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Review

A Review of the European Floating Structures for Hybrid Renewable Energy Systems

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Abstract

The energy transition and global decarbonization goals have accelerated the development of offshore renewable energy technologies, particularly in deep-water regions, where fixed foundations are limited by technical and economic constraints. Floating structures offer new opportunities for harnessing marine renewable resources, allowing them to be deployed in areas with favorable wind, wave, and oceanographic conditions. This paper presents a comprehensive analysis of European floating structures intended for hybrid renewable energy applications, combining environmental assessment, structural characteristics, hydrodynamic behavior, and energy integration aspects. Unlike previous analyses, which focused primarily on individual technologies, this study offers an integrated perspective on floating platform concepts—including spar, semi-submersible, tension-leg, barge, and FPSO-based solutions—as well as their potential for hybrid energy systems. The analysis shows that platform stability, motion response, and structural adaptability are critical factors affecting energy performance and operational reliability. Furthermore, the analysis highlights that hybrid configurations combining offshore wind, wave, and solar energy with energy storage technologies represent promising pathways toward more autonomous and sustainable offshore infrastructure. Key challenges related to design optimization, environmental loads, and system integration are also identified to support future developments in European offshore renewable energy.

Keywords: floating offshore platforms; floating offshore wind turbines; wave energy; hybrid offshore energy systems; hydrodynamics; structural dynamics; European nearshore structural dynamics

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1. Introduction

The exponential growth in global energy demand and the associated impact of fossil fuel use have led to an intensification of research into the development of renewable energy sources and a reduction in greenhouse gas emissions [1,2]. In recent decades, climate change and environmental degradation have become central issues in international energy policies, with the transition to sustainable, low-carbon energy systems being supported in the IPCC's reports on mitigation scenarios [3]. In this context, offshore renewable energy has emerged as a strategically important component of the European and global transition toward low-carbon and more resilient energy systems [3,4]. The marine environment offers favorable conditions for the development of renewable resources due to the high intensity and stability of wind and ocean resources compared to the terrestrial environments [5]. European offshore regions, particularly the North Sea and the Atlantic Ocean, exhibit among the highest values of wind and wave energy potential worldwide [6]. The development of offshore technologies has expanded significantly over the past two decades, with offshore wind energy becoming one of the most dynamic sectors of the renewable energy industry [7].

Initially, most offshore installations were developed using fixed foundations located in shallow waters [8]. However, the expansion of operations into deeper water has led to the need for floating offshore platforms capable of operating efficiently under complex hydrodynamic conditions [9]. Floating structures allow energy systems to be deployed in regions with superior wind and wave resources, where conventional solutions become technically and economically limited [9,10].

Offshore floating platforms represent an advanced category of marine infrastructure, initially developed in the oil and gas industry and subsequently adapted for renewable energy applications. From a structural standpoint, these include configurations such as semi-submersibles, spars, and tension-leg platforms (TLPs), each exhibiting distinct hydrodynamic behaviors and different response characteristics under marine environmental conditions [11,12]. The theoretical foundation of these configurations is based on the principles of marine hydrodynamics and offshore structural mechanics, as formulated in the studies of Newman and Faltinsen [13,14].

In parallel with the development of floating offshore wind turbines, research has increasingly shifted toward integrated offshore renewable energy systems capable of combining several energy conversion technologies within shared marine infrastructure. Floating platforms can accommodate offshore wind turbines together with wave energy converters, floating photovoltaic systems, energy storage technologies, and power-to-X applications. Such configurations may improve the utilization of offshore infrastructure and enable complementary renewable generation profiles, thereby reducing the variability associated with individual energy sources. Consequently, the development of offshore renewable energy is progressively moving from isolated technology deployment toward integrated and multi-source energy systems that combine energy conversion, storage, transmission, and, in some cases, hydrogen production functions [15–17].

Experience accumulated in the offshore oil and gas industry has provided an important technological foundation for the development of modern renewable energy conversion systems in the marine environment. In particular, Floating Production, Storage, and Offloading (FPSO) systems represent a mature category of floating offshore platforms originally developed for deepwater oil and gas applications. Their long-term operation under severe marine conditions has significantly advanced offshore engineering, particularly in hydrodynamic analysis, mooring system design, and structural reliability assessment [18,19]. Although FPSO systems were not originally intended for renewable energy applications, the engineering knowledge gained from these structures provides valuable insights for the design and operation of floating renewable energy platforms, especially regarding environmental loads, stability, long-term structural performance, and operational reliability under complex offshore conditions. This knowledge transfer is particularly relevant for floating wind turbines and hybrid offshore energy systems, where similar engineering challenges are encountered. The performance of floating structures is directly influenced by their hydrodynamic behavior in the marine environment [13,14].

The interaction between waves, wind, ocean currents, and the structure generates complex dynamic loads that affect the stability, structural response, and service life of offshore installations [20]. Hydrodynamic analysis is thus an essential element in the design and optimization of floating platforms, particularly in the case of integrated energy conversion systems [21].

The motions of floating platforms, such as pitch, roll, and yaw, can significantly influence the performance of offshore wind turbines and the efficiency of wave energy harvesting systems [22]. In addition, extreme environmental conditions, including severe storms and extreme waves, can lead to structural fatigue and damage to mooring systems. For this reason, numerous recent studies focus on developing advanced numerical simulation and experimental modeling methods to evaluate the dynamic response of floating offshore platforms [23,24].

The evolution of offshore renewable energy research in Europe has followed a progressive technological trajectory. The initial development of European offshore wind focused predominantly on fixed-bottom turbines installed in relatively shallow waters, followed by increasing research into the technical and economic challenges associated with deeper-water deployment. As offshore wind technology matured, floating support structures emerged as a solution for accessing deeper marine areas with favorable wind resources, leading to the development of successive generations of conceptual designs, laboratory-scale models, demonstration projects, and commercial-scale floating wind farms. Recent research has consequently moved beyond the development of individual floating platforms toward questions of industrial upscaling, installation and maintenance logistics, supply chain development, integrated offshore infrastructure, and the coupling of renewable electricity with storage and hydrogen production [25,26].

This technological evolution has not occurred uniformly across European marine regions, since the suitability of offshore renewable technologies depends strongly on local environmental conditions, water depth, infrastructure, and industrial capabilities. The North Sea is particularly suitable for large-scale offshore wind development and integrated offshore electricity and hydrogen systems, while the Atlantic margin combines strong wind and wave resources and is therefore well suited to floating wind and combined wind–wave energy concepts. The Mediterranean Sea presents a distinct development pathway, characterized by deep waters close to shore, strong solar resources, and regionally variable wind and wave conditions, which favor floating wind and multi-source hybrid offshore energy systems. The Black Sea represents an emerging offshore renewable energy region with increasing interest in wind–wave exploitation and future floating energy infrastructure, whereas the Baltic Sea requires technology solutions adapted to comparatively sheltered conditions and its specific seasonal wind and wave climate. These differences indicate that the future development of European floating renewable energy should follow region-specific deployment pathways rather than a single technology strategy [27].

At the same time as the development of floating wind platforms, research on the exploitation of wave energy and other marine renewable resources has intensified [28]. Wave energy is considered one of the most concentrated forms of renewable energy, with relatively high predictability compared to wind and solar energies [29]. The coasts of the European Atlantic have high potential for wave energy exploitation, particularly in the regions of Portugal, Ireland, Scotland, and Norway [30].

Following this regional and technological evolution, research has increasingly focused on optimizing hybrid offshore energy systems to improve energy yield, operational flexibility, and infrastructure utilization. By combining complementary renewable resources such as wind, wave, and solar energy on shared floating platforms, these systems can reduce power variability and enhance the continuity of electricity generation [15,16,31,32]. Furthermore, the integration of energy storage, hydrogen production, and offshore energy hubs creates new opportunities for coupling renewable electricity generation with broader energy-system requirements [16,17,33]. In this context, the integration of hydrogen into floating production, storage, and offloading (FPSO) units [34] represents a promising pathway toward sustainable hybrid offshore energy systems.

The implementation of hybrid offshore energy systems also offers important engineering and economic benefits. The shared use of mooring systems, subsea cables, and electrical infrastructure can reduce installation and operating costs while enabling more efficient use of marine space and improved energy production under varying climatic and oceanographic conditions [35–37].

Another important aspect in the development of floating offshore platforms is sustainable design and the impact on the marine environment [38]. The design of modern offshore infrastructure must include considerations regarding reducing the carbon footprint, optimizing material consumption, and minimizing effects on marine ecosystems [39]. In this regard, life-cycle assessment and the application of circular economy principles are becoming essential elements in the development of future offshore technologies [40].

Europe is currently one of the leading regions regarding their research demonstration and commercial deployment of floating renewable energy technologies [41]. Large-scale pilot and demonstration projects in Norway, Portugal, France, and the United Kingdom have confirmed the technical feasibility of floating offshore platforms while supporting the development of industrial supply chains, installation methodologies, and operational experience [42]. In parallel, European policy initiatives and decarbonization targets continue to stimulate investments in offshore renewable energy, integrated energy systems, and emerging technologies such as offshore hydrogen production, reinforcing the strategic role of floating platforms in the European energy transition [43].

Despite the rapid expansion of research on offshore renewable energy, several important knowledge gaps remain in the existing review literature. Most published reviews focus on individual technologies, such as floating offshore wind turbines, wave energy converters, or offshore hydrogen production, while comparatively fewer studies provide an integrated perspective that simultaneously considers floating platform hydrodynamics, hybrid renewable energy systems, regional deployment characteristics across European sea basins, and sustainable design principles. Furthermore, the increasing integration of energy storage, hydrogen production, and offshore energy hubs requires a broader systems-level assessment that reflects the ongoing evolution of offshore renewable energy from single-technology applications toward interconnected multi-source energy infrastructures.

To address these gaps, the present review adopts an integrated perspective that combines hydrodynamic analysis, hybrid renewable energy integration, regional assessment of European marine basins, and sustainable platform design within a unified framework. The review also discusses the technological evolution of floating renewable platforms, highlighting emerging trends related to energy storage, hydrogen production, and multifunctional offshore infrastructures. Accordingly, this paper provides a comprehensive review of European floating structures for hybrid renewable energy systems, with particular emphasis on hydrodynamic behavior, offshore renewable resource potential, platform configurations, and sustainable design principles. Furthermore, it compares the technological evolution and deployment conditions across the main European marine regions—including the North Sea, Atlantic, Mediterranean, Black Sea, and Baltic Sea—to identify region-specific technology pathways, key engineering challenges, energy performance considerations, and future research directions for integrated offshore renewable energy systems.

The paper is structured into six main sections. Following the introduction, Section 2 presents the European offshore context and the potential of renewable resources, analyzing climatic conditions, wave regimes, marine currents, and environmental factors relevant to the development of offshore infrastructure. Section 3 reviews the main types of floating structures used in Europe and their applications within hybrid offshore energy systems.

