	Lower efficiency, shorter lifespan, potential reliability issues
Vertical Bifacial PV 	Deployed on floats, buoys, or poles/mini piles needed	Moderate	High (up to 25%)	Dual-sided energy capture	High-cost, complex installations

3.1 Combination 1: floating solar, wind turbines, and battery storage

The floating solar, wind turbine, and battery storage configuration offers a unique, highly adaptable renewable energy solution for offshore environments (Mcowen et al.). Integrating floating solar panels and offshore wind turbines ensures continuous power generation, leveraging solar radiation and strong oceanic winds (Elliott, 2011). The floating solar panels, mounted on specialised platforms, capture solar energy efficiently and benefit from natural water cooling, enhancing their performance (Melikoglu, 2018). Offshore wind turbines, strategically positioned to harness consistent wind resources, complement solar energy production, ensuring a stable power supply even during periods of low sunlight (Lee et al., 2014). By combining generation profiles with energy storage, these systems can improve power smoothing, increase capacity utilisation, and provide greater operational flexibility. However, their practical implementation is associated with several technical and non-technical challenges that must be addressed from the early planning and design stages (Aschenbrenner and Winder, 2019; Perumal, 2024). One of the primary challenges relates to grid connection and configuration. Wind turbines and photovoltaic systems exhibit distinct electrical characteristics, including voltage levels, variability patterns, and power-electronics interfaces. Consequently, hybrid systems require coordinated grid design,

TABLE 4 OTEC types along with advantages and disadvantages (Zumerchik, 2009; Adiputra et al., 2020; van Niekerk and van der Pot, 1985).

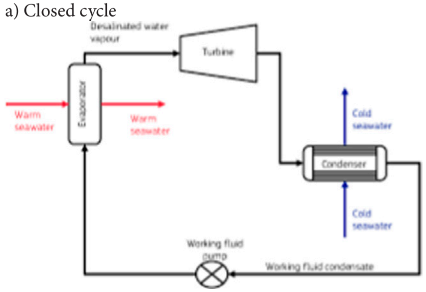
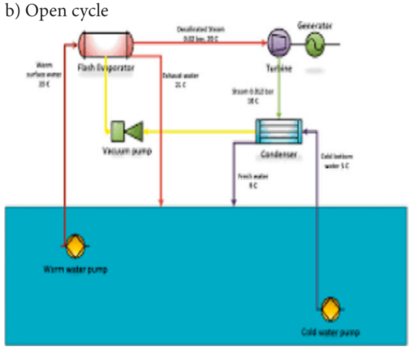
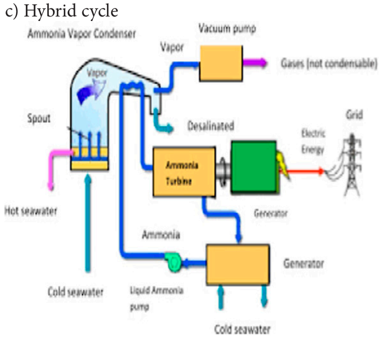
OTEC converter type	Description	Advantages	Disadvantages
a) Closed cycle 	Utilises a working fluid (e.g., ammonia) that vaporises using warm seawater, driving a turbine to generate electricity. The vapour is then condensed using cold, deep seawater.	- High efficiency: Can achieve efficiencies of 3%–5% due to the low boiling point of the working fluid. - Environmental safety: No direct contact with seawater minimises the environmental impact of the working fluid. - Versatility: Suitable for various environments (land-based, shelf-based, floating).	- High capital cost: The first investment is significant due to complex machinery and materials. - Complex system: Requires advanced technology and maintenance, which can complicate operations.
b) Open cycle 	Directly uses warm seawater to create steam, which drives a turbine. The steam then condensed back into water using cold seawater.	- Simple design: Fewer components make it easier to construct and use. - Freshwater production: Generates freshwater as a by product through condensation. - Low environmental impact: Minimal use of synthetic fluids reduces pollution risk.	- Lower efficiency: Less efficient than closed-cycle systems due to heat losses (typically 1%–2%). - Environmental concerns: Potential impacts from salt and marine life interaction with the steam process.
c) Hybrid cycle 	Combines features of both closed and open cycles, using warm seawater to vaporize a working fluid while producing freshwater.	- Enhanced efficiency: More efficient than closed or open cycles alone, often exceeding 5% efficiency. - Multiple outputs: Can produce electricity and freshwater simultaneously, maximizing resource use.- Flexibility: Adaptable to varying ocean conditions and energy needs.	- Complex system: Increased complexity in design and operation can lead to higher maintenance needs. - Higher capital cost: The first investment is typically more significant than pure cycle systems due to more components and technologies.

TABLE 5 Comparison of Onshore vs. Offshore Floating PV systems (Kaur et al., 2025).

Characteristics	Onshore floating PV systems	Offshore floating PV systems
Location	Freshwater bodies like lakes and reservoirs	Open seas and oceans
Environmental conditions	Less harsh; fewer corrosive factors	Harsh saltwater corrosion, high winds, UV degradation, and biofouling
Technical requirements	Lower, well-established designs and materials	Higher specialised materials and designs are needed for durability
Cost	Generally lower due to simpler construction and maintenance	Higher due to complex installation, specialised materials, and maintenance challenges
Energy yield	Enhanced by water cooling, but with less consistent irradiance	Enhanced by water cooling, irradiance can be consistent but affected by wave motion and wind
Space utilization	Utilises unused water surfaces, reducing land competition	Utilises vast ocean areas, ideal for land-constrained regions
Integration potential	Can be integrated with existing water management systems	Offers potential for integration with offshore wind and aquaculture
Technology maturity	More mature with established practices	Less mature; ongoing research and development needed
Environmental impact	Generally positive; reduces water evaporation and improves water quality	Potential impacts on marine ecosystems require careful assessment and mitigation strategies

advanced control strategies, and appropriately sized offshore substations and export cables to avoid congestion, curtailment, and power quality issues during periods of simultaneous peak generation. These considerations must be incorporated at the conceptual design stage to ensure grid compatibility and stable operation. Another critical aspect is optimising the solar-to-wind capacity ratio, which strongly influences overall system performance and storage requirements. The optimal ratio depends on site-specific factors, including local wind and solar resource complementarity, seasonal variability, demand profiles, and grid constraints. Beyond technical considerations, institutional and regulatory barriers play a significant role in the deployment of solar–wind–battery hybrid systems. Hybrid projects often involve multiple assets and stakeholders, raising challenges around ownership structures, revenue allocation, and operational responsibilities. Clear planning guidelines and harmonised regulatory approaches are therefore essential to facilitate large-scale implementation. To summarise these challenges and improve clarity, Table 6 presents an overview of the key technical, design, and policy considerations for solar–wind–battery hybrid systems.

3.2 Combination 2: wind energy, tidal energy, microturbines, and battery storage

This unique configuration combines offshore wind turbines, tidal energy systems, microturbines, and battery storage to create a highly efficient, renewable energy solution for ocean-based power generation (Boussari et al., 2023). Offshore wind turbines harness the power of high-altitude ocean winds, generating clean electricity (Claus and López, 2022). At the same time, tidal energy systems take advantage of the predictable and consistent tides to provide continuous power (Bin Abu Sofian et al., 2024). Supplementary power is generated by microturbines that capture energy from water currents, offering a small-scale yet effective contribution (Friel et al., 2019). Battery storage ensures that the variable energy from these sources is captured and stabilised for reliable use (Wang et al., 2023). One significant constraint relates to potential conflicts with existing coastal activities and sensitive ecosystems. Coastal zones are often intensively used by fisheries, aquaculture, shipping, and tourism, while also hosting ecologically valuable habitats such as seagrass meadows, coral reefs, and migratory corridors for marine species. The installation of tidal devices and microturbines may alter local hydrodynamics, sediment transport, and habitat conditions, potentially affecting fish stocks and benthic ecosystems. Table 7 indicates the environmental impact assessments and suggested remedial measures.

3.3 Combination 3: Floating solar, wind turbines, diesel generators, battery storage, desalination and hydrogen production

Hybrid systems integrating solar photovoltaics, offshore wind, diesel backup generation, battery storage, and hydrogen production offer a flexible pathway for decarbonising offshore energy supply while maintaining reliability (Rivas et al., 2025). The floating solar and wind turbines harness renewable energy from the sun and wind, while battery storage ensures a reliable power supply around the clock (Bin Abu Sofian et al., 2024). Seawater desalination units convert seawater into fresh water, providing a consistent, eco-friendly freshwater source for coastal and island communities (Bedekar et al., 2025). Additionally, excess energy is used to produce green hydrogen through electrolysis, which can fuel ships and vehicles and be exported to the mainland (Thorson et al., 2022; Rebecca Williams, 2022). Offshore refuelling activities are subject to maritime safety regulations, environmental protection standards, and jurisdictional constraints under national and international

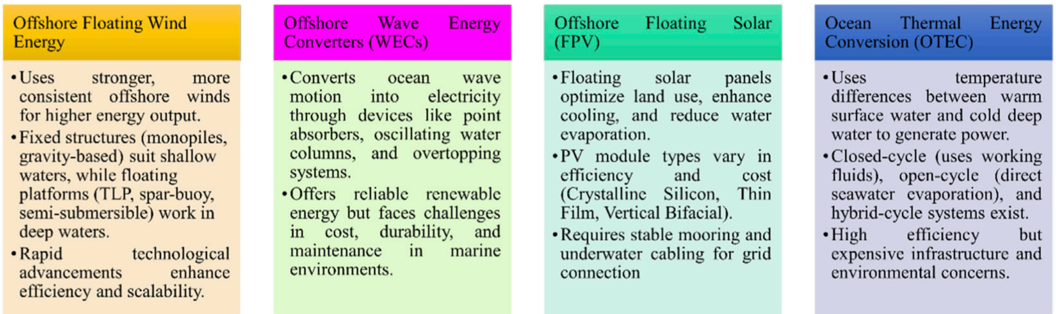


FIGURE 2
Summary of offshore renewable energy technologies.

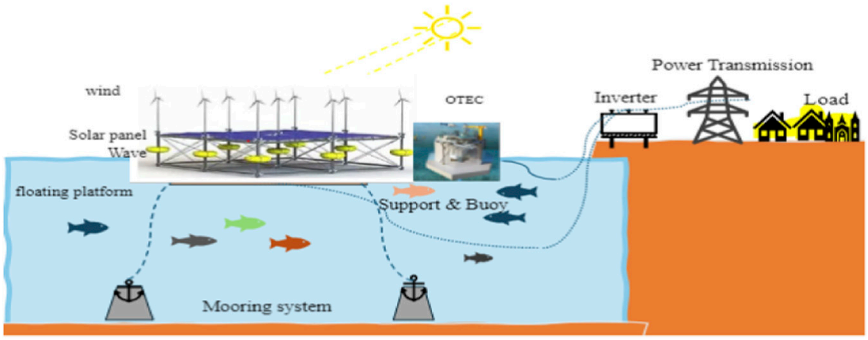


FIGURE 3
Schematic of offshore floating hybrid energy systems.

maritime law (Wang et al., 2023). These include requirements related to fuel transfer operations, safety zones, and port-state control. Offshore platforms operating beyond territorial waters may fall under flag-state jurisdiction, port-state control, or the jurisdiction of the coastal state, depending on the nature of the operation, the vessel involved, and the distance from shore. The legal status of an offshore hydrogen bunkering operation conducted in the Exclusive Economic Zone (EEZ), which lies neither in open sea nor in territorial waters, remains largely unresolved in most national legal frameworks (Rivas et al., 2025; Honniball, 2023). Additional barriers include the absence of standardised hydrogen bunkering safety protocols for offshore environments, the lack of certified offshore hydrogen transfer equipment, and the lack of insurance frameworks (Bedekar et al., 2025). Until these regulatory gaps are addressed through coordinated IMO rulemaking, mutual port-state agreements, and national governmental action, offshore hydrogen ship refuelling should be treated as a medium-to long-term application contingent on regulatory maturation rather than a near-term operational capability (Sarantopoulos, 2024; Abeyratne, 2024).

