

Review

# Electrical Power Supply of Remote Maritime Areas: A Review of Hybrid Systems Based on Marine Renewable Energies

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**Abstract:** Ocean energy holds out great potential for supplying remote maritime areas with their energy requirements, where the grid size is often small and unconnected to a continental grid. Thanks to their high maturity and competitive price, solar and wind energies are currently the most used to provide electrical energy. However, their intermittency and variability limit the power supply reliability. To solve this drawback, storage systems and Diesel generators are often used. Otherwise, among all marine renewable energies, tidal and wave energies are reaching an interesting technical level of maturity. The better predictability of these sources makes them more reliable than other alternatives. Thus, combining different renewable energy sources would reduce the intermittency and variability of the total production and so diminish the storage and genset requirements. To foster marine energy integration and new multisource system development, an up-to-date review of projects already carried out in this field is proposed. This article first presents the main characteristics of the different sources which can provide electrical energy in remote maritime areas: solar, wind, tidal, and wave energies. Then, a review of multi-source systems based on marine energies is presented, concerning not only industrial projects but also concepts and research work. Finally, the main advantages and limits are discussed.

**Keywords:** hybrid systems; multi-source systems; marine renewable energy; combined platform

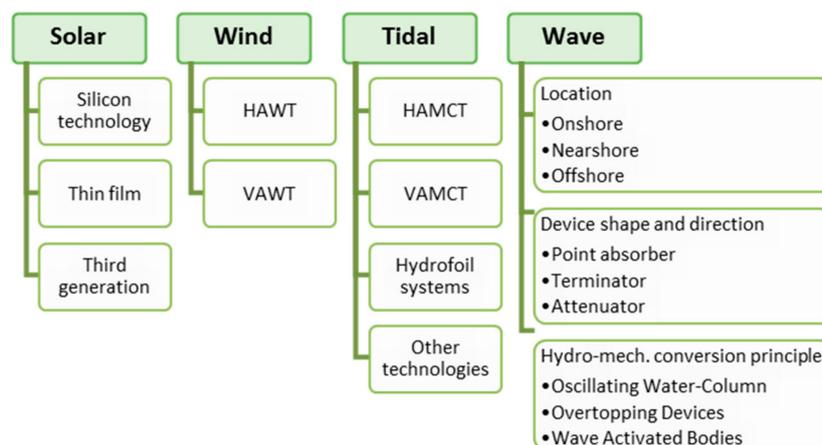
## 1. Introduction

The electricity supply of remote marine areas is mostly generated from solar and wind energy, thanks to their maturity and attractive prices compared to other renewable energies [1]. However, these renewable energy sources are based on the exploitation of intermittent resources. To resolve this drawback, storage systems such as batteries and Diesel generators can be used, but investment costs and induced pollution are often not favorable. Moreover, it is costly and logistically difficult to implement a diesel supply in remote marine areas. However, over the last few years, marine renewable energies have encountered some interest and a genuine development by the industry, because of their potential available energy [2]. Tidal and wave energies are the most developed among the different marine energies [3,4]. Hence, hybrid systems combining solar, wind, and marine energies can now be developed to provide sustainable and reliable electrical energy. Wind and wave hybrid energy systems have already been developed, according to reviews written by different authors [5–9].

Some multipurpose platforms have been studied in terms of feasibility [10,11]. The present paper aims to put forward a review of hybrid systems combining marine energies on the same platform or structure, such as wave, tidal, wind, and solar energies. Firstly, a brief review of these renewable energy sources is detailed, to show the basics and existing technologies. A comparison between the different temporal characteristics of each renewable source is given, to highlight the different temporal scales and forecast abilities. Then, a review of industrial and academic multisource systems is presented, from projects tested under real sea conditions to those still at the concept stage. Finally, some advantages and limitations of multisource systems based on marine energies are listed.

## 2. A Short Review of Renewable Energy Sources Concerned by This Study

Island areas in maritime environments present the advantage of having several primary resources in their neighborhoods. Concerning the development and maturity of renewable energies over recent years, the main sources that can be used seem to be solar and wind energies, which present a high technical level of maturity and the most interesting cost [1,2]. Furthermore, among the marine energies available from the ocean, tidal and wave energies are currently two of the most advanced and promising technologies, with a better maturity level than other marine energies such as thermal and salinity gradient conversion energies [4]. Marine energies have the advantage of a good predictability and a high available energy level [1,2]. This part of the review aims to briefly present these four renewable energy sources in terms of the operating principle, main technologies existing today, and temporal resource characteristics. An overview of the main technologies currently existing is shown in Figure 1.



**Figure 1.** Solar, wind, tidal current, and wave energy converter technologies classification.

### 2.1. Solar Energy

At present, solar energy is one of the most widely used renewable energies in the world. Photovoltaic panels used to convert solar energy into electrical energy have now reached a high maturity level, with many technologies available on the market for different kinds of application [12].

#### 2.1.1. Fundamentals of Operating Processes

A solar cell uses a semi-conductor material, often silicon, to absorb photons of incident solar radiation received by the cell [12]. A semi-conductor is based on two energy bands. One of them is called the valence band. Electron presence in this band is allowed. In the second energy band, called the conduction band, electrons are absent. The band between the valence band and the conduction band is called the band gap. An electron can move from the valence band to the conduction band if the amount of energy provided by incident solar radiation to the electron is larger than the band gap value. This electron can move into an external circuit due to the p-n junction. This process results

in a hole-electron pair formation. The electron moves to the n-region, whereas the hole moves to the p-region, resulting in a potential difference. This effect was explained by A. Einstein in 1905 and is called the photovoltaic effect [13]. It consists of transforming solar energy into electrical energy. To produce more power, photovoltaic cells are combined in serial and parallel configurations to reach the desired current and voltage levels, forming a photovoltaic module. The electrical output power depends on the global irradiance and the ambient temperature [14,15].

### 2.1.2. Main Technologies Currently Used

Different kinds of photovoltaic cells exist on the market at different technology readiness levels. Many articles have discussed the advantages and drawbacks of the different technologies [12,16–18]. Three main categories can be seen at the moment, based on the material used and the maturity level: first, second, and third generation.

The first generation is based on a crystalline structure with a silicon wafer (c-Si). These are the most frequently employed on the market. Two sub-categories can be found: the mono-crystalline (sc-Si) and the poly-crystalline (p-Si). The second generation of photovoltaic cells is characterized by the use of thin film layers. Different sub-categories exist: amorphous silicon (a-Si), micro-amorphous silicon (a-Si/ $\mu$ c-Si), cadmium telluride (CdTe), gallium arsenide (GaAs), copper indium selenide (CIS), and copper indium gallium diselenide (CIGS). Finally, the third generation of photovoltaic cells is based on new technologies [12], for example organic and polymer solar cells, dye-sensitized solar cells, etc. Moreover, concentrated systems are classified in the third generation of photovoltaic cells [17]. Among these technologies, perovskite solar cells, which belong to the dye-sensitized technologies, are one of the most promising technologies [12]. Several advantages are quoted in a previous paper [12], such as flexibility, transparency, and efficiency.

According to several past papers [12,17], the first and second generations are the most employed worldwide, due to their maturity levels, whereas the third category is still at the research state. These authors pointed out that multijunction cells present the highest efficiency level (around 40 to 45%), i.e., around twice as high as the silicon and thin film technologies (between 10% and 25%). A fourth generation exists, based on hybrid organic and inorganic technologies [12]. However, this photovoltaic cells generation is still at the research status.

## 2.2. Wind Energy

Among all existing energies, along with solar energy wind is one of the most developed renewable energies across the world. Wind energy systems have been greatly developed since the original windmill principle was discovered by the Persians around 200 B.C. High power modern designs were achieved in the 20th and 21st centuries, as described by the timeline of M.R. Islam et al. [19].