Section 4 is dedicated to the hydrodynamic behavior of floating structures and the influence of environmental factors on their stability and performance. Section 5 analyzes offshore renewable energy resources and concepts for hybrid offshore energy systems based on the integration of wind, wave, and solar energy. Section 6 highlights the main current challenges and future research directions in the field of floating structures for offshore energy applications. The paper closes with a series of conclusions that summarize the main results and development prospects of these technologies.

2. European Offshore Context and Renewable Energy Potential

European maritime regions represent some of the most favorable areas globally for the development of offshore infrastructure dedicated to renewable energy production. The climatic and oceanographic characteristics of European seas and oceans provide excellent conditions for the exploitation of offshore wind energy, wave energy, and, in certain regions, floating solar energy [5,6]. The diversity of environmental conditions in the Atlantic Ocean, the North Sea, the Baltic Sea, and the Mediterranean Sea directly influences the designs of floating structures, the performances of energy systems, and the hydrodynamic behaviors of offshore platforms [28].

Figure 1, based on data from the EMODnet platform (European Marine Observation and Data Network [44]), illustrates the spatial distribution of ocean energy projects in Europe, highlighting the locations of facilities and experimental sites dedicated to harnessing wave, tidal, and current energy, as well as other types of marine energy. An analysis of the distribution of these projects reveals a significant concentration in Western and Northern Europe, particularly along the coasts of the North Atlantic and the North Sea, reflecting the high energy potential of these regions and the more advanced technological level of the marine energy sector in Europe.

2.1. Climate Conditions and Wave Regimes in European Offshore Areas

The European marine climate is characterized by significant variations in meteorological and oceanographic parameters, depending on the region under analysis. The Atlantic Ocean and the North Sea are dominated by an oceanic climate with strong winds and severe wave regimes, while the Mediterranean Sea exhibits more moderate conditions but with pronounced seasonal variability.

The North Sea is considered one of the most important regions for the development of offshore wind energy due to its high and relatively constant wind speeds [45]. In this region, the average annual wind speed at the height of offshore turbines can exceed 9–10 m/s, favoring high-capacity factors for wind turbines [8]. In addition, the extensive continental shelf and the existence of a developed energy infrastructure have contributed to accelerating the implementation of offshore wind farms in countries such as the United Kingdom, Germany, Denmark, and the Netherlands [40].

The Atlantic Ocean has one of the highest wave energy potentials in the world [29]. The coasts of Portugal, Ireland, and Scotland are exposed to waves generated over long oceanic propagation distances, leading to high values of wave energy flux [30]. Studies on the European wave climate indicate energy densities that can exceed 50–70 kW/m^2 in certain regions of the North Atlantic.

The Mediterranean Sea has a different wave climate compared to the Atlantic, characterized by shorter wave periods and significantly lower wave heights. However, phenomena such as the Mistral, Bora, and Sirocco winds can generate severe storm episodes and significant hydrodynamic loads on offshore structures [8,46]. In the Baltic Sea, oceanographic conditions are more moderate; however, low temperatures and the presence of seasonal ice impose additional requirements regarding structural strength and operational safety [43].

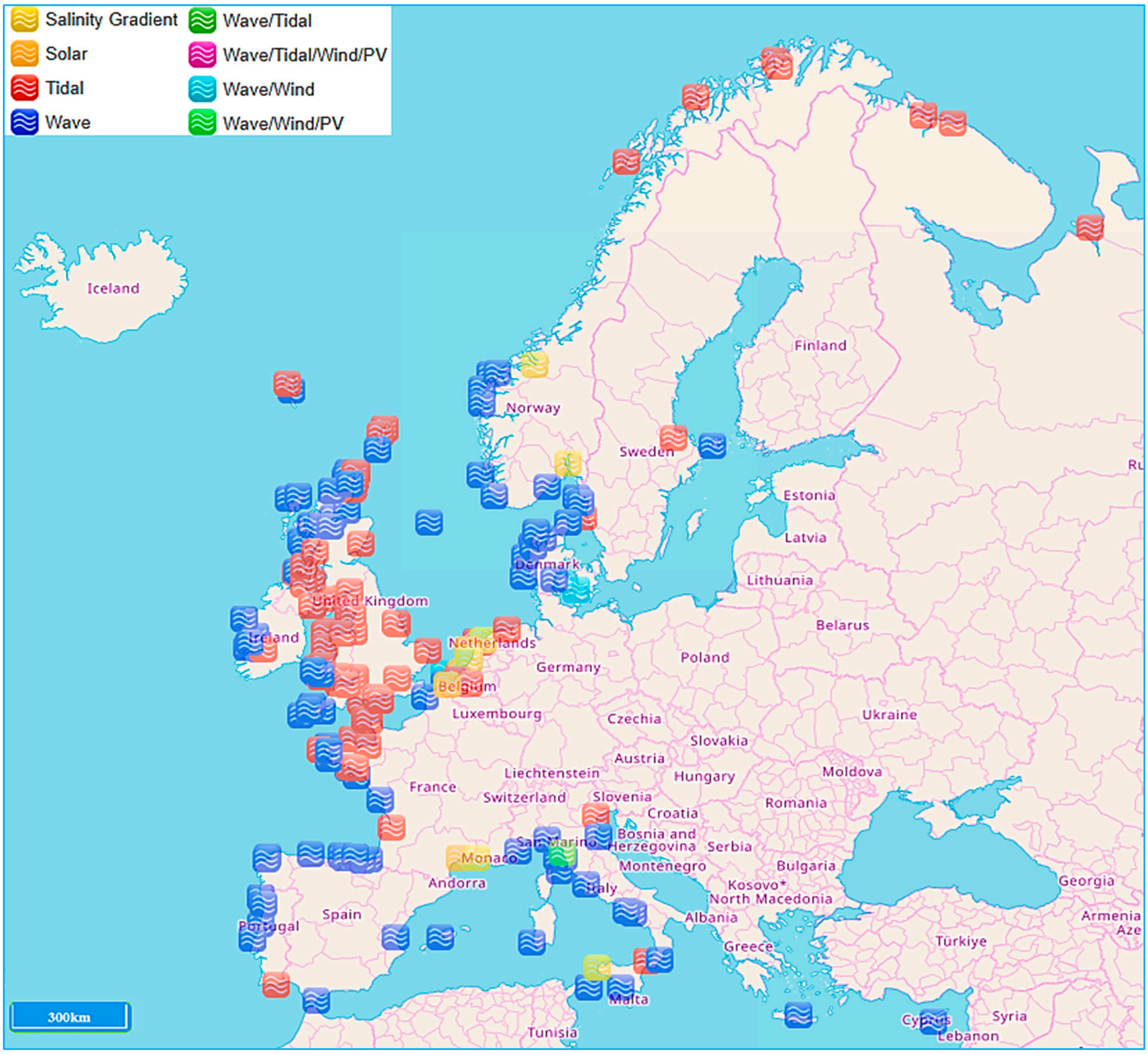


Figure 1. Spatial Overview of Ocean Energy Projects in Europe (Map processed and generated by the authors using the EMODnet platform [44]).

2.2. Marine Currents and Offshore Environmental Conditions

Marine currents influence the stability and performance of offshore floating structures through continuous hydrodynamic actions on mooring systems and floating platforms [13]. In the Atlantic Ocean, ocean circulation is dominated by large-scale currents, such as the North Atlantic Drift, which influence wave energy distribution and regional climatic conditions [47].

In the North Sea and the North Atlantic, the interaction between ocean currents, waves, and wind leads to complex hydrodynamic conditions that must be considered during the design phase of floating platforms [14]. The analysis of metoceanic conditions is an essential step in evaluating structural loads and the dynamic response of offshore systems [20].

Furthermore, seasonal variations in water temperature, salinity, and fluid density influence corrosion processes and the durability of offshore infrastructure [40]. The European marine environment is characterized by conditions that are aggressive to structural materials, which necessitate the use of advanced corrosion protection and structural monitoring solutions [11,48].

2.3. Relevant Offshore Areas for Floating Structures

Offshore floating structures become technically and economically viable in marine areas with water depths greater than approximately 50–60 m [12]. Under such conditions, the fixed foundations used for conventional offshore turbines become difficult to implement and result in high costs [9].

Europe's Atlantic coast is one of the most important regions for the development of floating structures due to the rapid increase in water depth near the shore [41]. Norway, Portugal, and western Scotland have become strategic areas for testing and implementing offshore floating technologies [21].

The North Sea remains the main European hub for offshore wind energy development, but many regions have water depths that favor the transition to floating turbines [10]. At the same time, certain areas of the Mediterranean Sea and the Atlantic Ocean are considered promising for the development of hybrid offshore energy systems due to the favorable combination of wind resources, wave energy, and solar radiation [31].

Besides water depth, the selection of floating platform locations is influenced by several additional factors. Seabed conditions, including sediment characteristics, slope, and geological stability, determine the feasibility of anchoring solutions and the required mooring design. Environmental constraints, such as extreme wind and wave conditions, marine ecosystems, and interactions with existing coastal activities, must also be considered to ensure safe and sustainable operation. Furthermore, installation strategies, including vessel availability, port infrastructure, distance from shore, and maintenance accessibility, play important roles in the economic feasibility of floating projects.

Seabed morphology significantly influences the choice of mooring systems and the stability of floating structures [49]. Areas with soft sediments, steep slopes, or complex underwater topography require advanced design and monitoring solutions for mooring systems [50]. In addition, in regions such as the Mediterranean Sea, where coastal zones often include tourism activities, recreational areas, and major passenger shipping routes, spatial planning constraints may influence the location and configuration of floating structures. These aspects can affect installation procedures, navigation safety, and long-term operational requirements.

FPSO systems are also used in the European offshore sector, particularly in the North Sea, where they are employed in the development of deepwater oil and gas fields. These structures operate under severe meteorological and oceanographic conditions characterized by high waves, strong winds, and complex ocean currents, making them a relevant benchmark for the design of offshore structures. The operational experience gained in this region has contributed to the development of advanced solutions for mooring systems, corrosion protection, and structural reliability assessment. These solutions are directly applicable to the design of floating platforms for renewable energy, where environmental conditions and long-term operational requirements are similar [18,51].

Knowledge transfer between the oil and gas sector and the renewable energy sector is an important factor in the evolution of modern offshore technologies.

To provide a clearer overview of the current development of offshore wind energy across Europe and to support the regional comparison of marine renewable energy resources, Figure 2 presents the spatial distribution of offshore wind farm locations based on data from the European Marine Observation and Data Network (EMODnet) [44]. The map includes operational, approved, planned, under-construction, dismantled, production, and test-site wind energy projects, providing a comprehensive overview of the geographical distribution of offshore wind infrastructure. As shown, offshore wind development is predominantly concentrated in the North Sea, the Baltic Sea, and the Atlantic coastal regions of Western and Northern Europe, where favorable wind conditions, shallow continental shelves, and well-developed infrastructure have enabled large-scale deployment. These regions also represent the most promising areas for the future integration of hybrid renewable energy systems by combining wind energy with wave, tidal, or other marine energy resources. In contrast, the Mediterranean and the Black Sea currently exhibit a lower density of wind farm installations, although both regions have significant long-term potential for floating offshore platforms technologies and hybrid renewable energy systems due to their favorable environmental conditions and increasing technological interest.