The various combination of the offshore floating system along with design parameters in Figure 4. Furthermore, real-world case studies of installed hybrid systems provide critical insights into their performance and serve as a foundation for advancing offshore renewable energy technologies.

4 Methodology

Comprehensive research on the current state of the art of offshore floating renewables was conducted using the following methods to identify the field's leading trends, challenges, and opportunities in floating offshore hybrid energy systems (Figure 5).

4.1 Literature review and case study selection

The study is based on a systematic review of peer-reviewed literature and online industry reports related to offshore hybrid renewable energy systems, conducted in January–March 2024 across three major academic databases: Scopus, Web of Science (WoS), and Google Scholar. The search covered peer-reviewed journal articles, conference proceedings, technical reports, and industry documentation published between 2000 and 2024, with particular emphasis on studies published since 2015 to capture recent advances in floating offshore hybrid systems. The following Boolean search string was applied across title, abstract, and keyword fields ("offshore hybrid energy" OR "floating photovoltaic" OR "floating solar") AND ("offshore wind" OR "wave energy") AND ("integration" OR "hybrid platform" OR "multi-source"). Additional keyword combinations

TABLE 6 Key challenges and planning considerations for solar–wind–battery hybrid systems.

Category	Description	Key challenges	Recommended actions
Grid connection Configuration	Must be addressed at the system design stage; retrofitting grid architecture post-installation is prohibitively costly.	Wind and solar outputs differ in frequency, voltage profile, and variability. Shared offshore grid infrastructure must accommodate both *via* compatible power electronics, converter architectures, and transmission capacity. Risk of grid instability and curtailment if not properly co-designed.	Conduct integrated grid configuration studies during the feasibility phase. Define unified technical standards for hybrid offshore connections. Engage grid operators early to align transmission capacity with projected combined output.
Solar-to-wind capacity ratio	The optimum ratio is site-specific and must be determined in the planning phase; it directly affects battery sizing, LCOE, and capacity factor.	An imbalanced ratio leads to periods of overproduction or underutilisation of battery storage, reducing overall system efficiency. No universal optimum ratio exists — it depends on local irradiance, wind resource profiles, and load demand.	Perform site-specific resource assessments and multi-objective optimisation modelling to identify the ratio that maximises capacity factor and minimises LCOE. Sensitivity analysis across seasonal resource variability is recommended.
Ownership model	The ownership structure must be defined before financial close; misalignment among asset owners creates operational and legal complexity.	Solar, wind, and battery assets may be owned by different entities, complicating coordination of dispatch strategies, revenue sharing, and grid access rights. Fragmented ownership can obstruct integrated operational management and reduce overall system performance.	Develop co-development or joint venture contractual frameworks that align incentives among asset owners. Define clear protocols for energy dispatch, curtailment decisions, and revenue allocation in the project agreement.
Regulatory framework and government support	Regulatory clarity is a prerequisite for investment; ambiguity delays permitting and increases project risk during planning.	Most existing offshore energy regulations address single-technology systems. Hybrid offshore installations face jurisdictional gaps in permitting, grid connection standards, feed-in tariff eligibility, and marine spatial planning. Inconsistency across regions deters cross-border investment.	Advocate for dedicated national and EU-level regulatory frameworks for hybrid offshore systems. Engage policymakers to harmonise permitting procedures, establish clear grid connection codes for multi-source plants, and design subsidy mechanisms that explicitly cover hybrid configurations.

included “floating offshore wind farm,” “wave energy converter,” “levelized cost of energy offshore,” and “capacity factor hybrid renewable.” Supplementary grey literature was retrieved from industry bodies (IEA Ocean Energy Systems, IRENA, the European Commission’s SET-Plan) and project-specific technical documentation. Inclusion criteria required that sources: (i) addressed at least two offshore renewable energy sources in an integrated or co-located configuration; (ii) reported quantitative performance metrics such as capacity factor, AEY, or LCOE; and (iii) were written in English. Studies focusing exclusively on onshore or land-based floating PV systems, tidal Energy alone. Retrieved literature was organised into thematic categories: technology integration, structural and mooring design, energy performance, economic viability, and environmental considerations to structure the comparative analysis presented in Sections 4–6.

4.2 Technology combinations of offshore hybrid renewable energy

Three case studies were selected from the final literature pool through a structured scoring process applied to all hybrid offshore projects for which sufficient quantitative data were publicly available (n = 11 projects identified). Each candidate project was evaluated against four criteria: (1) geographical and environmental diversity (weighting 25%) — to capture a broad range of metocean conditions and regulatory contexts; (2) energy source combination (25%) preference for projects combining at least two of the three target technologies (FPV, wind, wave); (3) technology readiness level (TRL) and deployment status (25%) — preference for projects at TRL seven, i.e., prototype demonstrated in operational environment or beyond; and The three projects that scored highest under this framework were: the SPIC floating solar–wind project (China,

TABLE 7 Key conflicts, spatial challenges, and feasibility considerations for wind–tidal–microturbine–battery hybrid systems in coastal areas.

Issue/Conflict type	Affected coastal activity or ecosystem	Spatial and feasibility challenges	Suggested mitigation measures	References
Fisheries conflict	Commercial and artisanal fisheries; aquaculture operations; fishing vessel navigation routes.	Turbine foundations, tidal device arrays, mooring lines, and inter-array cables physically displace fishing grounds and obstruct vessel access. Tidal devices require placement in high-velocity flow zones that frequently overlap with productive benthic fishing areas. Exclusion zones around energy infrastructure can result in significant losses in fishing income.	Conduct early stakeholder engagement with local fishing communities. Use marine spatial planning (MSP) tools to identify low-conflict siting zones. Consider shared-use agreements or compensation frameworks. Design device arrays with vessel access corridors where feasible.	(Tsai et al., 2022; Singh et al., 2025)
Sensitive ecosystem disturbance	Seagrass beds, kelp forests, tidal wetlands, coral habitats, marine protected areas (MPAs), and migratory species corridors.	Foundation installation, cable laying, and tidal device operation generate underwater noise, seabed disturbance, and altered hydrodynamic flow patterns. These effects can damage benthic habitats, disrupt tidal flushing in estuaries, and impede the migration of fish and marine mammals. Proximity to MPAs may trigger legal constraints or require enhanced environmental impact assessment.	Undertake a detailed environmental impact assessment (EIA) including cumulative effects. Apply exclusion buffers around designated habitats and MPAs. Use noise mitigation measures (e.g., bubble curtains) during construction. Implement long-term ecological monitoring programmes post-installation.	(Mcowen et al.; Elliott, 2011)
Spatial Configuration feasibility	Co-location of wind, tidal, and microturbine technologies with differing siting requirements and operational envelopes.	Tidal stream devices require high-velocity flow zones that do not always coincide with optimal wind resource areas. Wind turbines occupy the airspace above while tidal and microturbines operate in the water column and on the seabed; though vertically separated, shared mooring and cabling create structural interdependencies. Array layout optimisation must simultaneously satisfy conflicting resource, structural, and exclusion-zone constraints, thereby significantly increasing design complexity.	Apply multi-objective spatial optimisation models during the feasibility phase. Use GIS-based resource mapping to identify zones where wind, tidal, and current resources co-exist at viable intensity. Design modular, decoupled sub-arrays for each technology type to reduce structural interdependency. Validate layouts with hydrodynamic and structural simulation tools.	(Melikoglu, 2018; Aschenbrenner and Winder, 2019)

(*Continued*)

TABLE 7 Continued

Issue/Conflict type	Affected coastal activity or ecosystem	Spatial and feasibility challenges	Suggested mitigation measures	References
Shipping and navigation conflicts	Commercial shipping lanes, recreational boating, ferry routes, and port approach corridors.	Energy farm footprints in nearshore coastal waters can intersect with established maritime traffic routes. Fixed and floating infrastructure pose navigational hazards, particularly in areas with high vessel density or poor visibility. Port authorities and coast guards may impose strict setback requirements that further constrain available siting area.	Coordinate with maritime authorities and port operators during the planning phase. Submit marine traffic impact assessments. Ensure all structures comply with IALA buoyancy and lighting standards. Use AIS-based traffic density mapping to identify low-conflict corridors for infrastructure routing.	(Perumal, 2024; Kusters et al., 2025)
Cumulative and multi-use spatial pressure	Overlap of multiple competing uses: energy, fisheries, conservation, tourism, aquaculture, and defence.	Coastal zones are inherently multi-use spaces with high spatial demand. A hybrid energy farm adds another layer of use pressure, and its cumulative interaction with existing activities may be underestimated if assessed in isolation. Regulatory frameworks that address only single sector uses may be inadequate to resolve multi-use conflicts at the planning stage.	Integrate hybrid energy farm planning within a formal marine spatial planning (MSP) process. Develop cross-sector governance mechanisms that bring together energy developers, fisheries bodies, conservation agencies, and local authorities. Commission cumulative impact assessments that consider the full range of co-located activities.	(Hammar et al., 2020; Boussari et al., 2023)

TRL 8–9), representing the Asia-Pacific region and the solar–wind technology combination; the Poseidon 37 wind–wave platform (Denmark, TRL 7–8), representing Northern Europe and the wind–wave combination; and the NoviOcean solar–wind–wave system (United Kingdom, TRL 6–7), representing Western Europe and the only available tri-source hybrid with public performance estimates. Together, these three projects span three continents, three distinct energy-source combinations, and two stages of commercial maturity (pilot/demonstration and pre-commercial), enabling a meaningful comparative assessment of technical performance, economic possibility, and scalability.

4.2.1 Case study 1: SPIC (China)

State Power Investment Corporation (SPIC) commissioned the world's first commercial offshore floating photovoltaic (FPV) power plant integrated with an offshore wind turbine off the coast of Haiyang, Shandong Province, China (Figure 6). The project, launched in November 2022, represents a pioneering demonstration of hybrid offshore renewable energy systems. The system employs Ocean Sun's patented floating solar technology, consisting of two FPV floaters with a total installed capacity of 0.5 MWp. These floaters are electrically connected to a transformer mounted on a SPIC-owned offshore wind turbine, with power exported to the onshore grid *via* a subsea cable (SPIC). Owing to the deep-water conditions at the site, floating foundations were adopted for both the wind turbine and the FPV units, making fixed-bottom solutions unsuitable (Table 8) (Huang, 2025; Harsono, 2025; Zhang, 2023). As the first commercial-scale integration of offshore wind and floating solar technologies, this pilot project demonstrates the technical feasibility of shared infrastructure and hybrid energy generation in offshore environments. The project aims to improve overall energy yield, enhance space utilisation, and reduce the levelized cost of electricity through infrastructure sharing and complementary resource exploitation. Owing to its innovative configuration and real-world operational relevance, the SPIC project is selected as a representative case study for detailed analysis in this work.