### 2.2.1. Fundamentals of Operating Processes

Wind turbines use wind speed to produce electricity. As explained by several authors, wind turbines convert wind kinetic energy into rotational kinetic energy [20–22]. The wind speed induces the rotation of blades around an axis, which can be either horizontal or vertical. Wind exerts two forces on the blades: a drag force, which is parallel to the airflow, and a lift force, which is perpendicular to it [20,23]. The mechanical energy of this rotation is transformed into electrical energy by an electrical generator, sometimes after a rotational speed increase due to a gearbox. The electrical output power depends on the wind speed cubed [20].

### 2.2.2. Main Technologies Currently Used

Wind turbine technologies can be separated into two categories, according to the rotating axis position, as has been explained in several references [19,20,23,24]. The most common category with the best technical and economic maturity levels is the horizontal axis wind turbine (HAWT); the second is

the vertical axis wind turbine (VAWT). The two technologies are compared by M.R. Islam et al. [19]. The main characteristics of each of them are discussed in the following two paragraphs.

HAWT are characterized by a turbine placed on a nacelle at the top of a hub, with a rotation axis parallel to the ground. As explained in a previous paper [24], different technologies exist. They are classified according to different criteria: the number of blades (two, three or more), the rotor orientation (upwind or downwind), the hub design, the rotor control (stall or pitch), and the yaw orientation system (active or free). The low cut-in speed and the high power coefficient are often cited as advantages of horizontal turbines. However, a nacelle orientation system should be used to follow the wind direction changes and the installation presents more constraints [19,20]. This kind of wind turbine is mostly used in large scale systems. Wind turbines with three blades and upwind rotor orientation are the most widely used technology today [19].

For VAWT, the blades rotate around a vertical axis. The main advantage of this is that there is no need for an orientation system, as this kind of turbine can absorb wind from any direction, and it operates better than HAWT in the case of turbulent winds [19,20]. Among the different sub-technologies of VAWT, two categories are often found: the Darrieus turbines, which are based on lift forces, and the Savonius turbines driven by drag forces [20,24]. VAWT are mostly used for small applications and small power systems, for example residential networks [19,20,23].

The offshore wind turbines can be also distinguished according to the substructure and the foundations. Three categories can be found, according to the water depth and the distance to the shore [5,23,25]:

- In case of shallow water installation (water depth lower than 30 m), several bottom-fixed substructures can be used: the gravity-based substructures and the monopile substructures which are currently the most frequently used [5,25], and the suction bucket still at a development stage [5].
- For transitional water (water depth between 30 m and 80 m), others kinds of bottom-fixed structures are used. The jacket frames structures, the tri-piles structures, and the tripod structures are the most used [5].
- Finally, in case of water depth larger than 80 m, floating structures are used [5]. The mast is mounted on a floating structure moored to the seabed. Three kinds of floating structures exist: the ballast stabilized structures (or spar floaters), the tensioned-leg platforms (also called mooring line stabilized), and the semi-submersible platforms [5,25]. Floating wind turbines are mainly considered for offshore wind farms far from the shore, as the wind resource available is larger than along the coast.

More details related to offshore wind turbine technologies can be found in previous papers [5,23,25].

### 2.3. Tidal Current Energy

Among all existing marine renewable energy converters, tidal energy converters are one of the most developed technologies [2,4,26]. Belonging to the hydrokinetic type of energy [27], two kinds of tidal energy can be distinguished [28,29]. The first is tidal kinetic energy, which is induced by water movement according to tide cycles, for which turbines are used to produce electricity. The second is the tidal potential energy, where tidal barrages are used to extract the energy resulting from the water elevation cycle (also called tidal range devices). In this paper, only the tidal kinetic energy is studied, as the extracting technology (a turbine), the power density, the size requirements, and the power range are more suitable for coastal areas [29]. Moreover, the geographical areas suitable for tidal range devices are quite rare in the world [29]. Indeed, their installation is possible only in areas with a water level elevation about several meters. Thus, the use of tidal range systems to provide electricity for maritime remote areas, such as islands, is not discussed in this article.

### 2.3.1. Fundamentals of Operating Processes

Tidal current turbines produce electrical power from the kinetic energy of the rise and fall movements of tides in coastal areas. Indeed, due to the gravitational and rotational forces induced by the Earth, Sun, and Moon positions, ocean water moves horizontally according to cycles that are easily predictable, and which are related to the time and location on the Earth [2,30,31]. Water flow allows the submerged turbine rotation on which blades are mounted, similarly to the process used in wind turbines [2,28]. The turbine drives a generator, for which many technologies can be used [28,32,33]. The output power depends on the tidal current speed [33]. This kind of turbine can also be used to extract kinetic energy from river currents [26]. Tidal turbines are often compared to wind turbines with respect to the turbine operating principles. However, the tidal turbine performs better due to the water density, which is greater than air density, increasing the power density [26,29].

### 2.3.2. Main Technologies Currently Used

Extracting tidal kinetic energy can be carried out by several techniques, as explained and classified by many past papers [2,26–31,33–35]. The following categories can be distinguished primarily, according to the type of device used.

In Horizontal Axis Marine Current Turbines (HAMCT), the turbine is composed of two or more blades rotating around an axis parallel to the water flow direction [26,28,29,31]. A list of projects is given by Zhang et al. [33]. This is currently the most common tidal turbine on the market [4], due to its good technical and economical maturity level. Thus, HAMCT now reach the megawatt scale [36]. Moreover, floating systems have encountered some interest in the last few years and they are now the subject of active research [36].

Vertical Axis Marine Current Turbines (VAMCT) can harness tidal flow from any direction with two, three, or more blades rotating around an axis that is perpendicular to the current direction [26,29,31,33]. Two main kinds of vertical axis turbines exist: the Darrieus turbine and the helical turbine (also called the Gorlov turbine) [26,31]. However, some disadvantages limit their development. The low self-starting capacity and efficiency, along with torque variations are often cited [36].

Another category exists, that of oscillating hydrofoil systems. Tidal currents make a pressure difference on a foil section, which creates drag and lift forces on the oscillating foil attached to a lever arm [29]. A linear generator is often used to generate the electrical output power [33]. However, this technology is still at the development level [27].

Other kinds of devices can be found. Among them, ducted turbines, the tidal kite, and helical screw systems (also called the Archimedes screw) can be cited [26,29,31,35]. A further classification of tidal kinetic energy converter technologies exists, based on the water flow harnessing techniques. Axial-flow and cross-flow turbines can be distinguished, and horizontal and vertical designs exist for both of these [29].

## 2.4. Wave Energy

Concerning other renewable energy sources, wave energy received attention from academics and industrialists, mostly since the 1980s, as the available worldwide resource is considerable [2,37]. Many wave energy converter technologies have been developed up to today, invoking especially a large number of patent publications [4]. Wave energy is sometimes classified among the hydrokinetic energy category [26]. Moreover, wave energy is now considered to be suitable for the electricity supply of small islands and coastal areas [1,3,38]. The Atlantic Ocean is often considered for wave energy projects due to the high wave power density available [39], but some recent articles have analyzed several islands case studies in Mediterranean Sea [40–42], involving some changes in technologies in order to fit the wave characteristics of the considered location [40].