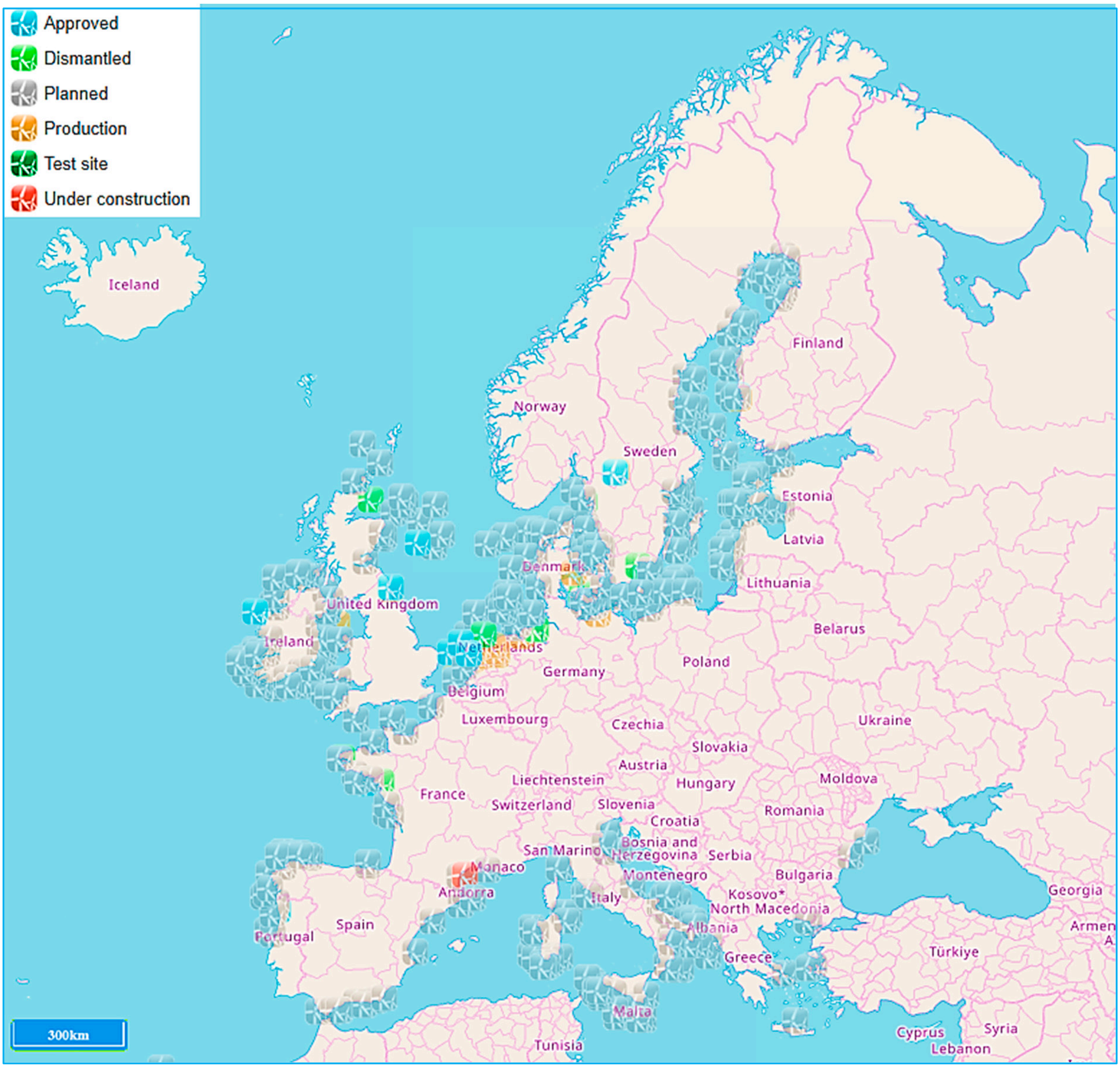


Figure 2. Spatial Overview of Locations of wind farms in Europe (Map processed and generated by the authors using the EMODnet platform [44]).

The spatial distribution presented in Figure 2 provides an important framework for evaluating regional offshore renewable energy potential and future development opportunities.

2.4. Extreme Environmental Events and Structural Stability

Extreme weather events represent one of the main challenges for floating offshore platforms infrastructure [52]. Severe storms in the North Atlantic and the North Sea generate extreme waves, high wind speeds, and significant dynamic loads on offshore structures [53].

During severe storms, significant wave heights can exceed 15–20 m, and long wave periods generate significant structural motions. These conditions can lead to the amplification of structural fatigue phenomena and the deterioration of mooring systems [22].

A relevant example is the European storms of 2013–2014, which produced extreme metoceanic conditions in the North Sea and the North Atlantic, affecting several offshore installations and causing operational disruptions [54]. Furthermore, studies on floating platforms such as Wind Float and Hywind have highlighted the importance of evaluating dynamic response under severe operating conditions [41].

In the Mediterranean Sea, although extreme storms are rarer compared to the Atlantic, episodes of strong winds and short waves with high amplitudes can impose significant loads on floating structures [55].

The performance and long-term reliability of floating offshore platforms are strongly influenced by environmental conditions encountered in the marine environment. Wind, waves, ocean currents, temperature variations, and corrosion processes generate complex loads that affect structural behavior and operational safety. Evaluating these environmental factors is therefore essential for the design, optimization, and maintenance of offshore energy systems. The main environmental parameters influencing floating offshore platforms are summarized in Table 1.

Table 1. Environmental factors affecting offshore floating structures.

Environmental Factor	Structural Impact	Mitigation
Wind	Aerodynamic loading and turbine response	Turbine control systems
Waves	Platform motions and fatigue loads	Motion damping and optimized design
Ocean Currents	Mooring loads and drift forces	Reinforced mooring systems
Water Temperature	Material degradation and corrosion processes	Protective coatings
Salinity	Accelerated corrosion mechanisms	Cathodic protection
Extreme Storms	Increased dynamic loading and structural risk	Extreme-event design criteria

Table 1 illustrates the wide range of environmental factors that influence the behavior of floating offshore platforms throughout their operational life. Among these factors, wave loading and wind forces are generally the dominant contributors to platform motions and structural stresses. Ocean currents, corrosion processes, and temperature variations further affect system reliability and maintenance requirements. The combined action of these environmental parameters must therefore be considered during both the design and operational phases to ensure structural safety, energy efficiency, and long-term durability.

2.5. Offshore Renewable Energy Resources

Europe has significant potential for harnessing offshore renewable energy, particularly in the areas of wind and wave energies [4]. Offshore wind energy is currently the dominant technology in the European marine energy sector due to its technological maturity and high-energy efficiency [56].

In the North Sea, the capacity factors of the offshore turbines frequently exceed 45–50%, values higher than those for the onshore installations [40]. The development of floating turbines allows access to regions with even higher wind resources, located at greater distances from the coast [57].

Wave energy represents an important complementary resource for offshore energy systems [56]. The European Atlantic has some of the highest levels of wave energy flux density, which favors the development of wave energy converters and integrated hybrid offshore energy systems [28].

At the same time, floating solar technologies are beginning to be explored for offshore applications, particularly in southern Europe, where annual solar radiation is high [57]. Integrating photovoltaic panels into offshore platforms can help increase energy flexibility and reduce production variability [58,59].

2.6. Relevance for Hybrid Offshore Energy Systems

The integration of multiple renewable sources on the same floating infrastructure represents one of the most promising directions for the future development of offshore energy [26]. Hybrid offshore energy systems allow for the combination of wind, wave, and solar energy to achieve more stable and efficient power generation [33].

The complementarity of renewable resources helps reduce intermittency and improve the continuity of the energy supply. For example, under certain weather conditions, wave energy production can compensate for reduced wind speeds, helping to stabilize total energy production.

The use of shared infrastructure for multiple energy technologies leads to reduced installation and operating costs, as well as a more efficient use of marine space. Furthermore, hybrid offshore energy systems are considered essential for the development of future maritime energy networks and for supporting the European energy transition [35].

3. Types of European Floating Structures for Hybrid Offshore Energy Systems Applications

The rapid development of offshore energy in Europe has led to a diversification of the types of floating structures used to support renewable energy conversion systems. Depending on water depth, hydrodynamic conditions, and the type of integrated energy technology, several structural configurations have been developed, each with specific advantages and limitations. The main categories include spar platforms, semi-submersibles, tension-leg platforms (TLPs), and barge-type platforms, all of which have subsequently been adapted for applications in wind, wave, and hybrid offshore energy systems [12,60,61].

3.1. Basic Types of Floating Structures

Spar-type platforms are characterized by a low center of gravity and high stability and are frequently used for offshore wind turbines in deep water. These structures exhibit favorable dynamic behavior with respect to rotational motions but are sensitive to heaving motions under extreme wave conditions [12,60].

Semi-submersible platforms represent one of the most flexible solutions, consisting of multiple columns connected by structural beams. They offer good stability and are relatively easy to transport and install, which is why they are widely used in floating wind energy pilot projects in Northern Europe [41,42,61].

TLPs (tension-leg platforms) use tensioned cables for anchoring, which significantly reduces vertical movements. This type of structure is advantageous for applications requiring high stability but involves higher installation and maintenance costs [62].

Barge-type platforms are simple, low-cost structures, but their hydrodynamic performance is more sensitive to wave conditions. They are used primarily in experimental projects or in small-scale hybrid offshore energy systems [18,60,61].

Floating offshore platforms constitute the fundamental support systems for renewable energy technologies operating in deep-water environments. Various platform concepts have been developed to address different hydrodynamic conditions, water depths, and operational requirements. Understanding the characteristics of each platform type is essential for selecting appropriate solutions for offshore wind, wave, and hybrid offshore energy systems applications. Table 2 and Figure 3 present the main types of floating offshore platforms and their key engineering features.

Table 2. Main types of floating offshore platforms.

Platform Type	Main Characteristics	Advantages	Limitations
Spar	Deep draft; low center of gravity	Excellent stability	Complex installation
Semi-submersible	Multiple columns connected by pontoons	Flexible design; easy transport	Larger footprint
Tension-Leg Platform (TLP)	Anchored by tensioned tendons	Reduced heave motion	Higher installation cost
Barge	Shallow draft and simple geometry	Low construction cost	Sensitive to wave action
FPSO	Ship-shaped unit with production and storage systems	High flexibility; large storage capacity	High cost; complex integration

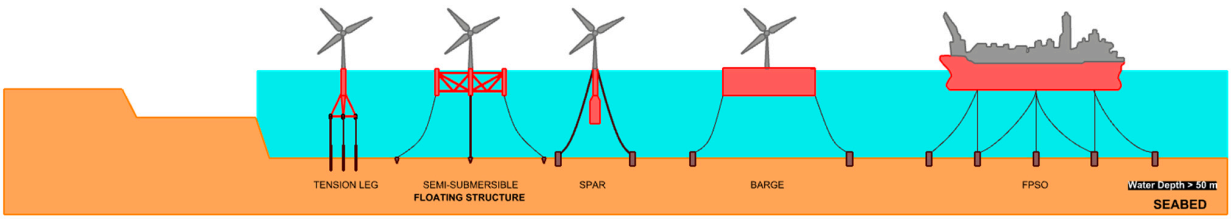


Figure 3. Main types of floating offshore platforms. (Figure designed by the authors based on the reviewed literature).