4.2.2 Case study 2: poseidon 37 (Denmark)

The project's prototype, Poseidon 37, features a 37-m-wide, 25-m-long platform weighing approximately 350 tons. Poseidon 37,

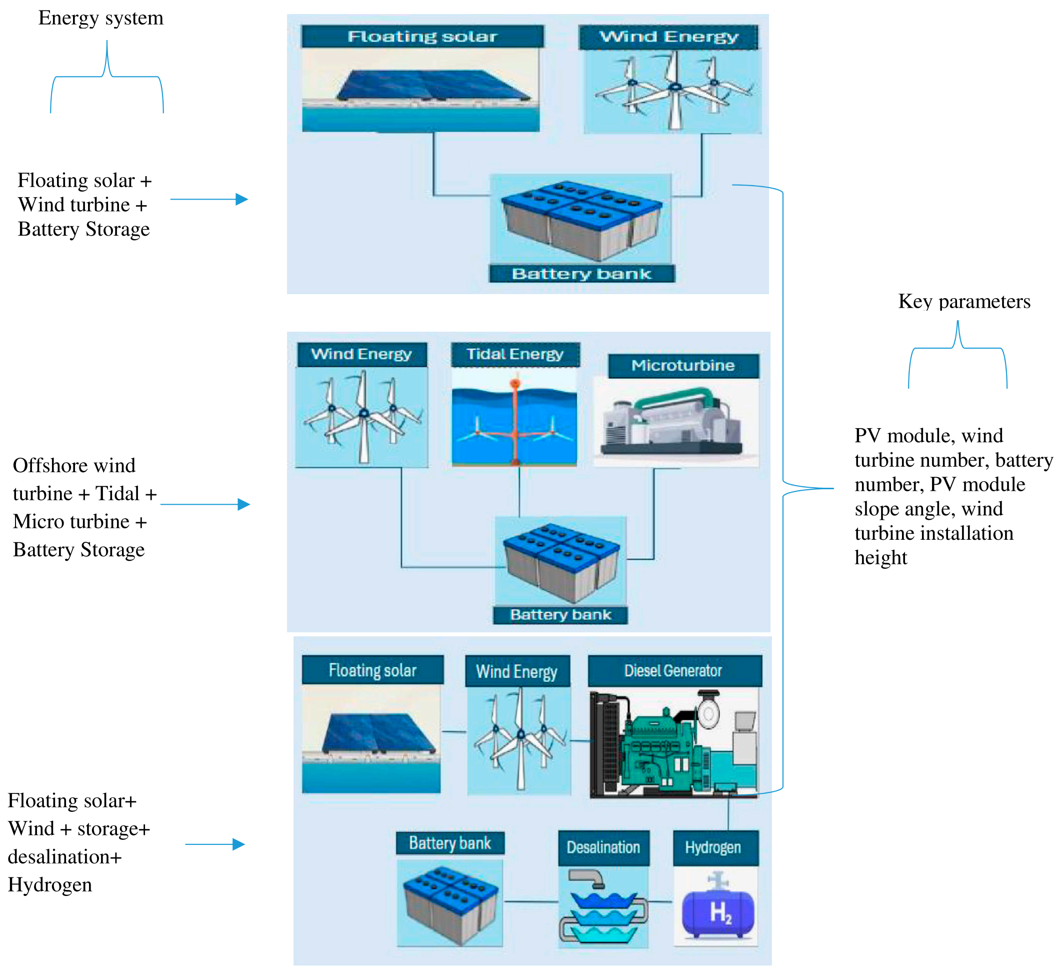


FIGURE 4
Potential combinations of the offshore floating system along with design parameters.

located in the Baltic Sea, near Lolland, Denmark, was used under a 7-year test license granted by Danish authorities at the Vindeby test site (Figure 7). The Poseidon project, developed by Danish cleantech company Floating Power Plant (FPP), is an innovative hybrid renewable energy solution that integrates wave energy converters with offshore wind turbines on a single floating platform. Poseidon 37 began real-sea testing in 2008 and completed four grid-connected trials by 2013, using connections at 690V and 10 kV installed in collaboration with DONG Energy. Between 2008 and 2013, Poseidon 37 underwent extensive real-sea testing, successfully delivering power to the grid and proving the feasibility of the hybrid energy concept.

4.2.3 Case study 3: NoviOcean project (United Kingdom)

The NoviOcean project, developed by Novige, is an innovative, multi-energy offshore power solution that combines wave, wind, and solar energy for a total output of 1 MW. The wave power plant is designed as a large rectangular raft, 38 m long, 12 m high, and 8 m wide, which floats parallel to ocean waves (Figure 8). Beneath the structure is a water-filled cylinder connected to the seabed *via* a piston rod and cable, which keeps the raft stable and at the water's surface. Four anchors extend from each side to keep the power plant optimally oriented against ocean currents. The simple mechanics of a garden pump inspire the wave power generation system. The system harnesses wave energy by trapping 600 cubic meters of air below the surface as the float moves with the waves, then releasing it at the correct pressure to generate 600 tons of lifting force, powering a Pelton turbine and generating electricity. Once raised, the water is directed toward a Pelton turbine, achieving speeds of up to 300 km/h and flow rates of 800 L (0.8 cubic meters) per second. This turbine, coupled with a generator, converts the kinetic energy into electrical power. Jan Skjoldhammer, the project leader, describes the system as a combination of a raft, a garden pump, and an inverted hydropower plant, with innovative patented technology enabling the entire setup to function efficiently (NoviOceana).

4.3 System performance evaluation

This section defines the performance and economic indicators used to evaluate the hybrid offshore energy systems analysed

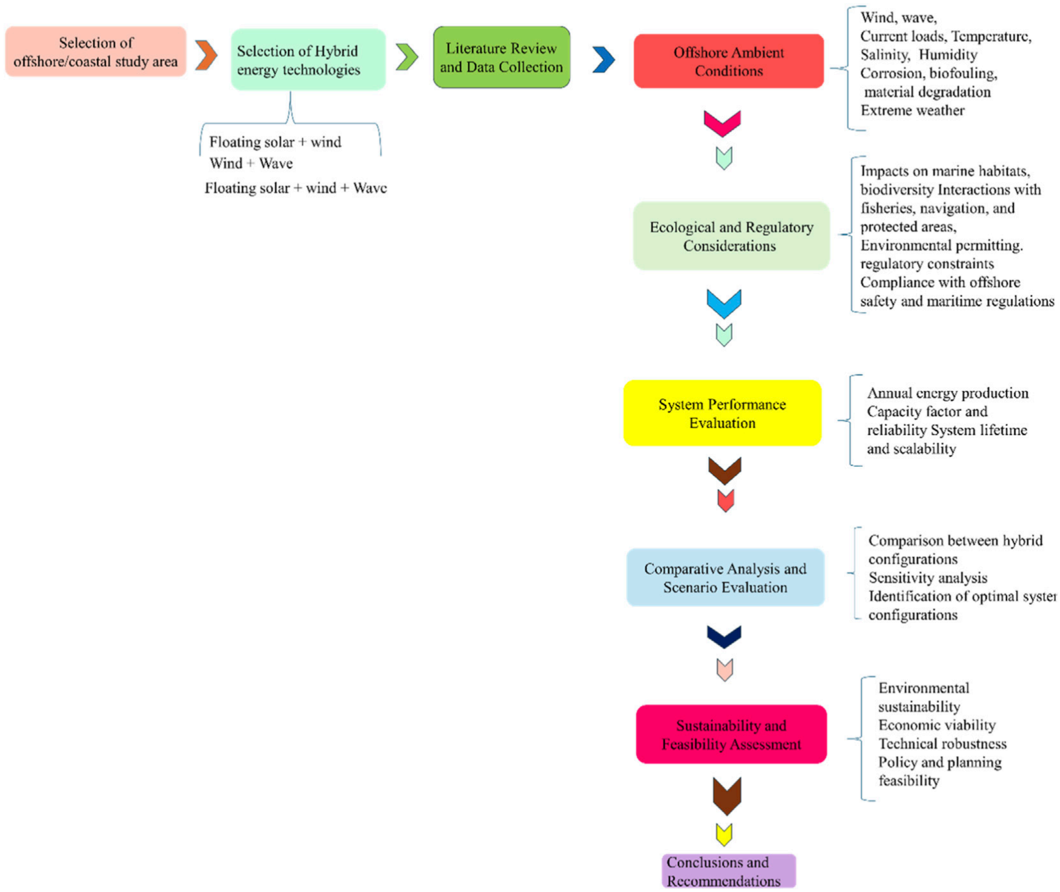


FIGURE 5
Methodological framework of offshore hybrid renewable energy (OHRE) systems.

FIGURE 6
SPIC project in China (SPIC).

in the case studies. The formulations presented here provide a consistent analytical basis for quantifying system efficiency, energy output, and economic performance. All indicators defined in this section are applied to the case studies discussed in Section 5, ensuring transparency and comparability across different hybrid configurations.

4.3.1 Capacity factor (CF)

The capacity factor (CF) is a widely used metric for assessing how effectively a renewable energy system utilises its installed capacity. It represents the ratio of the actual electricity generated over a specified period to the maximum theoretical energy output if the system operated continuously at its rated capacity.

$$CF = \frac{\text{Actual electricity produced}}{\text{Rated capacity} \times 8,760} \tag{1}$$

Where,
actual electricity produced = total energy generated over 1 year, rated capacity = installed nominal power (MW or kW), 8,760 represents the total number of hours in a year.

4.3.2 Annual energy yield

The annual energy yield (AEY) is the total electricity generated by the system over 1 year and reflects both resource availability and

TABLE 8 Highlights of offshore hybrid solar and wind case study.

Case study name	SPIC offshore floating solar-wind hybrid project
Concept	World's first hybrid offshore floating photovoltaic (FPV) and wind project
Design features	Two solar floaters (0.5 MWp) integrated with a wind turbine.
Wind turbines	SPIC-owned offshore wind turbine
Solar panels	Ocean Sun's patented floating solar technology
Capacity factor	Higher due to hybrid solar and wind integration
Total capacity	0.5 MWp (pilot); planned expansion to 20 MW
Power generation capacity	Solar peaks during the day; wind complements in the afternoon/evening
Annual energy production	Enhanced by a hybrid setup and water-cooling effect
Innovative mechanism	Shared infrastructure (transformers, subsea cables) reduces costs.
Patents and global potential	Ocean Sun's proprietary floating solar technology is scalable globally
Project leadership	State power investment corporation (SPIC)
Environmental benefits	Reduces greenhouse gas emissions by utilising renewable energy sources.
Durability in extreme weather	Ensuring the structure's resilience against typhoons and harsh marine conditions, including waves, corrosion, and strong winds.
Technical complexity	Integrating diverse renewable energy technologies, such as solar and wind, poses significant technical challenges in system design, control, and maintenance.
Cost and funding	High initial investment costs for large-scale projects require substantial funding and financial support.
Environmental impact	Potential environmental impacts on marine ecosystems, such as habitat disruption and effects on marine life, need careful assessment and mitigation through environmental impact assessments and monitoring.

overall system efficiency. It is calculated as.

$$AEY = CF \times \text{Rated capacity} \times 8,760 \tag{2}$$

CF = capacity factor (dimensionless).
Rated Capacity = MW or kW.