#### 2.4.1. Fundamentals of Operating Processes

A wave energy converter transforms wave energy into electrical energy. Wave energy comes from the effect of wind on the sea surface, creating waves. These follow the wind direction across several thousands of kilometers, creating significant swell, until they reach the narrow waters near the shore where the wave speed decreases. The power output of a wave energy converter depends on the wave height and its peak period [26,37,43]. Harnessing wave energy and converting it into electrical energy is a complex process compared to other renewable energy sources. Indeed, several conversion stages are necessary: primary, secondary, and tertiary conversion stages, according to A.E. Price [44] and several other past papers [39,45,46]. In the case of these papers, short descriptions are given below.

The primary conversion stage aims to convert wave motion into body motion, air-flow or water-flow, using mechanical, pneumatic, or hydraulic systems, called prime movers. This stage converts a low frequency motion (the wave) into a faster motion. The second conversion stage transforms the fluid energy of the first stage into electrical energy. Depending on the fluid used in the primary stage, the converter used in this step can be an air turbine, a hydraulic one, or a hydraulic motor connected to an electrical generator. They are called Power Take-Off systems (PTO). This step converts the low frequency fluid or mechanical motion into high rotational speed with the electrical generator. The tertiary stage conversion aims to adapt the electrical output characteristics of the wave energy converter to the grid requirements with power electronic interfaces. Some wave energy converters show merged primary and secondary conversion stages, where wave energy is directly transformed into electrical energy with a linear generator [39,46].

#### 2.4.2. Main Technologies Currently Used

Many wave energy converter designs currently exist, but this renewable energy source is still at the research and development stage, and the technical maturity level is currently lower than that of other renewable energy sources [4]. Moreover, different classifications can be found in the literature, according to different reviews of recently published wave energy converter technologies [3,4,38,39,43–53]. Often, wave energy converters are classified according to the criteria listed below [3,4,37,39,43–46,50,53].

Location: onshore or shoreline, nearshore or offshore. Onshore systems are placed on a cliff, a dam, or land without a mooring system. Nearshore systems often lie between 0.5 and 2 km from shore, in shallow waters (between 10 and 25 m deep). The first generation of wave energy converters was based on onshore and nearshore systems [54]. Offshore wave energy converters are at several kilometers from the shore in deep water (>40 m), with the ability to harness high wave energy levels [2,37,39,43,45,46,53].

Device shape and direction concerning the swell propagation direction [4,37–39,43,45,46,53]. Three cases are possible:

- Point absorber: they are small with respect to the wavelength and they can absorb energy from any wave direction.
- Terminator: the device axis is perpendicular to the wave propagation direction.
- Attenuator: the device axis is parallel to the wave propagation direction.

Hydro-mechanical conversion principle (primary conversion stage) [4,26,37–39,43,45,46,48,50,53]. Three categories can be found:

- Oscillating Water Columns (OWC) are based on the compression and decompression forces in the air chamber created by water level variations which drive a turbine. OWC devices can be either deployed in shallow water as a stationary structure, or in deep water, for which floating systems can be used [55]. Recently, a new OWC device, called U-OWC has been developed [56]. Based on a vertical U-duct, this new structure avoids the wave to propagate into the inner body as in a traditional OWC device.

- Overtopping Devices (OTD) use the water level difference between the sea and the partially submerged reservoir to produce electricity (potential energy) when the wave overtops the structure and falls into the reservoir. The turbine rotates by releasing the water back into the sea. Some overtopping devices are integrated to a breakwater [57,58]. Moreover, structural design of some overtopping devices can be suitable for other maritime needs [59].
- Wave Activated Bodies (WAB) or Oscillating Devices are based on the use of one or more moving bodies [26,37,48]. Three categories of wave activated bodies can be distinguished: heaving buoy, surface attenuator, and oscillating wave surge converter [43]. The performances of these devices depend on the mooring system, for which different configurations exist [60].

Some references classify wave energy converters according to other criteria. A review of electrical generators used, control methods employed, mechanical and/or electrical controllers applied, wave conditions considered, and power electronic converters used for different projects is proposed by E. Ozkop and I.H. Altas [52]. Classification by the power take-off technology (second conversion stage) is also given in [46], resulting in three main sub-categories: the hydraulic PTO, the turbine PTO, and the all-electric PTO, as discussed in the previous Section. Mooring configurations are also discussed [43,48,51]. A new classification based on the operating principle has recently been carried out [38]. A. Babarit proposed a comparison of the existing technologies based on the so-called capture width ratio [47].

Some development trends concerning the different criteria listed earlier are highlighted in previous papers [4,39]. Offshore application, floating installation, and point absorber technology are the most common aspects considered for the projects reviewed.

### 2.5. Intermittency and Variability Comparison

The four renewable sources introduced in the previous sections present different temporal characteristics. Indeed, as they are based on the use of different primary resources, their intermittency and variability are different, with more or less predictability, so they cannot be dispatched as conventional sources could be [61]. A limited number of studies have discussed these aspects considering all the sources. In one of these [61], Widén et al. presents the main intermittencies and variabilities of the four sources, with a review of existing forecast methods. The standard deviation of each source according to the different time scales (frequency bands) is studied by J. Olauson et al. at the level of a country [62]. The highest standard deviation rate for the different sources is related to short-term timescales for solar (<2 days), mid/short-term for wind (2 days to 2 weeks), long-term for wave (>4 months), and mid-term for tidal (2 weeks to 4 months) energies [62]. Natural cycle timescales of solar, wind, tidal, and wave resources are also discussed in the International Energy Agency report [63]. Variability of solar, wind, and tidal resources for the UK is studied by P. Coker et al. considering the persistence, statistical distribution, frequency, and correlation with demand [64]. G. Reikard et al. studied the variabilities of solar, wind, and wave energy for integration to the grid, with a forecasting system proposed for the three sources based on a regression method. Wave energy is shown to be more predictable than solar and wind, due to the strong weather impact for the latter two sources [65]. Recently, a review of solar and wind space-time variabilities has been conducted by K. Engeland et al. but this does not include tidal and wave resources [66]. Table 1 presents the main characteristics in terms of variability and intermittency for each source, with the origin and existing methods to evaluate temporal variations according to different publications [61–66].

**Table 1.** Main variabilities characteristics of solar, wind, tidal, and wave energies.

Source	Kind/Scale of Variability	Origin	Variability Assessment Methods and Models	Determinist or Stochastic Behavior
Solar	Seasonal	Position of Sun and Earth Geographical position on the Earth	Mathematical model	Deterministic
	Daily	Diurnal cycle due to Earth rotation	Mathematical model	Deterministic
	Short-term: from second to hour	Weather conditions	Predicted by ground measurements, satellite data or weather models	Stochastic
Wind	Decadal	Climatic and atmospheric condition changes	Historical climatic observations data analysis	Stochastic
	Yearly and seasonal	Weather conditions depending on the location and the seasonal cycles	- Statistical: autoregressive, Monte-Carlo method with Markov chains, neural network, wavelets . . . ;	Stochastic
	Weak scale (synoptic peak around 4 days)	Weather conditions	- Physical: historical weather data or weather models;	Stochastic
	Daily and infra-day	Diurnal peak and weather conditions	- Hybrid: statistical and physical methods	Stochastic
	Short-term: from Sub-seconds to few minutes (turbulence peak around 1 min)	Random, caused by turbulences	Hardly predictable	Stochastic
Tidal current	Bi-monthly: depending on the tide cycle (1 cycle = 14.76 days), with spring and neap tides	Tide cycles: depending on the position of the Earth, the Moon and the Sun (tidal currents are the fastest when they are aligned)	Harmonic analysis	Deterministic
	Infra-day	- Tide type: diurnal, semi-diurnal, semi-diurnal with diurnal inequality, or mixed;	Harmonic and geographical analysis	Deterministic
		- Depending on the location on the Earth, and the attraction between the Moon and the Earth and between the Sun and the Earth		
Short-term: seconds, minutes or hours, due to turbulences	Sea bed, geography of the location, Weather effect: storms, waves . . .	Geography study and weather forecasts	Stochastic	
Wave	Seasonal and monthly	Climate and weather conditions depending on the location	- Scatter diagram get by statistical or empirical methods; - Power variation coefficient; - Seasonal Variability Index (3 months average level)	Stochastic
	Infra-day	Weather conditions depending on the location	Weather forecast	Stochastic

### 3. Review of Multisource Projects Including Renewable Marine Sources

As explained in the previous section, the most developed marine energies at the current time are tidal kinetics and wave energies. Thus, they can be used to provide electrical power in maritime areas, as for example in floating systems or islands communities. During recent decades, renewable energies used in these applications were often solar and wind energies, but intermittencies of these sources involved the use of Diesel generators or storage capacities. According to the time characteristics of solar, wind, tidal, and wave energies, the development of multisource systems combining several of these sources could bring a sustainable and reliable power level to ensure the load supply in the future.