As shown in Table 2, each floating platform concept exhibits specific advantages depending on the environmental conditions and operational objectives. Spar platforms provide excellent stability in deep-water environments, while semi-submersible structures offer greater flexibility and simplified installation procedures. Tension-leg platforms minimize vertical motions but require more complex mooring systems. Barge-type structures remain attractive due to their simplicity and lower construction costs, although their hydrodynamic performance is generally less favorable. Consequently, platform selection must be based on a comprehensive assessment of site conditions, energy objectives, and economic constraints.

3.2. Distribution of Floating Structures in Europe

In Europe, the development of floating structures is concentrated primarily in regions with high wind potential and deep waters, where fixed foundations are not feasible. The

North Sea region is the main hub for floating offshore wind turbines projects, followed by the North Atlantic and the coastal areas of Norway and Scotland [42,63].

Projects such as Hywind Scotland and Hywind Tampen have demonstrated the viability of floating technologies under real operating conditions, contributing to the sector's technological maturity [39,41]. At the same time, France, Portugal, and Spain have developed pilot projects in the Atlantic, focused on integrating floating wind systems into the national energy mix.

This geographic distribution is closely correlated with European oceanographic conditions, including water depth, wave conditions, and wind intensity, which are essential factors in selecting the type of floating structure [44,61].

3.3. Floating Platforms for Renewable Energy

Modern floating platforms are primarily designed to support offshore wind turbines, but their use has expanded to other forms of renewable energy, including wave energy and offshore solar energy. The integration of these technologies enables increased energy efficiency and optimal use of marine infrastructure.

Floating structures for wind energy must meet strict dynamic stability requirements, as the air–structure–water interaction generates complex effects on the system's behavior. The numerical models used to analyze these structures are based on the coupling between fluid dynamics and structural response and are validated through experimental tests and advanced CFD simulations [21,64,65].

In Europe, most operational floating systems are still in the demonstration or pre-commercialization phase, but the trend toward industrial scaling is growing, supported by European energy policies and private investment [20,36,42].

From a structural and hydrodynamic standpoint, FPSO systems represent a distinct category of floating offshore platforms, characterized by ship-like hulls optimized for the processing and storage of hydrocarbons, rather than for energy conversion. Unlike floating platforms used for offshore wind energy, such as spar, semi-submersible, or TLP configurations, FPSOs are designed for continuous industrial operations under long-term operating conditions. However, both types of systems present similar engineering challenges, such as hydrodynamic response, mooring system design, fatigue stresses, and stability under extreme environmental conditions. For this reason, FPSOs can be considered precursor technology for modern floating structures used in hybrid offshore energy systems, providing an important foundation of engineering and operational experience [18,66]. The similarity in hydrodynamic behavior and structural stress highlights the continuity of offshore technology evolution from the oil industry to the renewable energy sector.

The practical implementation of floating offshore platforms technologies in European waters has led to the emergence of a wide variety of platform designs adapted to different water depths, environmental conditions, and operational requirements. Current floating renewable energy projects are primarily based on spar, semi-submersible, barge-type, and tension-leg platform concepts, each offering specific advantages in terms of stability, installation strategy, hydrodynamic performance, and scalability. The preliminary design and optimization of floating support structures require integrated numerical approaches capable of evaluating hydrodynamic behavior, structural response, and operational constraints during different development stages [67]. The choice of floating platform configuration is strongly influenced by the interaction between aerodynamic loads, hydrodynamic response, structural behavior, and position-keeping requirements. Representative European floating structures, currently under development or in operation, are presented in Table 3 [42,60,61,68].

Table 3. Representative European floating structures and their mooring systems.

Platform	Location	Platform Type	Mooring System	Water Depth (m)	Capacity/ Production	Status	Key Features
Hywind Scotland	Scotland, UK	Spar	Three-point catenary chain	95–120	30 MW	Operational	First commercial floating offshore wind turbines farm; excellent hydrodynamic stability
Hywind Tampen	Norwegian North Sea	Spar	Catenary chain	260–300	88 MW	Operational	Supplies renewable electricity to Snorre and Gullfaks platforms; reduced CO_2 emissions
WindFloat Atlantic	Portugal	Semi-submersible	Catenary chain	~100	25 MW	Operational	Modular steel structure; tow-to-port maintenance; no heavy-lift installation required
Kincardine Offshore Wind Farm	Scotland, UK	Semi-submersible	Catenary chain	60–80	50 MW	Operational	One of Europe's largest floating wind farms; commercial-scale deployment
Floatgen	Le Croisic, France	Barge	Catenary chain	~33	2 MW	Demonstration	First floating offshore wind turbines in France; concrete floating foundation
TetraSpar Demo	Norway	Tetrahedral spar	Catenary chain	~200	3.6 MW	Demonstration	Modular steel design enabling cost-effective manufacturing and transport
Goliat FPSO	Barents Sea, Norway	Circular FPSO	Internal turret mooring	360–420	100,000 bbl/day	Operational	Designed for Arctic conditions; high station-keeping capability; disconnectable turret
Johan Castberg FPSO	Barents Sea, Norway	Ship-shaped FPSO	Internal turret mooring	360–390	220,000 bbl/day	Operational	High-production Arctic FPSO with advanced safety and environmental systems

The projects presented in Table 3 demonstrate the technological diversity and growing maturity of floating renewable platforms systems in Europe. Spar-type platforms, such as Hywind Scotland and Hywind Tampen, offer excellent stability characteristics due to their deep draft and low center of gravity, making them suitable for deep-water applications. In contrast, semi-submersible concepts, such as WindFloat Atlantic and Kincardine, offer greater flexibility in terms of manufacturing, transport, and installation, which is a significant advantage for future large-scale deployments. These characteristics explain the growing interest in semi-submersible solutions for regions where water depths exceed the economic limits of fixed-bottom offshore wind foundations [42,61,69–71].

Although FPSO units are not designed as renewable energy converters, the operational experience gained from their use provides valuable insights for the development of future multifunctional floating energy platforms. The Goliat and Johan Castberg FPSOs demonstrate the ability of floating systems to operate under extreme offshore conditions, where environmental stresses, material fatigue, and position-keeping requirements pose major engineering challenges. The methodologies developed for the hydrodynamic analysis of FPSO platforms, the design of mooring systems, and the assessment of structural reliability can support the future integration of renewable energy technologies, hydrogen production, and energy storage solutions within floating offshore platforms infrastructures [18,19,66]. Mooring systems represent a critical component of floating platform design, directly influencing station-keeping performance, structural loads, fatigue behavior, and operational reliability. The selection of the mooring configuration depends on water depth, environmental conditions, platform characteristics, and installation requirements. Catenary mooring systems remain the dominant solution for European floating wind projects due to their technological maturity and proven offshore performance. However, the transition toward deeper waters and larger turbines has increased interest in alternative solutions, including taut-leg, tension-leg, and optimized mooring configurations, aiming to reduce material consumption, improve dynamic response, and enhance economic competitiveness [68,72,73].

3.4. Multifunctional Floating Structures (Hybrid Offshore Energy Systems)

An emerging trend in offshore engineering is the development of multifunctional platforms capable of integrating multiple energy conversion technologies onto a single structure. These offshore energy systems typically combine offshore wind energy with wave energy and, in some cases, with solar photovoltaic energy [31,32,58].

The main advantage of these configurations lies in the complementarity of energy resources, which reduces production variability and increases the system's overall capacity factor. Recent studies show that the integration of hybrid offshore energy systems can significantly improve energy stability and economic efficiency of offshore projects [31,33,36].

From a structural standpoint, these platforms require advanced design, as they must simultaneously withstand aerodynamic, hydrodynamic, and dynamic loads generated by multiple energy systems. This complexity necessitates the use of coupled aero-hydro-elastic simulation models [64,65].

3.5. Integration of Multiple Energy Technologies

The integration of multiple technologies on floating platforms represents one of the most promising directions for the development of offshore energy. Hybrid offshore energy systems enable the efficient use of shared infrastructure, reduce installation and operating costs, and minimize the impact on the marine environment [31,35,36].

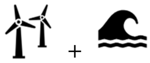
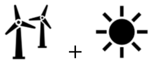
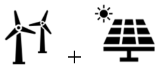
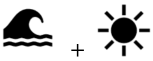
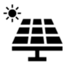
However, integrating these technologies poses significant challenges for structural stability, layout optimization, and energy system control. Interactions between energy components can generate complex dynamic effects that must be taken into account as early as the design phase [33,37,48].

In the European context, the development of these systems is supported by strategic initiatives promoting hybrid offshore wind turbines farms capable of combining wind, wave, and solar energy production into a single integrated energy ecosystem [35,36,42]. The diversification of floating structure types and the shift toward hybrid offshore energy systems represent an essential step in the European energy transition, offering flexible and efficient solutions for harnessing renewable marine resources.

The development of hybrid offshore energy systems has generated a wide variety of platform configurations combining multiple renewable energy technologies. Each configuration presents distinct advantages and limitations in terms of energy production, structural complexity, operational stability, and economic performance. A comparative overview of the main hybrid offshore energy concepts is therefore necessary to identify the most promising solutions for future large-scale deployment. The principal characteristics of the most common hybrid offshore energy systems configurations are summarized in Table 4.

The comparison presented in Table 4 highlights the diversity of hybrid offshore energy systems concepts currently under development. Wind–wave systems appear to be the most mature solutions due to the complementary nature of the two resources and the relatively advanced technological readiness of both conversion technologies. Configurations integrating solar energy offer additional flexibility, particularly in regions characterized by high solar irradiation. However, increasing the number of integrated technologies also increases structural complexity and operational requirements. Overall, hybrid offshore energy systems demonstrate significant potential for improving energy production stability and maximizing the utilization of offshore infrastructure.

Table 4. Comparison of hybrid offshore energy systems configuration.