4.3.3 Levelized cost of energy (LCOE)

LCOE provides a measure of the average cost per unit of electricity generated over the lifetime of the system, accounting for

FIGURE 7
Poseidon floating power system integration of wind and wave energy (TETHYS, 2014)

both capital and operational expenditures.

$$LCOE = \frac{\text{Total lifetime cost}}{\text{Total lifetime energy production}} \tag{3}$$

4.4 Identification of technical challenges and mitigation approaches

This section describes the methodological approach used to identify and categorise the technical challenges associated with offshore hybrid renewable energy systems. Rather than presenting outcomes, this step forms part of the analytical framework applied to the selected case studies. Based on the collected technical data, system configurations, and operational characteristics of the case studies, key engineering challenges were systematically identified and grouped into major categories, including technology integration, grid connection and stability, mooring and foundation design, operation and maintenance, subsea cabling, and energy storage requirements. This categorisation enabled a consistent evaluation of constraints across different hybrid configurations. For each challenge category, potential mitigation approaches were identified through cross-comparison of case study practices and reported engineering solutions.

4.5 Comparative synthesis and state-of-the-art assessment

This section uses a method to combine insights from the case studies and the supporting literature to establish a structured overview of the current state of the art in offshore hybrid energy systems. A comparative analysis was conducted across the selected case studies to identify commonalities and differences in system configuration, technology integration, implementation strategies, and performance outcomes. Quantitative indicators such as energy output, capacity factor, and cost metrics were analysed alongside qualitative factors, including design choices, regulatory context, and operational experience. This combined long-term operational data and assessment enabled a consistent comparison of technical performance, economic viability. In parallel, findings from the literature review were integrated to contextualise the

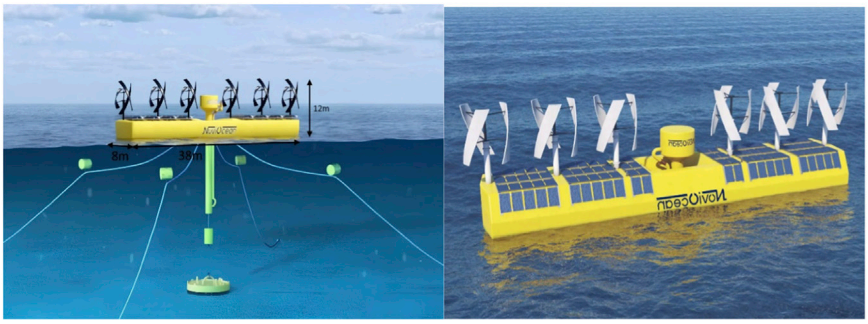


FIGURE 8
Novi Ocean system integrating wave power, wind power, and solar power (NoviOceanc).

case study results within broader technological developments and research trends. This synthesis approach allows the identification of prevailing technologies, recent advancements, and recurring challenges, providing a structured representation of the current state of the art. The outcomes of this synthesis are presented and discussed in Section 5 to support conclusions regarding future practical implementation and research needs.

5 Results and discussion

5.1 Case study 1 (floating solar + wind energy)

This project is planned to expand to a 20 MW floating wind-solar farm using Ocean Sun's technology, pending the pilot's success. This innovative design increases efficiency by leveraging the cooling effect of water beneath the solar panels, improving power generation efficiency by over 10%. The hybrid setup also reduces the levelized cost of electricity (LCOE) by sharing infrastructure such as transformers and subsea cables. Combining solar and wind energy increases generation efficiency, as solar output peaks during the day, while offshore wind turbines generate more power in the afternoon and evening (Table 8). The site is exposed to challenging conditions, including annual typhoons with extreme wave heights of up to 10 m. The project is designed to withstand these stresses and will provide valuable data for future installations. Additionally, floating solar installations reduce water evaporation and avoid land use conflicts while leveraging offshore wind infrastructure. This project is significant as it is the world's first commercial offshore floating solar plant integrated with an offshore wind turbine. The success of this project could unlock significant potential for hybrid offshore power plants worldwide, particularly in regions with limited land availability or high renewable energy targets (SPIC; Proctor, 2022).

5.2 Case study II (offshore wind + wave energy)

Research on hybrid offshore wind-wave energy systems is still in its preliminary stages. This dual-source approach ensures a more stable and consistent power output by balancing wave energy variability with wind power, providing a sustainable approach to offshore renewable energy production, as shown in Table 6. Building on this success, FPP designed Poseidon P80—a larger 80-m-wide platform capable of supporting 5–8 MW wind turbines alongside 2–3.6 MW wave energy converters. The first commercial deployment was planned in the UK in collaboration with DP Energy (TETHYS, 2014). Given the novelty of this platform, FPP (Floating Power Plant) has incorporated existing Environmental Impact Assessment (EIA) data from offshore wind farms and other marine installations to assess environmental impact, clearly monitoring bird interactions with the platform to assess potential disturbances and habitat effects (European Com mission EU). Poseidon's hybrid energy system is estimated to generate electricity for 10–15-euro cents per kWh, making it a competitive renewable energy source in Europe. By combining wind and wave power, the platform maximises the use of renewable resources while minimising environmental impact. The Poseidon project represents a significant step toward commercialising hybrid renewable energy technologies (Table 9). It aims to contribute to the deep-water offshore renewables segment while addressing global energy transition goals (European Commission) (European Commission).

5.3 Case study (solar + wind + wave energy)

This 1 MW project combines 650 kW of wave energy, 300 kW of wind energy, and 50 kW of solar energy. Above the raft, six vertically oriented wind turbines contributed around 300 kW to the total output, while solar panels added between 50 and 80 kW. Together, these sources constitute a 1 MW potential, with an estimated capacity factor of 40% and 3.5 GWh/unit/year, which accounts for the consistent average power output over time (Technology – NoviOcean). Novi Ocean has secured patents for this technology in 20 countries, demonstrating the global potential of its pioneering hybrid energy solution for sustainable offshore power (Table 10).

5.4 Summary of case studies and critical insights

The three case studies examined here SPIC's floating solar-wind platform in China, Poseidon's wind-wave system in Denmark,

TABLE 9 Highlights of offshore hybrid wind and wave case study.

Case study	Poseidon project
Concept	Hybrid floating platform integrating wave energy converters and offshore wind turbines for dual renewable energy generation.
Location	Baltic sea, near lolland, Denmark (poseidon 37).
Design features dimensions	Offshore wind turbines, tidal energy systems, microturbines, and battery storage are integrated into a hybrid renewable energy system. Poseidon 37: 37 m wide, 25 m long, 6 m high, weighing ~350 tons. Poseidon P80: 80 m wide, designed to support 5–8 MW wind turbines and 2–3.6 MW wave energy converters.
Wind turbines	Harness high-altitude ocean winds to generate clean electricity.
Solar panels	Not explicitly included in this configuration but could complement the system in future designs.
Capacity factor	Varies by location and resource availability; tidal and wind systems typically have high capacity factors due to predictable energy sources.
Total capacity	Examples include 315 kW (wind), 175 kW (tidal), and 290 kW (microturbines) in some configurations.
Power generation capacity	The poseidon P80 platform supports 5–8 MW wind turbines and 2–3.6 MW wave energy converters.
Annual energy production	Estimated at competitive rates of 10–15 euro cents per kWh for hybrid systems like poseidon P80.
Innovative mechanism	Combines diverse renewable sources for stability; includes advanced energy storage for reliable power supply.
Patents and global potential	Poseidon P80 and similar platforms demonstrate scalability and potential for global deployment, particularly in Europe.
Project leadership	Includes floating power plant (FPP) and collaborations with entities like DP energy for deployment.
Environmental considerations	Incorporates environmental impact assessments (EIA) to monitor bird interactions and minimize habitat disturbances.
Lifespan and testing	Designed for long-term use with rigorous testing to ensure reliability in harsh marine environments.
Installation location	Coastal areas, ports, and offshore sites; first commercial deployment planned in the UK.
Expected construction cost	High initial investment due to advanced tidal and microturbine technologies, but competitive operational costs over time.
Grid connection capability	DC marine cables are integrated with onshore AC networks for seamless power delivery.
Maintenance requirements	Complex installation and maintenance due to deep-water operations; requires specialized infrastructure.
Operational efficiency	High reliability from diverse energy sources; battery storage stabilizes variable outputs for consistent performance.
Future development plans	Focus on scaling up hybrid systems like poseidon P80, integrating additional renewable sources, and expanding deployments globally to support energy transition goals.

and Novi Ocean's multisource hybrid in the UK, collectively demonstrate that offshore hybrid renewable energy systems can deliver meaningful improvements in capacity factor, LCOE, and grid stability relative to single-source installations, while also validating distinct technological pathways whose implications extend well beyond individual projects. Table 11 compares the key quantitative performance indicators for the three case studies, enabling a direct side-by-side comparison of Capacity Factor (CF), Annual Energy Yield (AEY), installed capacity, and LCOE. Values are drawn from published projects, literature and estimated values.

The SPIC project is notable as the world's first commercial offshore FPV-wind integration, connecting 0.5 MWp of floating solar to an existing wind turbine *via* a shared subsea cable. This co-location approach directly corroborates the theoretical framework proposed by Bi and Law (Huang, 2025), who modelled combined wind-solar offshore platforms and found that co-location substantially reduces both capital expenditure per installed MW and transmission losses by sharing electrical infrastructure (Zhu et al., 2022). The planned scale-up to 20 MW at Haiyang would be among the largest offshore FPV installations globally, potentially establishing commercially replicable cost benchmarks that are currently absent from the literature.