This Section aims to present a review of projects combining the use of some or all of the four sources presented previously, on the same platform. The details depend on the kind of project and the development status. Firstly, hybrid system projects developed by companies will be reviewed; from hybrid devices tested in offshore conditions to projects that are still at concept status. Also, a review of several energy island concepts will be given. Then, an up-to-date review of studies concerning sizing optimization and energy management systems will be carried out,

considering the published papers in these fields. Several projects presented in the following sections have already been more thoroughly reviewed [5–11,67], especially for hybrid wind-wave systems. However, farms and colocated systems such as the independent and combined arrays described by C. Pérez-Collazo et al. [5] are not part of the focus of this article, since they are not considered as combined systems.

### 3.1. Review of Industrial Hybrid System Projects Including Marine Energies

Multisource systems that include marine energy are still scarce. As wind turbines now reach a high level of maturity, most of these projects consider offshore wind turbine use. Two categories of projects can be identified, according to the maturity level and the development status. Several projects have been tested under real sea conditions (meaning potentially severe environmental conditions) either at a reduced-scale or at full-scale (Section 3.1.1), whereas others have still not progressed beyond the concept step (Section 3.1.2). A review is given below and is summarized in Tables 2 and 3. Technologies are characterized according to the classification given in the previous Section when the technical information is available. An overview of industrial hybrid system projects according to their power scale and to their furthest known development status is given in Figure 2. Finally, some island energy concepts will be presented (Section 3.1.3).

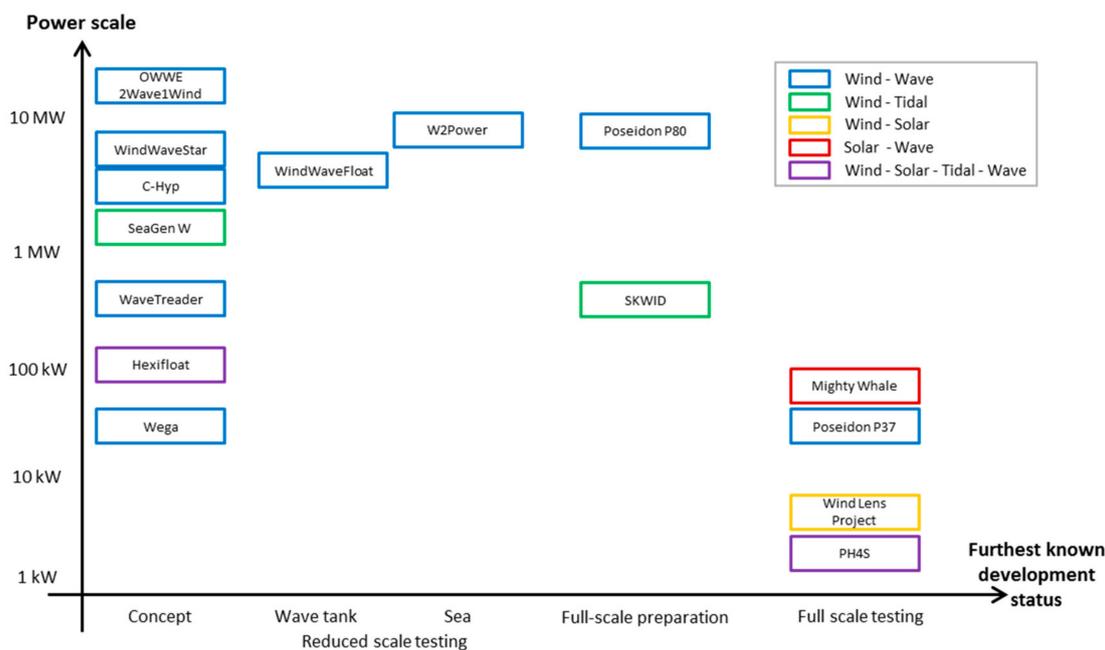


Figure 2. Overview of hybrid systems including marine energies.

#### 3.1.1. Projects Tested under Real Sea Conditions

Despite their current scarcity, multisource systems tested under real sea conditions can be classified according to the sources used. These systems relied on either wind or wave energies combined with one or more renewable sources, whereas other projects only consider wind and wave energies. A single industrial project uses solar, wind, tidal and wave energies on the same platform [68]. Details of these systems are given below, according to the sources used.

- Wind and wave: several projects have considered these sources. The Poseidon P37 product, designed by Floating Power Plant, is currently the most advanced technology in the multisource floating platforms field, as it was the first hybrid system connected to the grid. Twenty months of grid-connected tests were effected successfully on the Danish coasts, with three 11 kW wind turbines and 30 kW of wave energy converters. A Megawatt scale will be reached with the

P80 device, which is expected for 2020 [69,70]. The W2Power device designed by Pelagic Power uses the same energies, with 10 MW installed on the platform [71–73]. However, this project is still at reduced scale test status, as the platform currently tested in the Canary Islands concerns the WIP10+ device, which is a 1:6 scale prototype with only wind turbines [74]. Previously, wave tank tests allowed the mooring system to be validated and the behavior in both operational and survival modes to be assessed [72].

- Wind and solar: although photovoltaic panels and wind turbines now reach a high maturity level, projects combining both energies on a floating platform are still scarce. The Wind Lens hybrid project, developed by the Kyushu University (Fukuoka, Japan), has considered wind turbines (Wind Lens turbine) and solar panels on a floating platform [75–78], connected to batteries to ensure the electrical power supply of measurement and control devices. The total power installed reached 8 kW. Authors have observed that offshore wind turbine production is better than the similar land-based turbine due to higher wind speed values. In winter, the energy produced by the offshore wind turbine is two to three times the energy produced by the land-based wind turbine [76]. A more powerful platform is expected in the future according to [76].
- Wind and tidal: The Skwid system designed by the MODEC company seems currently to be the only project combining wind and tidal turbines at an industrial scale. However, little information is available concerning this project, since the system sank during installation in 2014 [79,80]. The turbines used could harness wind and tidal current flowing from any direction thanks to their vertical axis, avoiding complex orientation systems needed by horizontal axis turbines.
- Wave and solar: The Mighty Whale project is one of the oldest multisource systems which considers the use of ocean energy [81]. During tests at sea between 1998 and 2002, observations showed that combining the use of wave and solar energies allowed the power production to be smoothed and reduced the auxiliary generator use by storing the energy in batteries. However, the results presented in a previous paper [81] are strongly dependent on climatic conditions (Sea of Japan).
- Wind, solar, tidal, and wave: the PH4S device developed by the French company Geps Techno is currently the only platform combining the four renewable sources [68]. A prototype is currently being tested on the French Atlantic coast and the first observations from this company show a reduction of global power intermittency.