Configuration	Technologies Integrated	Main Benefits	Main Challenges
	 + WECs	Resource complementarity	Coupled hydrodynamic interactions
		Increased energy production	Space allocation and maintenance
	WECs + 	Improved utilization of the marine area	Lower technological maturity
	Integrated hybrid offshore energy systems	Maximum resource utilization	High design and control complexity

To integrate hybrid offshore energy systems on a large scale, there is also a need to develop an electrical infrastructure capable of collecting and transmitting the energy generated by multiple renewable sources. In this context, Floating Offshore Substations (FOSS) represent a promising solution for deep-water locations where the use of fixed substations is technically and economically difficult or unfeasible. These platforms enable the collection of energy generated by floating wind turbines, wave energy converters, and other marine technologies, performing voltage transformation and transmitting the energy to the power grid via dynamic subsea cables [16,74]. The main advantages of floating offshore substations are the reduction in the length of intermediate cables, the optimization of offshore grid architecture, and increased flexibility in the development of floating power parks. In addition, they facilitate the expansion of projects into areas with wind and marine resources located farther from shore and at depths that exceed the limits of conventional fixed structures. In terms of significant technical challenges, the platform's movements caused by waves and wind affect the operation of high-voltage electrical equipment, and the interaction between the floating structure, the mooring system, and the dynamic power cables requires complex coupled analyses [16].

4. Hydrodynamic Behavior of Floating Structures

The hydrodynamic behavior of floating structures is a fundamental aspect of designing offshore renewable energy systems, particularly for platforms intended for hybrid applications that integrate multiple energy resources. Different from fixed offshore structures, floating platforms are dynamic structures that are constantly exposed to the combined effects of waves, wind, ocean currents, and the mooring system. Furthermore, in the case of floating wind turbines and hybrid offshore energy systems, the hydrodynamic response affects not only structural integrity but also energy performance. Hence, the hydrodynamic analysis of floating structures is an essential component of marine energy system design [68,75,76].

In the context of the European energy transition, demand for such systems has grown rapidly, as they offer a technological solution for the optimized exploitation of energy resources in the North Sea, the Mediterranean Sea, the Black Sea, and other European maritime regions [77–80]. In Europe, the development of floating structures has been accelerated by a series of demonstration projects. Various platform concepts have been tested and validated under real operating conditions. Some examples are WindFloat Atlantic in Portugal, based on semi-submersible platforms [69], Hywind Scotland in the North Sea, which uses spar-type substructures [70], the Kincardine Offshore Wind Farm in Scotland, also on semi-submersible platforms [71], DemoSATH in Spain [81], the TetraSpar

Demonstrator in Norway [82], and Provence Grand Large in France, based on a tension-leg solution [83]. These demonstration projects show that hydrodynamic design must be adapted to the type of platform, site conditions, and the method of integrating multiple energy sources.

Therefore, hydrodynamic behavior is determined by several factors, such as the interaction between the platform's geometry, mass distribution, and the anchoring system's characteristics, as well as environmental conditions. This behavior can be evaluated through wave–structure interaction analysis, using numerical and experimental methods, and by verifying stability, limit states, and structural durability.

4.1. Wave–Structure Interaction

Wave–structure interaction depends on how waves generate forces and moments on a floating structure, as well as the way the structure modifies the propagation of waves around it. For offshore floating platforms, it is a key factor that impacts the structure's overall motion, the loads transmitted to structural members, and the operating conditions of the power generation systems.

Platform geometry (Table 5) influences the hydrodynamic response of the floating structure, affecting its buoyancy, stability, motion amplitudes, and the loads transmitted to the mooring system [84]. For offshore renewable energy systems, specifically hybrid offshore energy systems configurations, deciding on the type of platform depends on water depth, wave conditions, turbine power, installation strategy, operating and maintenance costs, as well as the potential for integrating additional technologies, such as wave energy converters or other complementary energy subsystems [85].

Table 5. Influence of platform type on wave–structure interaction in floating offshore platforms.

Platform Type	Geometry	Wave–Structure Interaction	Hybrid Offshore Energy Systems Integration
Spar	• Slender cylindrical hull • Deep draft • Ballast concentrated in the lower section • Relatively small waterplane area	• Reduced sensitivity to surface wave excitation due to deep draft • Low heave, pitch, and roll response • Favourable hydrodynamic behaviour in deep-water conditions	• Well-suited for deep-water applications and large wind turbines • Limited deck/platform area for the integration of WECs or floating PV systems • Hybridisation is feasible, but less flexible than for broader platform concepts
Semi-submersible	• Multiple vertical columns • Moderate draft • Large waterplane area • Distributed buoyancy over several floaters	• Wave-induced response strongly depends on column arrangement, spacing, and pontoon geometry • Moderate to high sensitivity in pitch, roll, and heave, depending on hull proportions and mass distribution • Coupled response is strongly influenced by mooring stiffness and platform layout	• High suitability for hybrid concepts due to geometric flexibility and available deck area • Favourable for the integration of WECs, floating PV, and auxiliary energy modules • Requires hydrodynamic and mooring optimization to control motions and line loads

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Table 5. *Cont.*

Platform Type	Geometry	Wave–Structure Interaction	Hybrid Offshore Energy Systems Integration
Tension-Leg Platform (TLP)	• High-buoyancy floating structure • Excess buoyancy is offset by the pre-tensioning of the cables • High vertical restoring stiffness	• The response to vertical motion is significantly reduced by the stiffness of the cables • Pitch and roll motions are smaller than in catenary-anchored designs • The hydrodynamic response is determined by the coupled behavior of the ship's hull, the cables, and the mooring system	• Suitable for pitch-sensitive turbines and high-performance power generation • The integration of additional equipment must be evaluated in relation to the loads exerted on the cables, the buoyancy allowance, and overall stability
Barge	• Wide hull form • Shallow draft • Large waterplane area • Buoyancy concentrated near the free surface	• Strong interaction with surface waves due to shallow draft and large waterplane area • Increased sensitivity to wave excitation, particularly in pitch and roll • More exposed to wave-induced motions than deep-draft concepts	• Svailable area for layouts combining WECs and floating PV • Attractive for demonstrators and multi-use hybrid platforms • Additional motion-control measures may be required to maintain acceptable operational performance

Table 5 summarizes the main characteristics of floating platforms used in offshore renewable energy systems, highlighting the relationship between their geometry, response to wave action, and potential for integration into hybrid offshore energy systems configurations. Each type of platform involves a compromise between stability, cost, technological complexity, and compatibility with various site conditions. Spar and TLPs tend to offer better control of motions due to their deep draft and the rigidity of their moorings, while semi-submersible and barge platforms are more sensitive to the geometry of the floating surface and to wave-induced excitation. At the same time, platforms with a larger available surface area, such as semi-submersible and barge-type platforms, offer greater potential for integrating additional technologies, such as wave energy converters or photovoltaic panels.

4.2. Hydrodynamic Analysis, Stability, and Structural Design of Floating Structures

The hydrodynamic evaluation of floating platforms involves a multi-level approach, where the analysis relies on a set of numerical and experimental methods, used in a complementary manner depending on the project phase. In the preliminary design stages, methods based on potential theory and frequency-domain analysis are typically applied, as they allow for the quick estimation of hydrodynamic coefficients, excitation forces, added masses, radiation damping, and response amplitude operators (RAOs). These results provide an initial overview of the overall response of the platform for comparing different floating platform concepts [76,84,86].

For hybrid offshore energy systems, time-domain coupled simulations that simultaneously integrate hydrodynamic, aerodynamic, structural, mooring system, and control system effects supplement these approaches. Such models provide an assessment of motions, accelerations, loads on the moorings, and the response of the dynamic cables under rough sea conditions [68,76,86].

In the case of flexible structural elements and components, where viscous effects become significant, Morison-type models or hybrid approaches are used, combining potential theory for the main body of the platform with inertial and resistance formulations for the mooring cables. CFD simulations and experimental tests are used to investigate local nonlinear phenomena, such as wave surges, wave impacts, green water, or complex interactions between multiple floating bodies. Consequently, the hydrodynamic analysis of a floating platform is not constrained to a single method and is carried out in a phased framework, using simplified models for concept selection and estimation of the overall response, while high-fidelity models are subsequently introduced to refine the solution and validate the design assumptions [76,85].

Table 6 presents a comparison of hydrodynamic analysis methods, emphasizing the main components of the evaluation process, the parameters under consideration, and their relevance to hybrid offshore energy systems.

Table 6. Key Elements of Hydrodynamic Analysis and Design Verification of Floating Structures.

Component	Main Purpose	Outputs	Relevance for Hybrid Offshore Energy Systems
Frequency-domain hydrodynamic analysis (potential flow/BEM)	• Preliminary assessment of global wave-induced response • Derivation of hydrodynamic coefficients for concept evaluation	• Added mass • Radiation damping • Wave excitation forces • RAOs/natural periods	• Provides hydrodynamic input for coupled simulations • Supports concept selection
Coupled time-domain analysis	• Assessment of the global response • Evaluation of platform behaviour in irregular environmental conditions	• 6-DOF motions • Platform accelerations • Mooring and cable loads	• Essential for hybrid offshore energy systems, where motions affect both structural loading and energy performance • Captures the coupled platform–mooring–turbine response
Morison-based/hybrid viscous models	• Representation of viscous loading on slender members and mooring components • Inclusion of local drag and inertia effects	• Drag and inertia forces • Viscous damping • Local member loads	• Relevant for mooring lines • Improves local load prediction
CFD and experimental testing	• Investigation of nonlinear local hydrodynamic phenomena • Validation and refinement of numerical models	• Verification of hydrostatic restoring capability • Assessment of motion compatibility with platform operation	• Required for complex hybrid layouts and multi-body interactions • Supports model calibration
Static and dynamic stability assessment	• Verification of hydrostatic capability • Assessment of motion compatibility with platform operation	• GM (metacentric height) • GZ curves (righting arm curves) • Pitch/roll/heave limits	• Checks whether the integration of WECs, PV modules, or auxiliary systems affects platform stability • Supports the assessment of restoring performance

Table 6. *Cont.*

Component	Main Purpose	Outputs	Relevance for Hybrid Offshore Energy Systems
Limit-state verification (ULS, FLS, ALS, SLS)	• Assessment of structural response under extreme, cyclic, accidental, and operational conditions • Verification of safety and serviceability throughout the design life	• Fatigue life • Motion/acceleration limits	• Critical for integrated hybrid offshore energy systems, where additional devices may increase mass, inertia, and load interaction • Supports the structural verification of the overall system
Structural durability and mooring integrity	• Long-term assessment of structural reliability and mooring performance • Evaluation of degradation under cyclic loading and marine exposure	• Fatigue damage • Cyclic mooring loads • Corrosion/cable motions	• Governs long-term reliability and lifecycle performance • Supports the design of durable mooring and cable systems

Apart from choosing the analysis method, the hydrodynamic behavior of a floating structure must be evaluated in close relation to the criteria governing both static and dynamic stability. Its stability depends on the relative positions of the center of gravity, the center of buoyancy, and the metacenter, as well as on characteristic parameters such as the metacentric height and the righting lever curves. The evaluation of these elements allows for the determination of the structure's ability to maintain its equilibrium and return to its initial position in the event of external disturbances.

In the case of floating renewable energy platforms, stability must be verified not only for the platform but also for the dynamic response, taking into account the operation of the turbine, wave energy converters, dynamic cables, and other energy subsystems. A platform with high righting capacity can limit tilts but may generate shorter natural periods and higher accelerations, which can have negative effects on structural response, fatigue, and energy performance [68,87–90]. In addition, the integration of additional devices can alter the mass distribution, the position of the center of gravity, the moments of inertia, and the way loads are transferred within the structural assembly.