The Poseidon project addresses a challenge that several reviews of floating wind have identified as a critical unsolved problem: platform motion-induced fatigue and power output variability. By integrating wave energy converters (WECs) directly onto the floating platform, Poseidon 37 demonstrated that WECs can simultaneously harvest wave energy and dampen platform motions, yielding the 22%–45% power output increase reported in associated studies (Mendez-Morales et al., 2025; Skov, 2023)

TABLE 10 **Highlights of Offshore Hybrid Solar + Wind + Wave energy system.**

Project details	Novi ocean hybrid energy system
Concept	Multi-energy offshore power solution combining wave, wind, and solar energy
Design features	A large rectangular raft floating parallel to ocean waves. Water-filled cylinder for stability Piston rod and cable connection to the seabed Four anchors for the best orientation
Wind turbines	Six vertically oriented turbines generating ~300 kW.
Solar panels	Contributing 50–80 kW of energy
Capacity factor	Estimated at 40%
Total capacity	1 MW
Power generation capacity	Wave energy: 650 kW Wind energy: 300 kW. Solar energy: 50–80 kW.
Wave power plant dimensions	38 m long 12 m height 8 m width
Annual energy production	Approximately 3.5 GWh/unit/year
Innovative mechanism	Inspired by garden pump mechanics, it uses a pelton turbine for electricity generation and has a circular water flow mechanism.
Patents and global potential	Secured patents in 20 countries
Project leadership	Jan skjoldhammer, project leader
Environmental considerations	Designed to perfect orientation against ocean currents; minimal ecological footprint expected; stability maintained to reduce impact on marine life.
Lifespan and testing	Designed for over 40 years; multiple tests in real-world environments completed.
Installation location	Offshore, UK, Taiwan and European countries
Expected construction cost	Approximately €3.6 million (US$4 million) per unit initially, with economies of scale reducing costs for later units.
Grid connection capability	Designed for grid integration to supply generated power directly to the electrical grid.
Maintenance requirements	Limited maintenance due to robust design and materials used; periodic inspections are needed for best performance.
Operational efficiency	Expected to run 24/7 with a capacity factor between 40% and 70%; designed to generate enough energy for about 324 homes annually.
Future development plans	Full-scale pilot expected by 2026–27, with commercial deployment targeted by 2031–32

TABLE 11 **Comparative performance indicators of selected offshore hybrid energy projects.**

Project	System configuratior	Capacity factor (CF)	LCOE (indicative)
SPIC (China)	Floating solar + offshore wind	Moderate–high (hybrid complementarity; pilot scale)	Reduced relative to standalone systems due to shared infrastructure
Poseidon (Europe)	Offshore wind + wave energy	Moderate–high (improved stability from wind–wave coupling)	~10–15 €c/kWh (reported estimates)
NoviOcean	Solar + Wave + wind (triple source design)	~40% (estimated)	LCOE < 40 €/MWh in commercial scale

and an LCOE in the range of 10–15 euro cents kWh^{-1} for the P80 design. This compares favourably with standalone floating wind LCOE estimates of EUR 80–150 MWh^{-1} reported in recent literature (Maienza et al., 2022), suggesting that wave energy synergies can partially offset the cost premium of floating foundations. Importantly, however, Poseidon has remained at the prototype stage for over a decade, highlighting a systemic challenge in the wave energy sector: the gap between promising prototype performance and bankable commercial projects remains wide, and addressing it will require dedicated long-duration funding mechanisms beyond what individual demonstration programmes can provide.

NoviOcean represents the most ambitious configuration reviewed here, integrating wave (650 kW), wind (300 kW), and solar (50–80 kW) on a single floating raft to achieve a projected 40% capacity factor and 3.5 GWh/unit/year. The combination of three complementary sources is consistent with modelling studies suggesting that multisource offshore platforms can exceed the intermittency limitations of any individual technology (Shannon, 2024; Wind), and the novel garden-pump-inspired Pelton turbine mechanism offers a potentially simpler and more maintainable wave conversion pathway than oscillating water column or point-absorber WEC designs reviewed by Dias (2017), NoviOcean. At an estimated construction cost of €3.6 million per unit, NoviOcean's economics are not yet competitive with mature offshore wind, but the patents secured in 20 countries and the targeted commercial deployment window of 2031–2032 indicate a credible pathway to market. The project would benefit from transparent long-term monitoring data to validate design-stage performance predictions and enable meaningful comparison with independently verified capacity factors from other hybrid concepts.

Taken together, the three case studies reveal a consistent pattern: hybrid offshore platforms achieve superior energy density and smoother grid output than single-source alternatives, but transition from pilot to commercial scale is constrained by funding gaps, limited long-term operational data, and the absence of standardised performance reporting. These findings are consistent with the broader hybrid systems literature (Abhinav et al., 2020), which emphasises that integrated techno-economic-environmental assessments—rather than purely technical feasibility studies are the missing link between demonstration success and commercial deployment. Future work should therefore prioritise (i) standardised monitoring and reporting protocols enabling cross-project comparison, (ii) bankability studies that account for the full life-cycle cost and revenue profile of multi-source platforms, and (iii) regulatory frameworks that recognise hybrid offshore configurations as a distinct asset class, streamlining permitting and enabling tailored support mechanisms.

6 Opportunities/strengths, challenges/risks, and mitigation strategies

6.1 Technical challenges and design considerations

The three case studies adopt notably different structural strategies to address their respective extreme loading environments. The SPIC platform faces annual typhoon conditions (Hs up to 10 m, wind speeds exceeding 50 m/s) and relies on Ocean Sun's flexible high-density polyethene (HDPE) membrane technology: a thin, compliant surface that deforms with wave orbital motion rather than resisting it, drastically reducing structural loads compared to rigid-frame alternatives. The Poseidon 37 platform, exposed to Baltic Sea storm conditions. The collected data and quantitative analyses informed the identification of critical engineering issues: technology integration, grid connection and stability, mooring and foundation design, operation and maintenance, subsea cabling, and energy-storage requirements. Potential mitigation measures include advanced composite materials, smart-grid controls, and modular mooring systems. Table. 12, below summarises the specific structural materials and engineering strategies employed or specified in each of the three case studies to address extreme weather conditions. These material-level decisions represent the practical engineering response to the extreme condition requirements identified across the three case studies and provide a basis for comparison as each project progresses toward commercial scale.

The mitigation strategy includes the use of advanced composite materials to improve structural durability, smart-grid and power management systems to enhance grid stability, modular mooring and foundation designs to reduce installation complexity, and optimised energy storage strategies to manage variability.

6.2 Ecological impacts on benthic ecosystems and marine biodiversity

While environmental assessments of offshore renewable energy systems have largely focused on avian interactions, offshore hybrid renewable energy (OHRE) systems present additional ecological considerations, particularly for benthic habitats and local marine

TABLE 12 **Structural materials and extreme-condition engineering strategies.**

Material approach	Application within hybrid offshore platforms	Key properties	Significance to typhoons and strong waves
High-strength low-alloy (HSLA) steel	Primary load-bearing structures (platform frames, columns, braces)	High yield strength, good fatigue resistance	Resists extreme wind and wave loads; improves structural stability under cyclic loading
Weathering and corrosion-resistant steels	Exposed structural elements above and near splash zone	Enhanced corrosion resistance in marine environments	Reduces material degradation under long-term exposure to saltwater and storm conditions
Glass fibre-reinforced polymers (GFRP)	Secondary structures, panels, floaters, protective housings	Lightweight, corrosion-resistant, high stiffness-to-weight ratio	Reduces platform mass and dynamic response to waves
Carbon fibre-reinforced polymers (CFRP)	High-stress components and connectors (limited use due to cost)	Very high strength and fatigue resistance	Improves performance under repeated extreme loading
Multi-layer protective coatings	Steel surfaces and joints	Corrosion protection, abrasion resistance	Maintains structural integrity during prolonged storm exposure
Cathodic protection systems	Subsea and splash-zone components	Electrochemical corrosion mitigation	Extends service life in aggressive marine environments
Fatigue-optimised joints and welds	Structural connections and interfaces	Reduced stress concentration, improved fatigue life	Limits crack initiation under repeated wave and wind loading
Semi-submersible/compliant platform designs	Floating foundations	Load redistribution, motion absorption	Reduces peak stresses during extreme wave events
Tuned mooring and anchoring systems	Station-keeping systems	Energy dissipation, controlled platform motion	Enhances stability during typhoons and high-sea states

biodiversity. Potential impacts are primarily associated with anchoring systems, subsea cabling, and the long-term presence of floating and semi-fixed structures. Installation activities may disturb seabed sediments, causing temporary turbidity and localised habitat alteration that can affect benthic invertebrates and demersal species. During operation, hybrid structures can modify local hydrodynamics and sediment transport, influencing benthic community composition. Submerged components may also function as artificial substrates, with ecological outcomes that are highly site dependent. Underwater noise from installation and maintenance can lead to behavioural disturbance in fish and marine mammals, while the spatial density of co-located technologies may alter ecological connectivity and movement pathways. Although some impacts are expected to be localised, cumulative effects remain poorly quantified. Empirical evidence on long-term benthic and ecosystem-level responses to multi-source offshore platforms is limited. Site-specific baseline surveys, long-term monitoring, and cumulative impact assessments are therefore essential to support environmentally responsible installation of OHRE systems.

7 Future innovations, research directions, and roadmap

Firstly, significant technological advancements are needed to support efficient energy generation, storage, and distribution from solar, wind, and wave power sources. The future of hybrid offshore renewable energy systems holds considerable promise, especially given the growing demand for stable, sustainable energy solutions in marine environments (Si et al., 2021). Improving the efficiency and reliability of wave energy converters to make them viable components of hybrid systems. Solar tracking systems can optimise energy capture by adjusting panel angles in response to sunlight conditions, thereby increasing energy yields. Beyond current combinations of solar, wind, and wave energy, future systems could integrate additional resources such as tidal power and ocean thermal energy conversion (OTEC) to create a multi-source platform (Kaur et al., 2025). Robust mooring systems are crucial for maintaining stability in harsh marine conditions, especially for multisource systems. Developing platforms that can support floating solar, wind turbines, and wave energy converters. Research into new materials and modular designs for floating structures to enhance durability and efficiency in harsh marine environments. Incorporating these with advanced energy storage solutions, such as offshore batteries or hydrogen production, would improve reliability and enable consistent power output despite fluctuating ocean conditions (Bajc and Kostadinović, 2023). Developing scalable storage solutions, like flow batteries and compressed air energy storage, to stabilise energy supply from intermittent sources. Excess energy can be used to produce green hydrogen, offering a versatile energy storage and transportation solution. Enhancing grid management systems to integrate hybrid offshore energy systems with onshore power networks efficiently. Implementing smart grid systems with advanced sensors and AI algorithms can optimise energy distribution from offshore floating systems, ensuring efficient grid integration. Advanced cable systems for transferring power from floating wind farms to the grid are needed to ensure reliability in deep waters. Real-time monitoring and control systems may help to manage power output variability from multiple energy sources, ensuring a stable grid supply. Using satellite data for weather forecasting and energy output prediction can enhance grid planning and stability. Expanding hybrid applications to remote or off-grid locations could support not only energy needs but also desalination, aquaculture, and possibly even underwater data centres, making efficient use of marine resources (Hammar et al., 2020). Further studies could assess the environmental effects and ecosystem interactions of such multi-energy systems, aiming to design systems that enhance efficiency with minimal ecological impact (Tawalbeh et al., 2021). These innovations may improve the performance and reliability of renewable energy systems and make them more cost-competitive with traditional energy sources. By leveraging advanced technologies, robust designs, and integrated solutions, hybrid systems can overcome these challenges and contribute to a sustainable energy future (Figure 9). Offshore integration technologies offer the perfect solution to global energy problems (Divan and Sharma, 2024).