The review shown in Table 2 demonstrates that devices tested under real sea conditions are still scarce and often used a few dozen kilowatt systems. All the projects have considered wind and/or wave energies on a floating or fixed platform. These structures often come from a previous wave energy converter platform (e.g., Poseidon P37, Mighty Whale) or an offshore wind turbine system (e.g., Skwid), to which another renewable source has been added. All of the offshore projects tested report that energies used present a positive complementary aspect, bringing a smoother electrical power output. When they are not connected to the grid, power sources are used to supply the platform measurement and control devices. However, projects tested under real sea conditions are still scarce. Most of them were tested at a reduced scale, initially in water tanks before sea installation.

### 3.1.2. Projects Still at the Concept Status

The industrial project review can be supplemented by projects that have remained at the concept status without sea installation. As detailed in Table 3, most of these concepts concern wind and wave systems, even if a wind-tidal concept [11] and a floating platform concept combining all of the sources considered in this study exist [82,83]. According to all these projects, the following points can be highlighted:

- Wind and wave: many wind-wave system concepts exist. Some of these have been partially tested, either in water tanks or at sea for one of both renewable sources. For example, Principle Power Ltd. (Emeryville, CA, USA) has designed a hybrid device called WindWaveFloat. To date, a 2 MW

wind turbine was successfully tested at sea in 2011 with grid connections. However the different wave energy converter technologies initially planned were not included in the tests [84,85]. WindWaveStar and Wega devices, developed respectively by Wavestar and Sea for Life companies, have never been tested with both energy sources. For the first device, tests only concerned the WaveStar wave energy converter in offshore conditions for a reduced scale prototype, whereas the Wega wave energy converter has been studied in wave tank tests. Other wind-wave hybrid system concepts have never surpassed the concept status (WaveTreader, OWWE 2Wave1Wind and C-Hyp).

- Wind and tidal: MCT has considered a wind turbine mounted on the tidal turbine structure in the SeaGen W device. However, this project seems only to be a concept according to the large scale tidal projects without the wind turbine recently developed by the company [11,86].
- Wind, solar, tidal, and wave: In 2012 Hann Ocean (Singapore) patented the layout and design of the Hexifloat device, a platform concept allowing four energies to be harnessed [83], but this is still at the concept status today according to the company's website [82].

Other concepts have been developed in the MARINA Platform framework (Marine Renewable Integrated Application Platform), a European project undertaken between 2010 and 2014 to study different aspects of combined offshore platforms, such as feasibility, economical profitability, engineering etc. Thus, several partners have worked on tools, methods, and protocols to ease multipurpose platform design. Among the different platforms proposed [87], three wind-wave hybrid system concepts have been considered: the Spar Torus Combination (STC) [88], the Semi-submersible Flap Combination (SFC), and the large floater with multiple Oscillating Water Columns and one wind turbine (OWC Array) [11].

The concepts reviewed here often considered wind and wave energies. This trend could be explained by the fact that some companies have already developed a wind or wave energy converter and would like to share their structure with another kind of renewable energy converter. Then costs could be reduced (design, equipment, installation, operation, maintenance, etc.) and power production could be increased with a smoother output level, as explained by Pérez-Collazo et al. [5], M. Karimirad [6], and Casale et al. [10]. Positive aspects of combined wind-wave devices are presented in these references. However, the review carried out in this section shows that many of these concepts have not gone beyond the idea step. High development costs can explain this trend. Also, as offshore tidal and wave energy converters alone are still scarce in the world, their maturity level is not as high as land-based renewable energies and offshore wind turbines. Casale et al. have suggested [10] building hybrid systems around proven and mature offshore systems, for example wind turbines after these technologies have been individually validated and tested. Thus, this consideration could help concepts to overcome this step, which is seen in a few cases where wave or wind energy converters have been tested on wave tanks or at sea [84,85,89,90]. For several projects listed in our review, little information is available to explain their current status and perspectives. It is supposed that some companies have cancelled their hybrid device concept, focusing on separated technologies.

**Table 2.** Summary of industrial hybrid systems concepts including marine energies tested under real sea conditions.

Reference	Project or Product Name <i>Company/Lab/Institution</i>	Sources Considered and Specifications	Used Storage	Grid Connection Load Considered in Off-Grid Case	Main Outcomes	Current Status
[69,70]	Poseidon P37 and P80 <i>Floating Power Plant (Denmark)</i>	<ul style="list-style-type: none"> <li>- P37: wind energy: 2 blades HAWT (3 × 11 kW) + wave energy: attenuator, OWC (10 × 3 kW);</li> <li>- P80: wind energy: 3 blades HAWT (from 2.3 to 5 MW) + wave energy: attenuator, OWC (2.6 MW)</li> </ul>	No storage	Grid connected	One of the highest efficiency rates among the wave energy converters existing on the market [10]	P37 tested between 2009 and 2013 P80 version expected for 2020
[71–73]	W2Power <i>Pelagic Power (Norway)</i>	<ul style="list-style-type: none"> <li>- Wind: HAWT (2 × 3.6 MW);</li> <li>- Wave: point absorber, WAB (2 to 3 MW)</li> </ul>	No storage	Grid connected and off-grid configurations are possible	Tested on tank at reduced scale (1:40) to study wind and wave interaction, mooring system, and physical limits	2017: Sea conditions tests at 1:6 scale for the WIP10+ device [74]
[75–78]	Wind Lens Project <i>Kyushu University (Japan)</i>	<ul style="list-style-type: none"> <li>- Solar (2 kW);</li> <li>- Wind: Wind Lens HAWT (2 × 3 kW)</li> </ul>	Battery	Off-grid Measurement and air-conditioning devices	Wind speed in offshore conditions is higher than in land case	1st version ended in 2012 after one year of offshore conditions tests, but a 2nd is expected according to [76]
[79,80]	SKWID <i>MODEC (Japan)</i>	<ul style="list-style-type: none"> <li>- Wind: VAWT-Darrieus;</li> <li>- Tidal: VAMCT-Savonius Total power of 500 kW</li> </ul>	No storage	No available information	<ul style="list-style-type: none"> <li>- Wind and tidal turbines can harness energy from wind and tidal current of any direction;</li> <li>- Prototype sank during offshore installation in 2014</li> </ul>	Cancelled in 2014
[81]	Mighty Whale <i>JAMSTEC: Japan Marine Science and Technology Center (Japan)</i>	<ul style="list-style-type: none"> <li>- Wave: nearshore, terminator, OWC (2 × 30 kW);</li> <li>- Solar: mono-crystalline (10 kW);</li> <li>- Auxiliary generator (20 kW)</li> </ul>	Battery (500 Ah)	Off-grid Measurement and control devices	Complementarity of wave and photovoltaic energies	Ended in 2002
[68]	PH4S <i>Geps Techno (France)</i>	<ul style="list-style-type: none"> <li>- Solar (1 kW);</li> <li>- Wind: VAWT (1.5 kW);</li> <li>- Tidal: VAMCT (500 W);</li> <li>- Wave (500 W)</li> </ul>	Battery and supercapacitors	Off-grid	Complementarity of the four sources	2017: offshore tests