In practice, structural verification is performed for the main limit states: Ultimate Limit State (ULS), Fatigue Limit State (FLS), Accidental Limit State (ALS), and Serviceability Limit State (SLS). ULS assesses the structure's resistance to extreme loads and aims to prevent collapse or loss of overall stability. FLS evaluates the cumulative damage caused by cyclic loads. ALS addresses accident scenarios, such as the failure of an anchor line or local loss of buoyancy, and SLS establishes the limits of motion, acceleration, and deformation compatible with the platform's normal operation [68,87–90].

Wave-induced motions, cyclic loads on moorings and cables, and continuous exposure to the marine environment led to the accumulation of fatigue damage, corrosion, and biofouling, affecting the system's reliability and operating costs. Therefore, the design of a floating structure cannot be limited to estimating instantaneous motions and loads only, and must include an assessment of fatigue life, the integrity of the moorings, and inspection and maintenance requirements.

4.3. Hydrodynamic Coupling in Hybrid Offshore Energy Systems

The dynamic response of hybrid offshore energy systems is driven by the simultaneous interaction of wind, waves, ocean currents, the mooring system, and energy conversion equipment. In contrast to conventional floating platforms designed exclusively for wind turbines, hybrid configurations integrate two or more energy conversion technologies, such as wind turbines, wave energy converters (WECs), floating photovoltaic systems, and, in some cases, tidal energy converters. As a result, the platform's motions are no longer influenced only by the hydrodynamic response of the floating body, but also by the interactions between the energy subsystems, leading to complex aero-hydro-servo-elastic coupling [91,92] and changes in the load distribution on the structure and the mooring system.

Studies based on coupled numerical models [92] highlight that wave energy conversion devices can serve a dual role in hybrid offshore energy systems, operating both as energy-generation systems and as hydrodynamic damping mechanisms. By modifying the damping characteristics and the dynamic response of the platform, they can reduce motions, redistribute loads within the mooring system, and improve not only the operational stability but also the total energy output of the integrated system.

These mechanisms need to be considered in relation to limit state checks and possible failure scenarios, such as overloading of mooring lines, fatigue of dynamic electrical cables, excessive platform movements, or mechanical interference between various power generation equipment. The main effects of hydrodynamic coupling and their implications for the design of hybrid offshore energy systems are summarized in Table 7. Analysis shows that these coupling mechanisms simultaneously influence the platform's dynamic response, the behavior of the mooring system, the integrity of the dynamic electrical cables, and the system's energy efficiency, and are essential for the design and reliability assessment of hybrid offshore energy systems.

Table 7. Main hydrodynamic coupling effects of floating structures.

Coupled Interaction	Main Hydrodynamic Effects	Design Implications	Potential Failure Risks
Wind turbine—floating platform	• Increased surge, pitch, and yaw motions • Aerodynamic–hydrodynamic interaction • Modified natural periods	• Increased tower-base loads • Reduced aerodynamic efficiency • Higher structural fatigue	• Tower fatigue • Excessive platform inclination • Turbine shutdown
Wave energy converter—floating platform	• Modified added mass and radiation damping • Altered wave-induced motions • Additional dynamic loading	• Changes in platform response • Increased loads on structural connections • Influence on power capture	• PTO overload • Joint fatigue • Mechanical damage
Floating PV—floating platform	• Increased topside mass • Modified centre of gravity • Larger wind-exposed area	• Reduced stability margin • Increased overturning moment • Higher deck loads	• Excessive heel • Structural overstressing • PV module damage

Table 7. *Cont.*

Coupled Interaction	Main Hydrodynamic Effects	Design Implications	Potential Failure Risks
Ocean current turbine—floating platform	• Additional hydrodynamic thrust • Increased drag forces • Asymmetric loading	• Increased mooring loads • Modified platform offset • Additional structural loading	• Mooring overload • Support structure fatigue • Station-keeping degradation
Platform—mooring system	• Nonlinear restoring forces • Cyclic line loading • Load redistribution	• Station-keeping performance • Increased fatigue accumulation • Reduced structural reliability	• Mooring line fatigue • Line failure • Excessive platform offset
Platform—dynamic power cable	• Cyclic bending and tension • Cable curvature variation • Touchdown point movement	• Reduced cable service life • Higher maintenance requirements • Electrical connection reliability	• Cable fatigue • Cable rupture • Loss of power transmission
Combined multi-device interaction	• Coupled aero–hydro–servo–elastic response • Load redistribution • Motion amplification or attenuation	• Complex dynamic behaviour • Interaction between energy subsystems • Need for integrated numerical analysis	• Excessive structural response • Reduced energy production • Reduced system availability

Therefore, the evaluation of hybrid offshore energy systems requires a fully coupled approach capable of capturing the interactions between the energy subsystems and their effects on the hydrodynamic response, structural behavior, and system reliability, representing an essential step toward optimizing the design and ensuring the safe implementation of these platforms under the specific conditions of the European offshore environment.

5. Offshore Renewable Energy Resources and Hybrid Offshore Energy Systems Concepts

5.1. Energy Potential Assessment in Europe

Along with the development and growing demand for renewable energy, the offshore industry exploiting marine resources has expanded. Hybrid offshore energy systems are among the most promising approaches for the simultaneous exploitation of waves, wind, and solar energy. The complementary nature of marine energy resources can also lead to more stable and predictable energy production, compensating for the variations inherent in each source. Furthermore, these technologies are being promoted by European strategies on offshore renewable energy, which aim to expand clean energy generation capacity and harness the significant potential of Europe's maritime basins to achieve climate neutrality goals [93].

Europe offers promising prospects for the development of renewable energy [5,94,95], given the diversity of available energy resources and the specific climatic conditions of the various maritime basins within its borders. The regions with the highest energy potential are the North Sea, the Baltic Sea, the Mediterranean Sea, and the Black Sea, each offering favorable conditions for exploiting renewable marine energy. The Baltic Sea and the North Sea offer both high wind energy potential and significant wave energy resources [96–98], while the Mediterranean Sea and the Black Sea [78,99–101] provide opportunities to develop hybrid offshore energy systems based on wind, wave, and solar resources.

Notably, the North Sea is Europe's leading hub for offshore wind energy development, benefiting from high and relatively constant wind speeds, moderate water depths, and a mature energy infrastructure [102,103]. According to recent studies, offshore renewable technologies will play a major role in the future of the North Sea's energy system by integrating wind power, green hydrogen, and other innovative energy storage and conversion solutions [96]. Furthermore, analyses conducted for the Baltic Sea and the Danish part of the North Sea have highlighted the existence of significant wave energy resources, with favorable prospects for the development of marine energy conversion technologies and their integration into hybrid offshore energy systems [97].

In Southern and Eastern Europe, although the Mediterranean Sea and the Black Sea have different conditions from the North Sea, their advantages are significant for the development of hybrid offshore energy systems [104]. High levels of solar radiation, moderate wind conditions, and the occurrence of deep-water areas located close to the coast provide favorable conditions for integrating offshore wind energy with solar energy and, in some areas, with wave energy [80].

The Black Sea's strategic location within the transport corridor connecting the Danube Basin to the North Sea via the Rhine–Main–Danube system highlights its economic and energy significance in the context of maritime infrastructure development and the transition to low-carbon energy sources [105]. The region's strategic importance is also reflected in the growing number of European initiatives and projects dedicated to the development of renewable energy in the Black Sea basin. These programs aim to harness offshore wind potential, integrate innovative wave energy technologies, and strengthen regional cooperation to promote the deployment of sustainable energy infrastructure, helping to meet the European Union's goals for energy security and climate neutrality [106].

Long-term climate projections [107,108] indicate that wind energy resources in the Black Sea coastal region will continue to have high development potential in the coming decades, which provides an additional level of confidence for investments in offshore infrastructure, as well as in hybrid offshore energy systems based on wind and wave energy. Furthermore, climate assessments conducted for a 30-year projection of the future wind energy resources [108] suggest that the Black Sea will remain competitive from an energy perspective, reinforcing the opportunity to implement floating hybrid offshore energy systems that combine wind energy with wave energy and other marine renewable sources.

5.2. Offshore Renewable Energy Sources

Hybrid offshore energy systems concepts are designed to integrate multiple sources of renewable energy available in the marine environment to increase total energy production and minimize the variability inherent in each resource. The approach is based on the use of a shared infrastructure that allows for the simultaneous exploitation of various energy resources, leading to lower costs associated with installation, operation, and maintenance. Moreover, the complementarity across the different energy resources available in the marine environment enhances the continuity of energy production and increases the overall efficiency of the system [85].

The main sources commonly used nowadays are offshore wind energy, wave energy, floating solar energy, and ocean current energy, and their key features are presented in Table 8.

Table 8. Key features of offshore renewable energy sources.

Key Feature	Offshore Wind Energy	Wave Energy	Floating Solar Energy	Ocean Current Energy
Technology	Fixed-bottom or floating wind turbines	Wave Energy Converters (WECs)	Floating photovoltaic panels	Marine current turbines
Technology maturity	High	Medium	Medium–High	Low–Medium
Development status in Europe	Commercial deployment	Demonstration stage	Early commercial deployment	Demonstration stage
Resource potential in Europe	Very high	High	Moderate	High
Operating water depth	>60–100 m (floating platforms)	>20–50 m	>20–100 m	>30–200 m
Compatibility with floating platforms	High	High	High	Medium–High
Energy density	High	High	Moderate	High
Temporal variability	Moderate	Low	High	Very low
Space requirements	Moderate	Low	High	Moderate
Maintenance requirements	Moderate	High	Low	High
Main advantages	• Abundant resources • Mature technology	• Complementary to wind energy • High energy density	• Modular design • Rapid deployment	• Predictable resources • High energy density
Main limitations	• Wind intermittency • High initial investment costs	• Technology still under development • High implementation costs	• Daytime-only generation • Sensitivity to weather conditions	• Early-stage technology • High installation costs
Complementarity with other resources	High	High	High	High
Role in hybrid offshore energy systems	Primary energy generation source	Production stabilization and fluctuation reduction	Diversification of the energy profile and increased platform utilization	Supplementary predictable power generation

Currently, offshore wind energy is the most advanced and widely used technology for generating renewable energy in the marine environment. Enjoying a high level of technological and commercial maturity, it represents one of the main areas of development in the marine energy sector [31,96,109]. Compared to onshore wind farms, offshore turbines operate under higher, more consistent wind speeds, lower turbulence, and greater energy availability. These advantages lead to increased energy production and more favorable capacity factors than are recorded for onshore wind farms. The development of floating technologies has enabled expansion into areas with depths greater than 60 m, where installing fixed foundations is technically and economically challenging [96,110].