7.1 Research directions: unresolved questions for advancing offshore hybrid technologies

Advancing offshore hybrid renewable energy technologies (combining floating solar, wind turbines, and wave energy converters) requires addressing several unresolved research questions. These questions span technical, environmental, economic, and social aspects. These questions help improve our research and technology. Below are 10 key future research questions that can guide innovation and development in this field:

Q1: How can we optimise the integration of various offshore renewable sources (wind, wave, solar, tidal, and OTEC) with wireless power transfer and storage solutions (hydrogen and batteries) to achieve consistent and reliable power delivery?

Q2: What are the most effective designs for floating platforms that can support hybrid systems while withstanding extreme waves, currents, and wind loads?

Q3: What innovative mooring and anchoring technologies can enhance the stability and efficiency of floating offshore hybrid platforms?

Q4: How can existing offshore oil and gas infrastructure be repurposed or integrated into future offshore hybrid energy systems?

Q5: What new materials or coatings can be developed to enhance the durability and corrosion resistance of offshore hybrid systems in harsh marine environments?

Q6: How will offshore hybrid systems be affected by climate change, including rising sea levels, increasing storm intensity, and changing wind and wave patterns?

Q7: What are the most cost-effective and sustainable materials for offshore hybrid technology development?

Q8: What are the long-term environmental impacts of offshore hybrid systems on marine ecosystems, including fish, mammals, and seabirds?

Q9: What are the challenges and opportunities for scaling up offshore hybrid systems from pilot projects to large-scale commercial deployments?

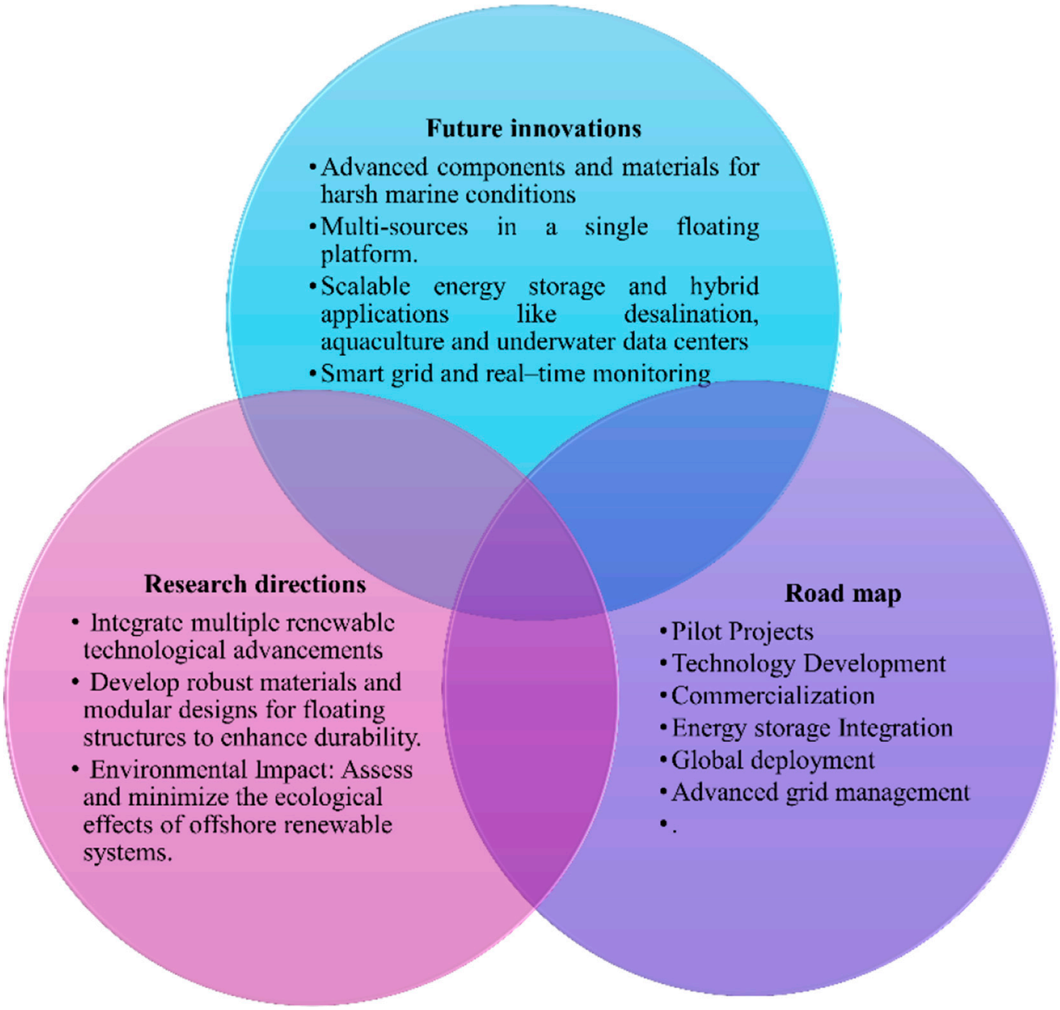


FIGURE 9
Technological advances, research directions, and roadmap.

Q10: How can local communities and stakeholders be effectively engaged in the planning and implementation of offshore hybrid projects to ensure their support?

Further studies are needed to evaluate these trade-offs and explore ways to improve the integration of renewable energy sources to ensure a stable, reliable power supply.

7.2 Roadmap

The proposed roadmap for hybrid offshore renewable energy systems was developed from comparative case study analysis and the synthesis of recent technical literature, rather than from direct stakeholder consultation. The sequencing reflects observed patterns in technology readiness, system integration complexity, and infrastructure requirements across existing pilot and early commercial projects. The roadmap, therefore, represents an evidence-based progression from experimental validation to large-scale system integration.

7.2.1 Short-term (2025–2030): demonstration and system validation

The initial phase focuses on pilot-scale deployments to validate hybrid offshore configurations under real marine conditions. Demonstration projects combining offshore wind, wave energy converters, and floating photovoltaic systems are required to generate operational data on energy yield, structural performance, grid interfacing, and maintenance demands. Design optimisation should prioritise material stability, corrosion resistance, and platform stability, given the exposure to extreme wave loading and cyclic fatigue. Environmental considerations at this stage include installation-related disturbances, underwater noise, and early-stage ecosystem interactions. Policy support is expected to play a facilitative role through targeted incentives and simplified permitting mechanisms to reduce financial and regulatory barriers to experimental installations.

7.2.2 Mid-term (2030–2040): early commercialisation and infrastructure integration

Building on validated pilot configurations, the mid-term phase emphasises scale-up toward commercial deployment. Modular system architectures and standardised components enable replication and cost reduction. The integration of short- and medium-duration energy storage is increasingly relevant for managing variability and improving supply. Offshore electrical infrastructure, including export cables and floating substations, must evolve to accommodate multi-source generation. At this stage, long-term environmental monitoring and cumulative impact assessments are required to inform adaptive management strategies, particularly in regions where offshore renewable systems coexist with fisheries, shipping routes, and ecologically sensitive habitats.

7.2.3 Long-term (2040–2050): large-scale installation and system

The final phase reflects a transition toward widespread installations of hybrid offshore energy systems as part of integrated marine energy hubs. Mature designs enable installation in deeper waters and harsher environments, including the reuse of existing offshore infrastructure where technically feasible. Advanced grid management approaches, including digital monitoring and real-time power balancing, support interaction between offshore hybrid systems and broader energy networks. Serial manufacturing and standardised installation practices contribute to further cost reductions. At this stage, hybrid offshore systems are positioned as a stable component of low-carbon electricity supply, complementing other renewable technologies within regional and transnational energy systems.

8 Conclusion

In conclusion, the pursuit of sustainable and clean energy solutions has driven significant innovation in hybrid offshore renewable-energy platforms combining floating solar photovoltaics (FPV), offshore wind, and wave power, which can markedly improve energy reliability, reduce the levelized cost of electricity (LCOE), and optimise the use of ocean space compared with single-source systems. Analysis of three representative projects—the SPIC floating solar–wind platform in China, Denmark's Poseidon wind–wave system, and the UK's NoviOcean solar–wind–wave concept—highlights several key outcomes. Coordinated operation of complementary resources raises capacity factors to about 45% and annual generation to roughly 3.5 GWh per unit, while shared electrical infrastructure lowers transmission losses and enhances grid stability. Economic benefits arise from infrastructure sharing and higher asset utilisation, with generation costs reported as low as 10–15-euro cents kWh^{-1} for wind–wave systems and significant savings for pilot-scale floating solar–wind projects. Technical innovations in modular floating platforms, robust mooring, and multi-resource energy conversion enable reliable performance even under extreme marine conditions, while reduced land conflict and potential artificial-reef effects provide notable environmental advantages when supported by rigorous impact assessments and monitoring. Challenges remain, including high capital costs, corrosion, and complex integration of multiple energy sources, which call for advanced materials, improved anchoring solutions, smart-grid controls, and supportive policy measures such as streamlined permitting and targeted subsidies. Social and regulatory barriers, such as maritime space conflicts and fragmented policies, further complicate deployment and scalability across diverse environments. Future research should focus on large-scale energy storage, offshore hydrogen production, smart-grid integration, and new materials to extend platform lifetimes, alongside refined environmental monitoring to protect marine ecosystems. With continued technological innovation, regulatory clarity, and sustained investment, hybrid offshore renewable systems are poised to play a pivotal role in global clean-energy expansion and the transition to a low-carbon economy.

Author contributions

NK: Methodology, Writing – original draft. KS: Supervision, Writing – review and editing. MM: Supervision, Writing – review and editing, Conceptualization. RB: Conceptualization, Writing – review and editing, Investigation. DB: Formal Analysis, Writing – review and editing, Conceptualization.

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Conflict of interest

Author DB was employed by Algorithm Intelligence.

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The author(s) declared that generative AI was used in the creation of this manuscript. We acknowledge the need to utilise generative AI tools, such as Scopus AI, to identify relevant references, and GPT-4, Claude, Deepseek, and Microsoft Copilot to enhance sentence clarity.