**Table 3.** Summary of industrial hybrid system concepts including marine energies.

Reference	Project or Product Name Company/Lab/Institution	Sources Considered and Specifications	Application and Load Considered	Main Outcomes	Current Status
[85,91]	WindWaveFloat Principle Power Ltd. (USA)	<ul style="list-style-type: none"> <li>- Wind: 3 blades HAWT (5 MW);</li> <li>- Wave: depending on the considered wave converter [85]</li> </ul>	No information	<ul style="list-style-type: none"> <li>- Study of several wave converter technologies;</li> <li>- Numerical tool development [91];</li> <li>- Test at 1:78.5 scale on wave tank</li> </ul>	Only a 2 MW floating wind turbine was tested in 2011 in offshore conditions, now removed after 5 years of grid-connected tests [84]
[89]	WindWaveStar Wavestar (Denmark)	<ul style="list-style-type: none"> <li>- Wind: 3 blades HAWT;</li> <li>- Wave: near shore, point absorber, WAB (6 MW at full scale)</li> </ul>	Grid connected	In 2010, tests were conducted at sea for a 1:2 scale prototype only composed of wave converters (total of 600 kW, connected to the grid)	The hybrid wind-wave system is only a concept today
[90]	Wega Sea for Life (Portugal)	<ul style="list-style-type: none"> <li>- Wind: HAWT;</li> <li>- Wave: point absorber, WAB</li> </ul>	No information	The power take-off system of WEC device is placed above water, reducing the corrosion risk and improving accessibility. Tests were done in 2010 with only one wave energy converter in a wave tank.	Hybrid wind-wave system is only a sharing infrastructure possibility of the WEC device, still at concept status
[92]	WaveTreader Green Ocean Energy (Scotland)	<ul style="list-style-type: none"> <li>- Wind: 3 blades HAWT;</li> <li>- Wave: offshore, point absorber, WAB surface attenuator Total power of 500 kW</li> </ul>	No information	WEC device is mounted on the monopile offshore WT	No information available since 2011
[9,93]	OWWE 2Wave1Wind Ocean Wave and Wind Energy (Norway)	<ul style="list-style-type: none"> <li>- Wind: 3 blades HAWT;</li> <li>- Wave: offshore, point absorber, OTD (depending on the concept)</li> </ul>	No information	This concept is known to be one of the largest wave energy platforms (600 m), that allows to harness a large amount of energy (1 TWh per year for 10 units)	Only a concept
[94]	C-Hyp LHEEA, EOSEA, Technip (France)	<ul style="list-style-type: none"> <li>- Wind: 3 blades HAWT (5 MW);</li> <li>- Wave: oscillating wave surge converter (1.89 MW)</li> </ul>	Grid connected	<ul style="list-style-type: none"> <li>- Feasibility analysis with numerical tool development;</li> <li>- The angular spatial share of WECs can smooth the electrical power produced.</li> <li>- WEC power seems to be higher than WT power for low wind speeds.</li> <li>- Costs are high and the size of this concept (100 m diameter) is challenging for the building phase.</li> </ul>	Only at concept status in the MARINA Platform project framework [11], but no further development
[11]	SeaGen W MCT-Atlantis (UK)	<ul style="list-style-type: none"> <li>- Wind: 3 blades HAWT (3 MW);</li> <li>- Tidal: HAMCT (1.2 MW)</li> </ul>	Grid connected	Concept of SeaGen W consists of a wind turbine added on the top of the existing Seagen tidal device	Only a concept
[82,83]	Hexifloat Renewable Energy Platform Hamm Ocean (Singapore)	<ul style="list-style-type: none"> <li>- Solar (48 kWp);</li> <li>- Wind: 3 blades HAWT (18 kWp);</li> <li>- Tidal: HAMCT (23 kWp) Wave (45 kWp)</li> </ul>	No information	Platform design	Patented in 2012 [83] concerning the design aspects, but not deployed today

### 3.1.3. Energy Island Concepts

Energy islands [10] or island systems [5] are considered to be large multipurpose platforms including several renewable energy sources and, in contrast to projects reviewed in the previous sections, infrastructures for other activities and functionalities [5,10]. C. Pérez-Collazo et al. divided this kind of project into two categories: artificial islands built on a reef or dyke, and floating islands, considered as very large floating platforms [5]. However, all projects in this field show that they are only at the steps of concepts and ideas. Among them, the following projects can be quoted:

- Kema Energy Island (by KEMA-DNV GL and Lievense): placed in an ocean, this artificial island concept consists of a large scale water tank used for pumped storage, surrounded by dykes on which wind turbines are placed to produce electrical power. According to the figures shown in [95], the KEMA Energy Island project encompasses a large scale storage capacity, with a power of 1.5 GW and an energy capacity of 20 GWh, to store surplus wind electrical power production. Other functionalities are proposed, such as the chemical industry, harbors, tourism, etc. This project has not seen further development than the preliminary design and evaluation steps, but it is still shown in a previous paper [96].
- Offshore Ocean Energy System (by Float Inc.): this concept can be classified in either the floating island or floating platform categories, according to its medium size. Wind, tidal, and wave energies have been considered as the heart of the structure. Moreover, other services have been proposed, such as aquaculture, fishing, and desalination facilities [97].
- OTEC Energy Island (by Energy Island Ltd.: London, UK): the four renewable energy sources discussed in this paper (solar, wind, tidal, and wave energies) have been considered in this floating island concept, along with ocean thermal energy conversion and geothermal energy. Moreover, several infrastructures and services such as a harbor and a water desalination system have been proposed at the design phase. The power considered is about 250 MW [10]. A patent was filed in 2003 [98], but as of today, no further development is known.
- TROPOS project concepts: three research programs have been integrated in “The Ocean of Tomorrow” European call: the TROPOS Project (2012–2015), the H2OCEAN Project (2012–2014), and the MERMAID project (2012–2015). Several research programs designed for the TROPOS project have seen a focus concerning innovative multi-use floating islands: the Leisure Island, the Green & Blue, and the Sustainable Service Hub [99]. The last of these seems to have the highest potential for near-term development. Economic, environmental, logistical requirements, social, and design aspects have been considered. In addition to the renewable energy converters used in these concepts (solar energy, wind energy, and OTEC), other infrastructures and services have been proposed, such as leisure (Leisure Island) or aquaculture (Green & Blue) [100].

All of these island concepts have apparently not gone beyond the idea stage. Also, the powers considered are higher than the floating platform power scales reviewed in previous sections. Thus, island projects seem to be far from reaching industrial and commercial status, concerning high costs, technical challenges, and the facilities required to build such projects [100]. Financial support should be found to overcome the concept status. However, sharing infrastructures with other concerns could help project development by involving different industrial and economic sectors [10,100].

### 3.2. Review of Academic Research Concerning Hybrid Systems with Marine Energies

Multisource systems with marine energies are still at early stages of developmental processes. Thus, several academic analyses studied combined renewable energies exploited in the sea. These analyses are often at an earlier stage than industrial development processes and they study above all theoretical hybrid systems. Among the different papers describing such systems from the electrical engineering point of view, two categories can be found. The first discusses energy management system and control aspects, whereas the second concerns sizing optimization aspects with method and tool design. Several papers are reviewed in the following sections according to this classification.

### 3.2.1. Energy Management System and Control Studies

Hybrid systems using marine energies have been modeled and simulated by several authors to design appropriate energy management systems and control strategies. As in the industrial project review presented in the previous section, these academic works can be subclassified with respect to the considered sources, as the requirements and specifications can be different according to the renewable source. Technical information and main outcomes are summarized in Table 4.