Wave energy is a complementary resource to wind energy due to the marine environment's inertia, which allows waves to retain their energy over longer periods. These characteristics help reduce the power fluctuations typical of wind energy and contribute to increased stability and reliability in hybrid offshore energy systems. Integrating wave energy converters with wind turbines [111,112] can lead to a more efficient use of shared infrastructure and improve the overall energy performance of offshore installations. Studies on the dynamics of wind and wave energy resources in the Mediterranean Sea and the Black Sea [101] show that these regions provide suitable conditions for the development of hybrid offshore energy systems based on the integration of wind and wave energy, with significant potential for further expansion into multi-source configurations.

In recent years, floating renewable platforms for solar power generation systems have gained increasing popularity as a solution for renewable energy production in the marine environment [58,113]. The installation of photovoltaic panels on floating platforms allows efficient use of available marine areas and enhances the usage of existing offshore infrastructure. Furthermore, the complementarity between solar and wind energy contributes to the diversification of the energy production profile, as periods of high solar radiation do not always coincide with periods of high wind speeds [109,114].

Ocean current energy is an emerging technology that relies on converting the kinetic energy of ocean currents using hydrokinetic turbines installed below the water's surface. As opposed to other types of renewable energy, it is highly predictable, which makes it a suitable complementary resource for hybrid offshore energy systems [115,116]. The development of this energy source for power generation is still limited due to the main challenges associated with high installation costs, difficult operating conditions, and the need for robust mooring and maintenance systems. At the European level, energy generated by ocean currents could meet approximately 10% of the region's electricity demand by 2050 [117], despite the challenges encountered. The greatest potential in Europe lies in the North Atlantic, around the British Isles [118], as well as in other regions known for high-speed ocean currents, such as the northern coasts of France [119].

Comparing the main offshore renewable energy sources highlights that each technology has specific advantages and limitations in technological maturity, energy density, and temporal variability. One of the main factors driving the development of hybrid offshore energy systems is the complementarity of renewable energy sources. In the North Atlantic and North Sea regions [117,120,121], wind and wave energy generally peak during the cold season, whereas floating photovoltaic system output is higher during the summer. At the same time, ocean current energy is highly predictable and exhibits lower variability compared to other sources, helping to reduce fluctuations in total output and increase the stability of hybrid offshore energy systems.

The main advantage of these systems consists of the time complementarity of renewable resources, which allows for compensation of fluctuations specific to each source and results in more stable energy production. The integration of wind, waves, and solar energy contributes to reducing intermittency, increasing the capacity factor, and improving the reliability of the offshore energy system, as illustrated in Figure 4.

The analysis of the complementarity among offshore renewable resources highlights the importance of integrating wind, wave, and solar energy into floating hybrid offshore energy systems, which can bring many benefits in terms of energy, operations, economics, and the power system overall.

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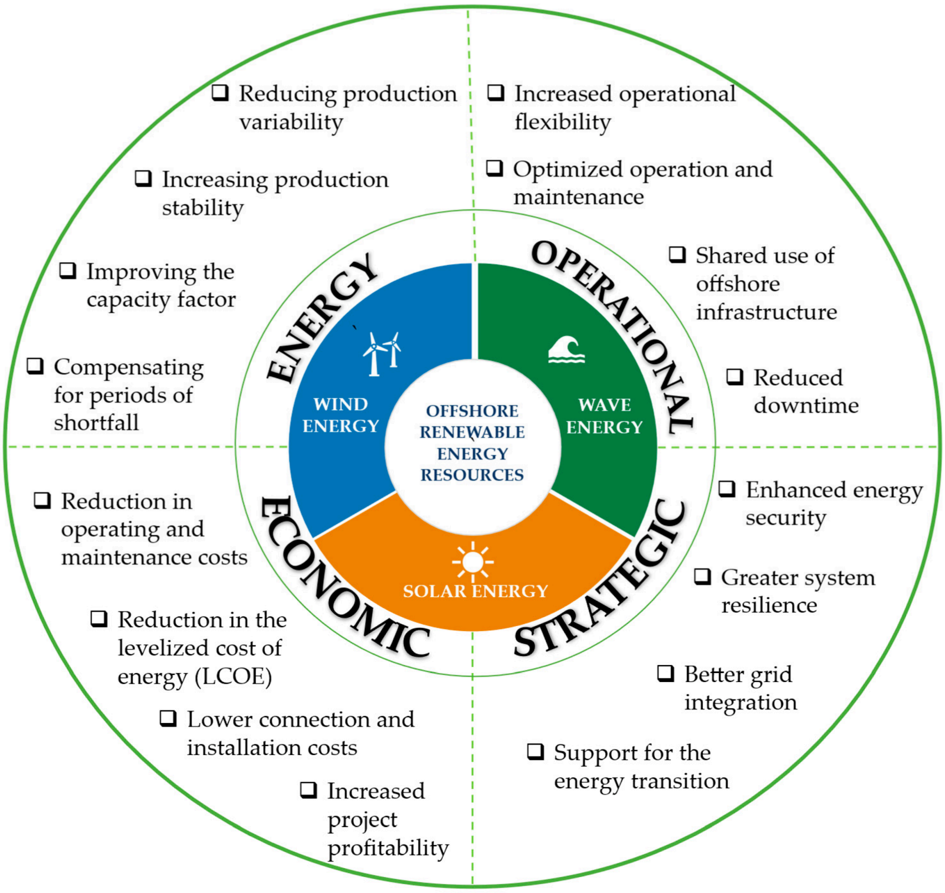

Figure 4. Benefits of the complementarity of offshore renewable resources.

5.3. Hybrid Wind–Wave–Solar Concepts

Hybrid wind–wave–solar systems represent the next generation of offshore energy platforms developed to simultaneously harness multiple renewable resources available in the marine environment. These systems aim to integrate wind turbines, wave energy converters (WECs), and floating photovoltaic panels into a joint infrastructure [122,123] able to increase energy production and reduce the effects of intermittency associated with each source.

Hybrid offshore energy systems are developed based on an integrated architecture that enables the collection, conversion, management, and distribution of the energy produced by each component. Wind turbines are the main source of energy, while wave energy converters help to supplement power generation and reduce its variability, and photovoltaic panels contribute to diversifying the energy mix and increasing the rate of utilization for offshore infrastructure [124].

Figure 5 shows the generic architecture of hybrid offshore wind–wave–solar systems, organized into four main functional levels, along with the system-level performance objectives.

The first level corresponds to the primary renewable resources that constitute the system's energy inputs. The second level consists of power generation and conversion subsystems. This includes the offshore wind turbine along with the generator and the AC/DC (alternating current/direct current) converter, the wave energy converter along with the PTO (Power Take-Off) system and the associated power interface, and the floating photovoltaic panels along with the MPPT (Maximum Power Point Tracking) algorithm and the DC/DC (direct current/direct current) converter. The third level consists of the shared offshore electrical and structural integration layer, which brings together the shared floating platform and the common AC/DC collection bus. This level is essential for exploiting the specific advantages of hybrid offshore energy systems, as it allows for the shared use of the platform, the electrical infrastructure, and maintenance operations [122,124,125]. The fourth level is related to energy management, storage, and delivery, including the EMS/SCADA (Energy Management System/Supervisory Control and Data Acquisition) system, storage units, and the export interface to local loads or the power grid. The final component of the scheme (presented in Figure 5) consists of system-level performance objectives, including reducing intermittency, increasing the capacity factor and energy production, improving operational flexibility, and more efficient use of offshore infrastructure.

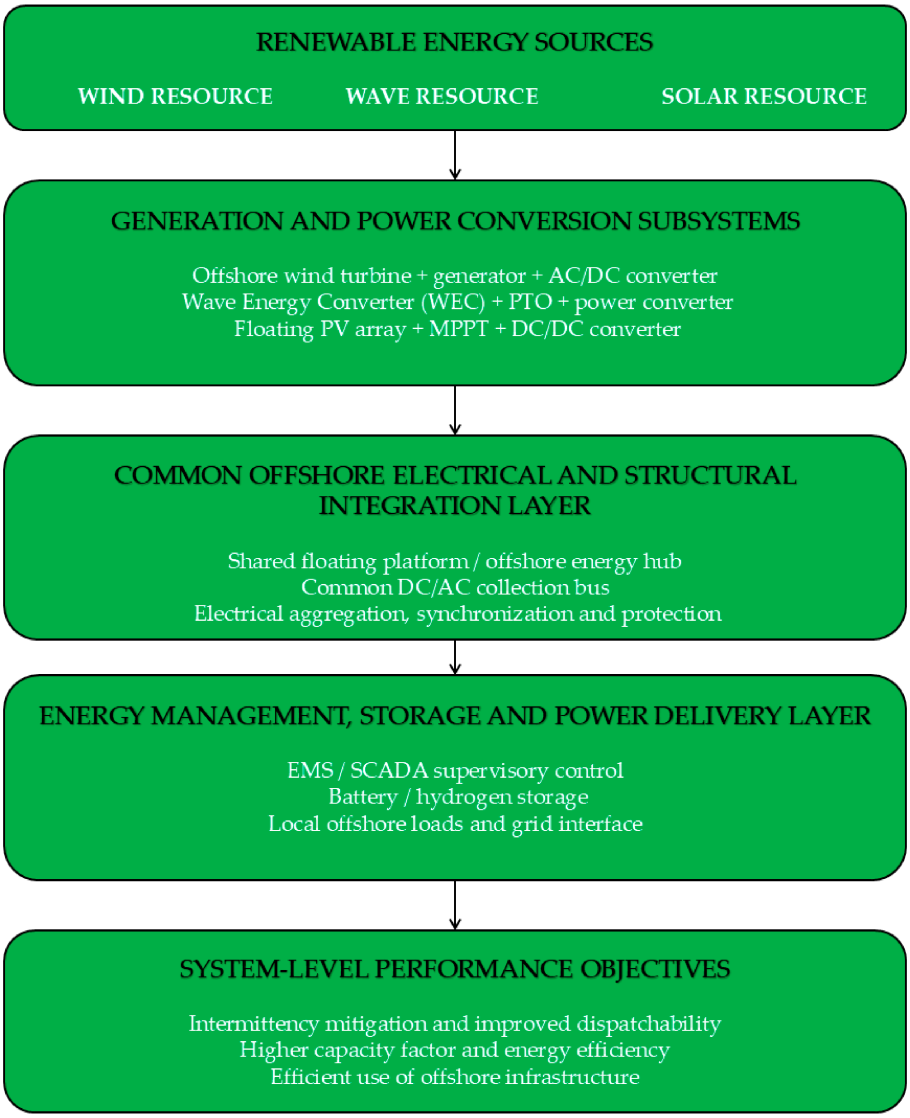

Figure 5. Conceptual Architecture of a Hybrid Offshore Wind–Wave–Solar Systems.

The analysis of hybrid wind–wave–solar concepts highlights their potential to overcome the limitations associated with the individual exploitation of offshore renewable energy sources.

In this context, the development of multi-source energy platforms can represent an important step in the future evolution of marine renewable energy, offering viable solutions for increasing energy security and achieving global decarbonization goals.