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References

Abaei, M. M., Arzaghi, E., Bao, M., Garaniya, V., Abdussamie, N., Pichard, A., et al. (2025). Performance evaluation of point-absorber wave energy converters; energy extraction and structural integrity aspects. *Ocean. Eng.* 317, 119983. doi:10.1016/j.oceaneng.2024.119983

Abeyratne, R. I. (2024). Treaties establishing ICAO and IMO – a comparative study. *J. Air Law Commer.* 89 (2), 297–351. doi:10.25172/jalc.89.2.5

Abhinav, K. A., Collu, M., Benjamins, S., Cai, H., Hughes, A., Jiang, B., et al. (2020). Offshore multi-purpose platforms for a blue growth: a technological, environmental and socio-economic review. *Sci. Total Environ.* 734, 138256. doi:10.1016/j.scitotenv.2020.138256

Adiputra, R., Utsunomiya, T., Koto, J., Yasunaga, T., and Ikegami, Y. (2020). *Preliminary design of a 100 MW-net ocean thermal energy conversion (OTEC) power plant study case*. Indonesia: Mentawai island. doi:10.1007/s00773-019-00630-7

Ahamed, R., McKee, K., and Howard, I. (2020). Advancements of wave energy converters based on power take off (PTO) systems: a review. *Ocean. Eng.* 204, 107248. doi:10.1016/j.oceaneng.2020.107248

Arguilé-Pérez, B., Ribeiro, A. S., Costoya, X., deCastro, M., Carracedo, P., Dias, J. M., et al. (2022). Harnessing of different WECs to harvest wave energy along the Galician Coast (NW Spain). *J. Mar. Sci. Eng.* 10 (6), 719. doi:10.3390/jmse10060719

Aschenbrenner, M., and Winder, G. M. (2019). Planning for a sustainable marine future? Marine spatial planning in the German exclusive economic zone of the North Sea. *Appl. Geogr.* 110, 102050. doi:10.1016/j.apgeog.2019.102050

Bajc, T., and Kostadinović, D. (2023). Potential of usage of the floating photovoltaic systems on natural and artificial lakes in the republic of serbia. *J. Clean. Prod.* 422. doi:10.1016/j.jclepro.2023.138598

Bashetty, S., and Ozcelik, S. (2021). Review on dynamics of offshore floating wind turbine platforms. *Energies* 14, 19. doi:10.3390/en14196026

Bedekar, K., Oterkus, E., and Oterkus, S. (2025). Ammonia bunkering—infrastructure, finance, insurance and regulatory issues: a review. *Sustain. Mar. Struct.* 07 (04), 104–131. doi:10.36956/sms.v7i4.2713

Bin Abu Sofian, A. D. A., Lim, H. R., Siti Halimatul Munawaroh, H., Ma, Z., Chew, K. W., and Show, P. L. (2024). Machine learning and the renewable energy revolution: exploring solar and wind energy solutions for a sustainable future including innovations in energy storage. *Sustain. Dev.* 32 (4), 3953–3978. doi:10.1002/sd.2885

Bostan, V., Guțu, M., and Rabei, I. (2019). Numerical simulation of transient aerodynamic processes in the vertical axis wind turbine rotor. *J. Eng. Sci. Innovat.* 4 (2), 145–154. doi:10.56958/jesi.2019.4.2.145

Boussarie, G., Kopp, D., Lavialle, G., Mouchet, M., and Morfin, M. (2023). Marine spatial planning to solve increasing conflicts at sea: a framework for prioritizing offshore windfarms and marine protected areas. *J. Environ. Manage.* 339, 117857. doi:10.1016/j.jenvman.2023.117857

Capanoglu, C. (2005). "Novel and marginal field offshore structures," in *Handbook of offshore engineering (2-volume set)*, 39–77. doi:10.1016/B978-008044381-2.50005-9

Castro-Santos, L., Martins, E., and Guedes Soares, C. (2016). Cost assessment methodology for combined wind and wave floating offshore renewable energy systems. *Renew. Energy* 97, 866–880. doi:10.1016/j.renene.2016.06.016

Chen, H. C. (2013). Optimum capacity determination of stand-alone hybrid generation system considering cost and reliability. *Appl. Energy* 103, 155–164. doi:10.1016/j.apenergy.2012.09.022

Claus, R., and López, M. (2022). Key issues in the design of floating photovoltaic structures for the marine environment. *Renew. Sustain. Energy Rev.* 164, 112502. doi:10.1016/j.rser.2022.112502

Dias, F., Renzi, E., Gallagher, S., Sarkar, D., Wei, Y., Abadie, T., et al. (2017). Analytical and computational modeling for wave energy systems: the example of oscillating wave surge converters. *Acta Mech. Sin.*, 33 (4), 647–662. doi:10.1007/s10409-017-0683-6

Divan, D., and Sharma, S. (2024). *Getting to a desired energy future: role of innovation*. doi:10.1007/978-3-031-49417-8_6

Elliott, M. (2011). Marine science and management means tackling exogenic unmanaged pressures and endogenic managed pressures - a numbered guide. *Mar. Pollut. Bull.* 62 (4), 651–655. doi:10.1016/j.marpolbul.2010.11.033

European Commission EU. *EU funding for offshore renewables*.

European Commission. *Market maturation of floating power Plant's floating Wind-Wave- energy device _ POSEIDON _ project _ news and multimedia _ H2020 _ CORDIS _ European Commission*.

Faria, V. A. D., Rodrigo de Queiroz, A., and DeCarolis, J. F. (2023). Scenario generation and risk-averse stochastic portfolio optimization applied to offshore renewable energy technologies. *Energy* 270, 126946. doi:10.1016/j.energy.2023.126946

Friel, D., Karimirad, M., Whittaker, T., Doran, J., and Howlin, E. (2019). "A review of floating photovoltaic design concepts and installed variations," in *4th international conference on offshore renewable energy. CORE2019 proceedings*, Glasgow, UK: ASRANet Ltd.

Gan, K. E., Taikan, O., Gan, T. Y., Weis, T., Yamazaki, D., and Schüttrumpf, H. (2023). Enhancing renewable energy systems, contributing to sustainable development goals of United Nation and building resilience against climate change impacts. *Energy Technol.* 11 (11), 2300275. doi:10.1002/ente.202300275

Garrod, A., Neda Hussain, S., Ghosh, A., Nahata, S., Wynne, C., and Paver, S. (2024). An assessment of floating photovoltaic systems and energy storage methods: a comprehensive review. *Results Eng.* 21, 101940. doi:10.1016/j.rineng.2024.101940

Geyer, B. (2024). *All floating PV technologies at a glance*. Germany: PV-Magazine headquartered in Berlin. Available online at: https://www.pv-magazine.com/2024/02/27/all-floating-pv-technologies-at-a-glance/.

Ghosh, A. (2023). A comprehensive review of water based PV: flotavoltaics, under water, offshore and canal top. *Ocean. Eng.* 281 (June), 115044. doi:10.1016/j.oceaneng.2023.115044

Gustavo, M., and Enrique, P. (2011). Modelling and control design of pitch-controlled variable speed wind turbines. *Wind Turbines*. doi:10.5772/15880

Hammar, L., Molander, S., Pålsson, J., Schmidtbauer Crona, J., Carneiro, G., Johansson, T., et al. (2020). Cumulative impact assessment for ecosystem-based marine spatial planning. *Sci. Total Environ.* 734, 139024. doi:10.1016/j.scitotenv.2020.139024

Harsono, H. (2025). China-brazil ties in emerging technologies: innovation, opportunity, and the challenge of digital sovereignty *Asia Policy* 20, (4): 123–140. doi:10.1353/asp.2025.a974351

Hasan, A. S. M. M., Kesapabutr, P., and Möller, B. (2024). Bangladesh's pathways to net-zero transition: reassessing country's solar PV potential with high-resolution GIS data. *Energy Sustain. Dev.* 81 (March). doi:10.1016/j.esd.2024.101511

Honniball, A. N. (2023). *Coastal state jurisdiction over living resources in the exclusive economic zone, written by Camille Goodman*. doi:10.1163/15718085-bja10134

Huang, L. (2025) *U.K. ocean renewable energy systems: harnessing wind, wave, tidal, and solar power at sea*. Springer Nature. doi:10.1007/978-3-032-10576-9

Huang, J., Zhou, Y., Ning, Z., and Gharavi, H. (2019). Wireless power transfer and energy harvesting: current status and future prospects. *IEEE Wirel. Commun.* 26 (4), 163–169. doi:10.1109/MWC.2019.1800378

Ibrahim, O. S., Singlitico, A., Proskovics, R., McDonagh, S., Desmond, C., and Murphy, J. D. (2022). Dedicated large-scale floating offshore wind to hydrogen: assessing design variables in proposed typologies. *Renew. Sustain. Energy Rev.* 160 (November 2021), 112310. doi:10.1016/j.rser.2022.112310

Islam, A., Ali, M. M. N., Al Mamun, A., Hossain, M. S., Maruf, H., and Shihavuddin, A. S. M. (2024). Energy conversion and management: x optimizing energy solutions: a techno-economic analysis of solar-wind hybrid power generation in the coastal regions of Bangladesh. *Energy Convers. Manag. X* 22 (February), 100605. doi:10.1016/j.ecmx.2024.100605

Jallad, J., Mekhilef, S., and Mokhlis, H. (2017). Frequency regulation strategies in grid integrated offshore wind turbines *via* VSC-HVDC technology: a review. *Energies (Basel).* 10 (9), 1–29. doi:10.3390/en10091244

Kaur, N., Sudhakar, K., Mohamed, M. R., Cuce, E., and Barbulescu, D. (2025). Floating solar sustainability on land and ocean: a strategic assessment using SWOT-TWOS-PESTLE analysis. *Sci. Tech. Energ. Transition.* (80) 27 doi:10.2516/stet/2024114

Kusters, J. E. H., van Kann, F. M. G., and Zuidema, C. (2025). Spatial conflict resolution in marine spatial plans and permitting procedures for offshore wind energy: an analysis of measures adopted in Denmark, England and the Netherlands. *Front. Mar. Sci.* 12 (February), 1–16. doi:10.3389/fmars.2025.1468734

Kusuma, Y. F., Fuadi, A. P., Hakim, B. A., Sasmito, C., Nugroho, A. C. P. T., Khoirudin, M. H., et al. (2024). Navigating challenges on the path to net zero emissions: a comprehensive review of wind turbine technology for implementation in Indonesia. *Results Eng.* 22 (January), 102008. doi:10.1016/j.rineng.2024.102008

Lee, Y. S., Choi, B. L., Lee, J. H., Kim, S. Y., and Han, S. (2014). Reliability-based design optimization of monopile transition piece for offshore wind turbine system. *Renew. Energy* 71, 729–741. doi:10.1016/j.renene.2014.06.017

Li, M., Cao, S., Zhu, X., and Xu, Y. (2022a). Techno-economic analysis of the transition towards the large-scale hybrid wind-tidal supported coastal zero-energy communities. *Appl. Energy* 316 (November 2021), 119118. doi:10.1016/j.apenergy.2022.119118

Li, M., Luo, H., Zhou, S., Senthil Kumar, G. M., Guo, X., Law, T. C., et al. (2022b). State-of-the-art review of the flexibility and feasibility of emerging offshore and coastal ocean energy technologies in East and Southeast Asia. *Renew. Sustain. Energy Rev.* 162 (March), 112404. doi:10.1016/j.rser.2022.112404

López, M., Rodríguez, N., and Iglesias, G. (2020). Combined floating offshore wind and solar PV. *J. Mar. Sci. Eng.* 8 (8), 576. doi:10.3390/JMSE8080576

Maienza, C., Avossa, A. M., Picozzi, V., and Ricciardelli, F. (2022). Feasibility analysis for floating offshore wind energy. *Int. J. Life Cycle Assess.* 27 (6), 796–812. doi:10.1007/s11367-022-02055-8

Mcowen, C., Chandler, G., Faessler, A. C., Bland, R., Vakhitova, V., Lamb, C., et al. *Meeting the demand: aligning marine biodiversity data supply with policy needs*, 1–47. doi:10.32942/X2665F

McTiernan, K. L., and Sharman, K. T. (2020). "Review of hybrid offshore wind and wave energy systems," in *Journal of physics: conference series*. doi:10.1088/1742-6596/1452/1/012016

Melikoglu, M. (2018). Current status and future of ocean energy sources: a global review. *Ocean. Eng.* 148 (June 2017), 563–573. doi:10.1016/j.oceaneng.2017.11.045

Mendez-Morales, M., Karipoglu, F., Ivanković, M., Lukić, T., and Rebelo, C. (2025). Transforming crete's sustainable energy landscape: a modular energy island approach. *Int. J. Energy Res.*, 2025 (1), 2363366. doi:10.1155/er/2363366

Nassar, W. M., Anaya-Lara, O., Ahmed, K. H., Campos-Gaona, D., and Elgenedy, M. (2020). Assessment of multi-use offshore platforms: structure classification and design challenges. *Sustain. Switz.* 12 (5), 1–23. doi:10.3390/su12051860

Nicholls-Lee, R. F., and Turnock, S. R. (2008). Tidal energy extraction: renewable, sustainable and predictable. *Sci. Prog.* 91 (1), 81–111. doi:10.3184/003685008X285582

NoviOcean, *The science behind our success: noviOcean – resilient, efficient wave*, Wind and Solar Energies. Available online at: https://noviocean.energy/technology/.