- Wave and wind: an off-grid wind-wave system with battery storage and variable AC load has been studied by S.Y. Lu et al. [101]. The converter control schemes developed allow ensuring current and voltage stabilities in transient load phases, concerning the 500 W to 1 kW situation validated by simulation and laboratory tests.
- Wave and solar: as solar energy has been widely used for island electrical power supply, several articles have considered wave energy to compensate the solar energy fluctuations. For example, the Perthian Island (Terengganu, Malaysia), studied by N.H. Samrat et al. [102], did not present sufficient solar resource for the load power required. To ensure the system reliability and power quality, appropriate converter controls have been developed. Thus, the DC voltage link is kept constant, even in the cases of resource or load fluctuations. Similar systems and studies were considered by S. Ahmad et al. [103]. A grid-connected solar-wave hybrid system was studied by L. Wang et al. [104], considering the generated power injected on the DC-link smoothed by a supercapacitor. The converter control schemes developed allow the maximum wave and solar powers to be harnessed. Grid injected power fluctuations are smoothed by inverter control, whereas the DC-link voltage is controlled by a DC/DC converter connected to the supercapacitor.
- Wind and tidal: many articles deal with hybrid wind-tidal systems. For example, Y. Da and A. Khaligh [105] have presented appropriate control schemes for tidal and wind turbines to optimize harnessed powers, considering mega-watt scale generators. Tidal current and wind speed fluctuations have been taken into consideration to validate the proposed strategies. Another wind-tidal hybrid concept called HOTT (Hybrid Off-shore and Tidal Turbine) has been studied in several papers concerning wind power fluctuation compensation [106–109]. Thus, M.L. Rahman et al. proposed [106] the use of a tidal generator as a flywheel storage system, with a one-way clutch ensuring mechanical separation. The tidal generator produces or stores electrical power depending on the inverter control. In a previous paper [107], wind power fluctuations are compensated by tidal generator control for the lowest frequencies and by battery control for the highest ones. The authors stated that tidal compensation reduced the battery capacity, whereas the highest long-term fluctuation compensations required a tidal turbine power increase. The battery storage system was studied in a previous paper [108]. Tidal generator control for wind power fluctuation is also considered in a previous paper [109]. Concerning the grid connection, two solutions for large-scale turbines have been studied by S. Pierre [110]. The DC-link connection between the two generators before the grid-tied inverter brings an easier fluctuation smoothing ability. The separated solution consisting of two back-to-back converters for the AC grid connection allows the extracted power to be maximized. Finally, Y. Fan et al. presented [111] a novel hybrid wind-tidal architecture, where a hydraulic accumulator is used as a storage and balance system, placed between both hydraulic pumps and the electrical generator. Hydraulic pumps transform the output turbine mechanical energy into hydraulic energy. Fluctuations of output turbine mechanical powers are limited by hydraulic pumps control, while the hydraulic accumulator is controlled according to the load demand.
- Wind, tidal, and wave: C. Qin et al. [112] simulated the compensation of short-term output power fluctuations induced by intermittent wind and wave energies (from seconds to minutes). Thus, the tidal generator was used to smooth the output power, according to the tidal current speed. When the tidal turbine cut-in speed is surpassed, a tidal generator produces electrical power.

Thus, its pitch angle and rotational speed are controlled simultaneously to reduce output power fluctuations. If the tidal current speed is lower than the cut-in speed, the tidal generator is used as a flywheel storage system to compensate for variations, after tidal turbine mechanical separation.

According to the articles reviewed in this Section, wind and tidal energies seem to be widely considered. Wind energy fluctuations are often cited as a weakness and a challenge to improve the renewable development in island areas. Different solutions have been investigated to limit these fluctuations. Among them, tidal energy attracted attention, concerning tidal generator control [105–107,109,111,112] and the possibility to use it as a flywheel storage system [106,112]. Another point of interest observed in academic research is the transient state system stability, not only for resource fluctuations but also for load change [101,102,104,107]. Tidal energy has also been considered to smooth wave energy fluctuations [112]. Storage solutions such as batteries [101,102,107] or supercapacitors [104] are sometimes used to smooth generated power fluctuations.

### 3.2.2. Sizing Optimization Studies

To ensure a high reliability level, the hybrid system should be designed carefully. A storage solution allows the load requirements to be met in terms of power and energy. To avoid an over-sized or under-sized system and to ensure reasonable costs, a sizing optimization must be carried out. Wind/solar systems with a battery and/or Diesel generator have been widely studied in terms of sizing optimization, as described in recent reviews [113–116]. As ocean energies have only been considered recently, such studies for marine energy hybrid systems are still rare. Several authors have proposed sizing optimization studies for both the renewable source sizes and the storage solutions considered to supply island systems.

Hybrid photovoltaic, wind, and tidal system sizing optimization was proposed in a few articles. In previous papers [117,118], O.H. Mohammed et al. considered the case of the remote Ouessant French Island, where the energy load is estimated at around 16 GWh per year, for a maximum power demand of 2 MW. To find the best sources and storage combinations according to the equivalent loss factor reliability index [117,118] and economic constraints [118], several sizing optimization algorithms have been developed: cascade calculation, genetic algorithms and particle swarm optimization. The combination of the three renewable sources is found to be more reliable than cases where only one source is considered [117]. In a previous paper [118], the levelized cost of energy is divided by seven between a configuration based only on solar energy (763.7 \$/MWh) and a solution based on PV, wind and tidal energies (127.2 \$/MWh). Also, the levelized cost of energy is lower when artificial intelligence approaches are considered for the sizing optimization, as the obtained values reach 94 \$/MWh with a genetic algorithm and a particle swarm optimization, whereas a cascade algorithm results in a 149 \$/MWh cost [118]. A metaheuristic solution called the crow-search algorithm has been proposed by A. Askarzadeh [119] to optimize a hybrid wind/solar/battery system into which tidal energy is included. Concerning the results, the author concludes that a hybrid solar/wind/tidal system is more cost-effective than a partial combination of these three sources. In the simulation conducted for a one year period, tidal turbines generate almost 25% of the total generated energy and the resulting tidal turbines net present cost for the optimized system represents 20% of the total cost. Moreover, batteries can reduce the cost and improve the reliability index. The net present cost related to a battery reaches 13% of the total net present cost, to ensure a maximum unmet load ratio of 10%. For the study carried out, the proposed crow-search algorithm is reputed to be more efficient than the particle swarm optimization and the genetic algorithm, giving the fastest convergence rate.

**Table 4.** Summary of academics hybrid systems including marine energies, concerning energy management and control aspects.

Reference	Sources Considered and Specifications	Storage Used	Application and Load Considered	Kind of Study	Main Outcomes
[101]	- Wind: HAWT (2 kW); - Wave: point absorber, WAB-AWS (1.5 kW)	Battery	Tests done in off-grid configuration with DC bus and adjustable AC resistive load	Modeling, simulation, and lab. scale platform tests	The considered DC micro-grid remains stable during load transient phases, observed in both simulated and measured results.
[102]	- Solar: p-Si (400 W); - Wave: OWC (3 kW)	Battery (14 Ah)	Connected to an island grid (Perhentian Island in Malaysia)	Modeling and simulation	The simulated DC link voltage controller (bi-directional buck-boost) ensures the voltage stability in case of generated power fluctuations and load variations, by charging and discharging the battery. Load side voltage presents a low voltage and current THD rates thanks to the inverter control and the passive L-C filter.
[104]	- Solar: sc-Si (50 kW); - Wave: point absorber, WAB-AWS (160 kW)	Supercapacitor (95 kW and 0.5 kWh)	Grid connected	Modeling, control strategies development, and simulation	The developed control scheme allows the power fluctuations to be smoothed with the supercapacitor, ensuring stability and extracting the maximum available power from wave and PV sources.
[105]	- Wind: HAWT (1.5 MW); - Tidal: HAMCT (1 MW)	No storage	Grid connected	Modeling, control strategies development, and simulation	The developed control schemes for both generators allow extraction of the maximum available power. Tidal energy is said to be more predictable and more available than wind energy.
[106]	- Wind: HAWT (1.5 kW); - Tidal: HAMCT (750 W)	Tidal generator as a flywheel storage system	Grid connected	Lab. scale platform tests	The induction generator of tidal energy chain conversion is used as a flywheel storage system, with appropriate rotation speed control and mechanical separation by a one-way clutch. Thus, wind turbine generated power fluctuations can be smoothed.
[107]	- Wind: HAWT (300 kW); - Tidal: HAMCT (100 kW)	Battery	Grid connected	Modeling, control strategies development, and simulation	The proposed tidal turbine control and battery control are able to reduce wind turbine power fluctuations and keep frequency stability. The lowest wind power fluctuation frequencies are compensated by the tidal generator control, whereas the highest frequencies are compensated by battery control.
[110]	- Wind: HAWT (5 MW); - Tidal: HAMCT (5 MW)	No storage	Grid connected	Modeling, control strategies development, and simulation	Two coupling modes have been considered for the tidal and wind system AC grid connection. The first one considers a DC-link coupling before a grid connected inverter. The second one considers two separated AC-DC-AC converters between source generators and AC grid.
[111]	- Wind: HAWT (5 MW); - Tidal: HAMCT (1 MW)	Hydraulic accumulator	Grid connected	Modeling, control strategies development, and simulation	The output power is balanced with the hydraulic accumulator storage, according to the requested and generated powers. Fluctuations are damped by the hydraulic pumps and accumulator control.
[112]	- Wind: HAWT (1.5 MW); - Tidal: HAMCT (1.5 MW); - Wave: point absorber, WAB; - Archimedes Wave Swing (200 kW)	Tidal generator as a flywheel storage system	Grid connected	Simulation of the control strategies	The tidal generator is used as a flywheel storage system when the tidal current speed is lower than the cut-in speed. Tidal generator control can smooth the short-term wind and wave power fluctuations.