6. Current Challenges and Future Research Directions

Even though hybrid offshore energy systems combining wind, wave, and solar energy are considered one of the most promising solutions for the development of offshore renewable energy, their implementation on a large scale comes with numerous technical, economic, and operational challenges. The complexity results from the need to integrate multiple energy technologies into a single floating infrastructure capable of operating in severe marine conditions and providing consistent energy production over time [126–128].

Compared to conventional offshore systems, hybrid offshore energy systems are simultaneously impacted by wind, waves, and ocean currents, which result in complex structural stresses and high demands on their stability and durability [127,129]. Apart from the technical challenges, the development of this type of system is influenced by the high costs associated with installation and maintenance, as well as the lack of unified technical standards for design and certification. At the same time, recent trends in the field highlight the need to develop sustainable materials and solutions that reduce environmental impact and extend the lifecycle of the platforms [127,129,130].

Given the European goals of climate neutrality and the expansion of offshore renewable energy generation capacity, current studies are focused on developing more efficient, reliable, and sustainable floating structures, and the main challenges and research directions are summarized in Table 9.

Table 9. Current Challenges and Future Research Directions for Hybrid Offshore Energy Systems.

Domain	Current Challenges	Future Research Directions
Technological limitations	• Complex hydrodynamic behavior • The interaction between wind turbines, wave energy converters, and photovoltaic panels • The lack of experimental validation for certain hybrid offshore energy systems concepts • Limited long-term operational data from European pilot projects	• Development of advanced numerical models • Full-scale testing • Validation using long-term monitoring data from European demonstration site
Costs and Maintenance	• High costs for installation, anchoring, and grid connection • Difficulties in accessing the site for offshore maintenance operations • Complex towing, installation, and offshore commissioning operation • Limited availability of suitable port infrastructure and specialized installation vessels in Europe	• Predictive maintenance strategies • Levelized cost of energy (LCOE) • Optimization of installation logistics and towing procedures • Development of dedicated offshore logistics hubs and port infrastructure
Hybrid Offshore Energy Systems Integration	• Simultaneous management of multiple energy sources • Fluctuations in production • Complex operational control • Integration with existing European offshore grids	• Smart systems based on artificial intelligence • Integration of energy storage and green hydrogen • Interoperable control systems for future European offshore energy hubs

Table 9. *Cont.*

Domain	Current Challenges	Future Research Directions
Sustainable materials	• Corrosion, structural fatigue, and degradation in the marine environment • Durability under North Atlantic and North Sea environmental conditions	• Advanced composite materials • Recycled materials and low-carbon solutions • Climate-resilient materials for harsh offshore environment
Standardization	• The lack of specific standards for multi-source hybrid offshore energy systems • Differing certification procedures • Differences in regulatory frameworks among European countries	• Developing international standards for the design, testing, and certification of hybrid offshore energy systems • Harmonization of European certification and permitting procedures
Opportunities for Sustainable Floating Structures in Europe	• The need to reduce costs and increase reliability • Expansion of exploitation in deep-water maritime areas • Limited grid infrastructure for large-scale offshore deployment • Cross-border regulatory coordination	• Modular multi-source platforms • Integration of offshore hydrogen production • Development of marine energy hubs and smart offshore infrastructure • Automation of offshore installation and towing operations • Coordinated transnational offshore energy networks and integrated planning in European sea basins

Overall, the future success of hybrid offshore energy systems will depend on the ability to integrate innovative solutions in the areas of structural design, materials, energy management, and digitalization. Advances in these fields can help reduce costs, increase reliability, and accelerate the deployment of hybrid offshore energy systems. The development of sustainable floating structures that can adapt to various marine conditions is therefore one of the main research priorities and a key element for achieving Europe's energy transition and climate neutrality goals.

In addition to technical challenges, the development of hybrid offshore energy systems in Europe is constrained by several aspects of the European implementation framework. Among the most significant are differences in national authorization and certification procedures, the limited availability of port infrastructure for the assembly and installation of large-scale floating structures, and the need to expand offshore power grids to integrate future maritime energy hubs. Therefore, in the context of the rapid development of floating wind energy and hybrid offshore energy systems in the North Sea and the Atlantic, with severe meteorological and oceanographic conditions imposing additional requirements on the design, installation, and operation of these platforms, addressing these issues is essential [16,93,117]. Key priorities include aligning technical standards and certification procedures at the European level, developing offshore energy hubs, expanding cross-border power grids, and implementing smart monitoring and control systems based on digital twins and artificial intelligence. These measures will help reduce the levelized cost of energy (LCOE) and increase the reliability and competitiveness of hybrid offshore energy systems, in line with the objectives of the European Green Deal and the EU's offshore energy strategy [93].

Beyond the technological and economic challenges presented in Table 9, installation and towing operations are a key factor in the large-scale deployment of hybrid offshore energy systems. Floating platforms are designed, constructed, and integrated in shipyards or port infrastructure, where assembly, testing, and pre-commissioning can be carried out under controlled conditions and with high operational efficiency. Once the integration phases are complete, the platforms are towed to the offshore site using tugboats, then connected in sequence to the mooring system, the dynamic power cables, and the power transmission infrastructure. The installation strategy minimizes the timeframe for offshore operations, reduces reliance on heavy-lift vessels, and limits exposure to adverse weather and oceanographic conditions [16]. Therefore, assembly at the dock, followed by towing to the location, contributes to reducing installation costs, optimizing project logistics, and increasing the reliability of the implementation process for hybrid offshore energy systems [16,26,40].

Figure 6 outlines the main stages of implementing hybrid offshore energy systems, starting with the design and integration of equipment in port and continuing with towing, offshore installation, commissioning, and commercial operation. Compared to fixed structures, this strategy reduces the time spent at sea and limits the use of large-capacity specialized vessels, but it requires careful coordination of logistical operations and rigorous planning for each stage of the deployment process.

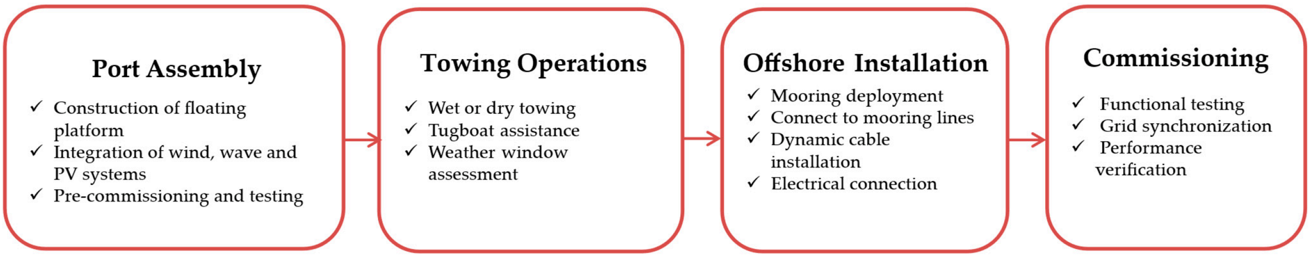

Figure 6. Main Stages in the Deployment of hybrid offshore energy systems.

Nevertheless, the safety of transportation and installation operations is influenced by numerous technical and environmental factors, such as wave height, wind speed, and the intensity of ocean currents, which limit the available window time for towing and installation. Furthermore, the type of floating platform significantly influences the transport and commissioning strategy. Examples include semi-submersible platforms, which can be towed directly to their operating position, while spar-type platforms require additional righting and offshore installation procedures. For hybrid offshore energy systems, which integrate wind turbines, wave energy converters, and floating photovoltaic systems, the complexity of operations increases with the number of equipment units and the mechanical and electrical connections that must be made under offshore conditions [26,87].

Another issue is the availability of port infrastructure for the assembly, handling, and launch of large floating platforms. Expanding port capacities and developing dedicated logistics hubs are considered essential for accelerating the implementation of offshore projects in Europe, particularly in the context of the development of floating wind farms and hybrid offshore energy systems. At the same time, standardizing installation procedures and optimizing offshore towing and connection operations are key steps toward increasing reliability and improving the competitiveness of offshore technologies [16,26].

7. Conclusions

Offshore floating structures represent a promising solution for harnessing Europe's renewable marine resources, especially in deep-water areas where fixed installations are difficult to deploy. They play an increasingly important role in the development of offshore renewable energy and can provide an effective solution for harnessing the marine resources available in this region.

Currently, as the search continues for cleaner and more sustainable alternatives for energy production, these types of systems are still under development. The marine environment offers significant potential for generating energy from sources such as wind, waves, and solar radiation, and combining these with hybrid offshore energy systems can yield significant benefits. However, the design and operation of floating structures depend heavily on offshore environmental conditions, making their safety, stability, and strength essential factors.

The analysis of recent studies in this field highlights the fact that the future development of hybrid offshore energy systems is no longer determined entirely by the individual performance of energy conversion technologies. Instead, it depends on their ability to function as an integrated system, in which the structural, hydrodynamic, and energy responses are highly interdependent. From this perspective, the overall behavior of the platform is governed by the interaction between aerodynamic loads, hydrodynamic stresses, the dynamics of the mooring system, dynamic power cables, and energy conversion devices. Consequently, the design of future hybrid offshore energy systems must be based on fully coupled numerical models capable of accurately reproducing these interactions under both normal operating conditions and extreme sea states.

Comparison of the main floating configurations reveals that semi-submersible platforms currently offer the greatest flexibility for integrating hybrid offshore energy systems due to their high hydrodynamic stability, the available surface area for accommodating multiple technologies, and their adaptability to a wide range of water depths. The selection of the best configuration cannot be based strictly on hydrodynamic performance, as it is necessary to simultaneously evaluate structural criteria, the behavior of the mooring system, installation and towing operations, operating costs, and long-term reliability. Within these circumstances, multidisciplinary approaches that integrate hydrodynamics, structural mechanics, dynamic cable analysis, and power generation are essential for optimizing future offshore systems.

Overall, hybrid offshore energy systems based on renewable resources have great potential and could become an important part of the transition to a cleaner and more sustainable energy system in the future; however, future progress depends on interdisciplinary research, technological innovation, and supportive policies for their large-scale implementation.

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Abbreviations

The following abbreviations are used in this manuscript:

6-DOF	Six Degrees of Freedom
AC/DC	Alternating Current/Direct Current
ALS	Accidental Limit State
BEM	Boundary Element Method
CFD	Computational Fluid Dynamics

DC/DC	Direct Current/Direct Current
EMODnet	European Marine Observation and Data Network
EMS/SCADA	Energy Management System/Supervisory Control and Data Acquisition
FLS	Fatigue Limit State
FOSS	Floating Offshore Substation
FPSO	Floating Production, Storage and Offloading
GM	Metacentric Height
GZ curves	Righting Arm Curves
IPCC	Intergovernmental Panel on Climate Change
LCOE	Levelized Cost of Energy
MPPT	Maximum Power Point Tracking
PTO	Power Take-Off
PV	Photovoltaic
RAO	Response Amplitude Operator
SLS	Serviceability Limit State
TLP	Tension-Leg Platform
ULS	Ultimate Limit State
WEC	Wave Energy Converter

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