NoviOcean (2024). *Saving the Climate with Profitable and Stable Ocean Energy. (n.d.) Stockholm Sweden*. Available online at: https://noviocean.energy/2024/10/22/hybrid-energy-raft-could-power-1000-homes-a-day-with-wave-wind-solar/.

NoviOcean. *NoviOcean_ saving the climate with profitable and stable ocean energy.*

Ocean Energy Europe. *Powered by the ocean - ocean energy Europe.*

Oliveira-Pinto, S., and Stokkermans, J. (2020a). Assessment of the potential of different floating solar technologies – overview and analysis of different case studies. *Energy Convers. Manag.* 211 (November 2019), 112747. doi:10.1016/j.enconman.2020.112747

Perumal, N. (2024). A study to examine vessel traffic services in the context of maritime autonomous surface ships: strait of Malacca as a case study. Available online at: https://commons.wmu.se/cgi/viewcontent.cgi?article=3409&context=all_dissertations (Accessed January 2026).

Petracca, E., Faraggiana, E., Ghigo, A., Sirigu, M., Bracco, G., and Mattiazzo, G. (2022). Design and techno-economic analysis of a novel hybrid offshore wind and wave energy system. *Energies (Basel).* 15 (8), 2739. doi:10.3390/en15082739

Pouran, H. M., Padilha Campos Lopes, M., Nogueira, T., Alves Castelo Branco, D., and Sheng, Y. (2022). Environmental and technical impacts of floating photovoltaic plants as an emerging clean energy technology. *iScience* 25 (11), 105253. doi:10.1016/j.isci.2022.105253

Prasad, S., Yadav, K. K., Kumar, S., Pandita, P., Bhutto, J. K., Alreshidi, M. A., et al. (2024). Review on biofuel production: sustainable development scenario, environment, and climate change perspectives – A sustainable approach. *J. Environ. Chem. Eng.* 12 (2). doi:10.1016/j.jece.2024.111996

Proctor, D. (2022). "China unveils world's first commercial offshore wind-plus-solar project," in *Power*. Washington, DC: Omni Shoreham. Available online at: https://www.powermag.com/china-unveils-worlds-first-commercial-offshore-wind-plus-solar-project/.

PUB Singapore's National Water Agency (2016). *Floating solar systems*.

Rebecca Williams, J. L. (2022). *Feng Zhao, "Global Offshore Wind Report 2022,"*. Global Wind Energy Council, 86–88.

Rivas, L., González, A. E., and Gutiérrez, A. (2025). Critical environmental factors in offshore wind–hydrogen projects: uruguay's exclusive economic zone. *Sustain. Switz.* 17 (13), 1–30. doi:10.3390/su17136096

Saeidtehrani, S., Fazeres-Ferradosa, T., Rosa-Santos, P., and Taveira-Pinto, F. (2022). Review on floating wave-wind energy converter plants: nonlinear dynamic assessment tools. *Sustain. Energy Technol. Assessments* 54, 102753. doi:10.1016/J.SETA.2022.102753

Sarantopoulos, F. (2024). Decarbonizing the shipping industry through innovative technologies, artificial intelligence and new regulations. Available online at: https://dspace.mit.edu/handle/1721.1/156005.

Science, E. (2005). "A study of the temperature distribution in the OTEC cold water pipe using a heat and mass transfer approach A study of the temperature distribution in the OTEC cold water pipe using a heat and mass transfer approach," doi:10.1088/1755-1315/1372/1/012018

Shannon, C. (2024). *3-in-1 Energy Generator Uses Waves*, Wind, and Solar. Available online at: https://eepower.com/news/3-in-1-energy-generator-uses-waves-wind-and-solar/.

Si, Y., Chen, Z., Zeng, W., Sun, J., Zhang, D., Ma, X., et al. (2021). The influence of power-take-off control on the dynamic response and power output of combined semi-submersible floating wind turbine and point-absorber wave energy converters. *Ocean. Eng.* 227 (January), 108835. doi:10.1016/j.oceaneng.2021.108835

Singh, P., Linnér, B. O., and Singh, A. A. (2025). Marine spatial planning and ocean governance in small island developing states. *Reg. Environ. Change* 25 (3), 91. doi:10.1007/s10113-025-02412-x

Skov, H. (2023). "Bat and bird monitoring guidance, 53" in *Peer-reviewed*, Editor N. I. R. A. S. Robin Ward. Available online at: https://www.dhigroup.com/upload/publications/2023/bat-and-bird-monitoring-guidance.pdf.

SPIC. *Ocean sun switch on offshore floating solar-wind pilot – Pv magazine international*. Available online at: https://www.pv-magazine.com/2022/11/02/spic-ocean-sun-build-worlds-first-offshore-floating-solar-wind-park/.

Santhakumar, S., Meerman, H., Faaij, A., Gordon, R. M., and Gusatu, L. F. (2024). The future role of offshore renewable energy technologies in the North Sea energy system. *Energy Convers. Manag.* 315, 118775. doi:10.2139/ssrn.4602495

Tawalbeh, M., Al-Othman, A., Kafiah, F., Abdelsalam, E., Almomani, F., and Alkasrawi, M. (2021). Environmental impacts of solar photovoltaic systems: a critical review of recent progress and future outlook. *Sci. Total Environ.* 759. doi:10.1016/j.scitotenv.2020.143528

Technology – NoviOcean. *NoviOcean's Next-Generation Hybrid Ocean Energy Converter*. Available online at: https://noviocean.energy/technology/.

TETHYS (2014). *Poseidon floating power (poseidon 37)*. New York, NY: Number Poseidon 37. Available online at: https://tethys.pnnl.gov/project-sites/poseidon-floating-power-poseidon-37.

Thorson, J., Matthews, C., Lawson, M., Anwar, M. B., Jadun, P., Thorson, J., et al. (2022). *Unlocking the potential of marine energy using hydrogen generation technologies*, 83. Available online at: https://docs.nlr.gov/docs/fy22osti/82538.pdf.

Trapani, K., Redón Santafé, M. (2015). A review of floating photovoltaic installations: 2007–2013. *Prog. Photovolt: Res. Appl.* 23, 524–532. doi:10.1002/pip.2466

Tsai, H. H., Tseng, H. S., Huang, C. K., and Yu, S. C. (2022). Review on the conflicts between offshore wind power and fishery rights: marine spatial planning in Taiwan. *Energies (Basel)* 15 (22), 1–15. doi:10.3390/en15228768

van Niekerk, C. J., and van der Pot, B. J. G. (1985). "Ocean thermal energy conversion," in Land and Water Int., 17–25. Available online at: https://www.sciencedirect.com/topics/engineering/ocean-thermal-energy-conversion.

Vo, T. T. E., Ko, H., Huh, J., and Park, N. (2021). *Overview of possibilities of solar floating photovoltaic systems in the offshore industry*. doi:10.3390/en14216988

Waewsak, J., Landry, M., and Gagnon, Y. (2015). Offshore wind power potential of the Gulf of Thailand. *Renew. Energy* 81 (2015), 609–626. doi:10.1016/j.renene.2015.03.069

Wagner, H. J., Baack, C., Eickelkamp, T., Epe, A., Lohmann, J., and Troy, S. (2011). Life cycle assessment of the offshore wind farm alpha ventus. *Energy* 36 (5), 2459–2464. doi:10.1016/j.energy.2011.01.036

Wang, L., Kolios, A., Cui, L., and Sheng, Q. (2018). Flexible multibody dynamics modelling of point-absorber wave energy converters. *Renew. Energy* 127, 790–801. doi:10.1016/j.renene.2018.05.029

Wang, Q., Zhang, Y., and Zhang, H. (2023). The development of floating nuclear power platforms: special marine environmental risks, existing regulatory dilemmas, and potential solutions. *Sustain. Switz.* 15 (4), 3022. doi:10.3390/su15043022

Wind. *How is electricity generated by wind?*

Wind energy in Europe (2025). *Statistics and the outlook for 2026-2030*. Available online at: https://windeurope.org/data/products/wind-energy-in-europe-2025-statistics-and-the-outlook-for-2026-2030/.

Windtech International (2024). *Global wind energy capacity grows by 117GW in 2024*. Groningen, The Netherlands: Windtech International. Available online at: https://www.windtech-international.com/industry-news/global-wind-energy-capacity-grows-by-117gw-in-2024.

Yamada, N., Hoshi, A., and Ikegami, Y. (2009). Performance simulation of solar-boosted ocean thermal energy conversion plant. *Renew. Energy* 34 (7), 1752–1758. doi:10.1016/j.renene.2008.12.028

Yang, B., Li, D., Zhang, Y., Fu, X., Wang, H., Gong, R., et al. (2024). Review of innovative design and application of hydraulic compressed air energy storage technology. *J. Energy Storage* 98 (June), 113031. doi:10.1016/j.est.2024.113031

Zhang, Y., Zhao, Y., Sun, W., and Li, J. (2021). Ocean wave energy converters: technical principle, device realization, and performance evaluation. *Renew.*

Sustain. Energy Rev. 141 (February), 110764. doi:10.1016/j.rser.2021.110764

Zhang, Y., Zhang, D., and Jiang, H. (2023). *A review of offshore wind and wave installations in some areas with an eye towards generating economic benefits and offering commercial inspiration*. Switzerland: Sustainability. doi:10.3390/su15108429

Zhang, Z., Chen, X., Wu, H., Liu, W., and Cui, L. (2023). Numerical study of a novel hybrid system with the Wavestar wave energy converter array and a SPIC semi-submersible floating platform. *J. Clean. Prod.*, 407, 137178. doi:10.1016/j.jclepro.2023.137178

Zhu, M., Qi, Y., and Hultman, N. (2022). Low-carbon energy transition from the commanding heights: How state-owned enterprises drive China's wind power "miracle". *Energy Res. Soc. Sci.* 85, 102392. doi:10.1016/j.erss.2021.102392

Zumerchik, J., and Danver, S. L. (2009). *Seas and Waterways of the World: An Encyclopedia of History*. United States: Bloomsbury Publishing United States