The sizing optimization for a wind/tidal hybrid system with battery storage has also been described in several articles. Among them, S.G. Mousavi proposed [120] the use of a genetic algorithm to determine the optimal size of a wind/tidal/micro-turbine/battery system, according to an economic analysis, i.e., evaluating for a year the capital cost, the battery replacement cost, the fuel cost and the operation, and maintenance costs. The objective function aims to find the optimal size with the lowest total annual system cost (sum of all the costs), considering the maximum load demand of the standalone system. The optimal configuration is based on a power capacity of 315 kW for wind turbine, 175 kW for tidal turbine, 290 kW for microturbine, and a capacity of 3.27 kAh for lead acid battery, leading to \$312,080 total cost. M.B. Anwar et al. presented [121] a methodology to size grid-connected large scale marine current and wind turbines (mounted on the same monopile), with a battery storage station to meet the grid code requirements. Sizing optimization aims to maximize the available power, at the same time respecting the injected power fluctuation requirements given by the grid.

Sizing optimization studies for systems dealing with marine energies are less numerous than studies carried out for solar/wind/battery systems. The first trends of these studies show that optimizing the size of a hybrid system which includes marine energies is necessary, as it allows the cost to be reduced and the reliability index to be improved [117–119]. The amount of power generated is expected to be higher and the intermittency to be reduced, but battery storage is still required to ensure the load energy requirements.

#### 4. Overview of Multisource Systems Based on Marine Renewable Energies

The review of industrial projects and academic research dealing with hybrid systems based on marine energies has shown that such systems have not yet reached commercial status. The interest of industries and researchers in this kind of multisource system is now clear. However, no significant results and operating experience exist to date and projects have often remained at a concept status [10]. Most projects considered a combination of two renewable energy sources. Although the advantages are numerous, some obstacles limit their development. This section aims to summarize the aspects found overall across the different projects and studies reviewed in previous sections, according to synergies and positive aspects, weaknesses and obstacles, and finally feasibility aspects.

##### 4.1. Positive Aspects, Synergies, and Applications

Combining several renewable energy sources in maritime areas presents many advantages and highlights some possible synergies. Thus, further developments in forthcoming years are expected, as potential applications are numerous.

According to several authors [5,6,9,10] and to the projects reviewed in previous sections, positive aspects and benefits brought about by marine energy hybrid systems concern many fields, as they can:

- Increase the energy production rate of an area (area share);
- Reduce the non-production hours, by managing the power flows harnessed from energies presenting different intermittency and variability characteristics (output power smooth). A storage solution can improve the reliability index and ensure the load requirements. Thus, the use of Diesel generators can be reduced;
- Provide sustainable electrical energy for maritime activities, such as fishing, aquaculture, water desalination, oil and gas industries, etc.;
- Share the infrastructure and equipment, allowing the global weight to be reduced;
- Attenuate the platform movement and improve its stability;
- Reduce some costs, with initial savings (infrastructure, mooring and anchoring systems, transmission, connection equipment, etc.) and lifetime savings linked to the operation and maintenance costs, compared to a separate device solution;
- Reduce the visual impact by placing the platform far from the coast (offshore systems).

Moreover, the design of multisource systems based on marine energies presents some positive aspects of synergies which could improve and accelerate their development. According to the synergies explained in several references, four categories can be found [5,6,10]:

- Areas sharing synergies: between renewable energy systems and other facilities (aquaculture, desalination, fishing etc.). Sharing areas allows the sea use densification to be improved, sharing the power produced for the surrounding activities and limiting the studies to a single place.
- Infrastructures, installation, and equipment sharing synergies: this kind of synergy concerns the installation equipment, the logistics (port and vessels), the grid connection, the supervisory control system, the storage and the operation, and maintenance. For each of these items, costs could be reduced by combining different kinds of sources.
- Process engineering synergies: hybrid systems based on marine energies can be combined with several marine activities, such as desalination, hydrogen production, aquaculture, breakwaters, algae production, oil and gas sector, etc.
- Legislative synergies: a common regulation is necessary to develop such hybrid systems. Thus, a legal regulatory framework, maritime spatial planning, a simplified licensing procedure, and a grid and auxiliary infrastructures planning are needed, as explained in a previous paper [5].

Hybrid systems including marine energies can be used in numerous applications in remote and maritime areas, allowing the use of Diesel generators to be reduced by replacing them with sustainable energy sources and/or storage. Among all of them, the following overall categories can be defined:

- Floating buoys: such as mooring or drifting buoys, usually used to measure meteorological or oceanographic parameters. Most of these buoys are currently based on solar energy and battery;
- Floating platforms: larger than floating buoys, they are used to produce electrical power, either for an island or for local use (aquaculture, oil and gas, fishing, etc.). Most of the projects presented in Tables 2 and 3 are based on floating platforms [68,69,71,75,79,81–83];
- Islands or coastal areas: several energy resources could be harnessed by onshore sources, such as PV panels and wind turbines, and by offshore systems, for example by the use of offshore wind turbines, tidal turbines, and wave energy converters [1,40–42,117];
- Artificial islands: as presented in several concepts [10,95,97,100], these are built on a reef or dyke. However, no further developments beyond the concept stage exist;
- Transport: maritime transport could use marine energy for their energetic needs [100].

#### 4.2. Obstacles, Weaknesses and Issues

The reviews presented in the previous sections have shown a mismatch between the number of projects that led up to sea test conditions and those that remained at a status concept. Indeed, hybrid system development requires careful consideration of several aspects to avoid premature project shutdown, by events such as financial, installation, logistical, equipment, environmental, legislation, etc. Several possible obstacles and weaknesses are cited in previous papers [5,6,122]:

- Unbalanced renewable energy converter maturity levels, such as photovoltaic panels which present a higher maturity level than wave energy converters, for which a lot of technologies exist;
- Lack of experience and data: as hybrid systems including marine energies are recent, they are still at an early developmental stage. Information which could help to avoid development or operation issues is still limited;
- Development time: as requirements of such systems are numerous, a lot of development time is needed before commercial status is reached;
- High costs: although several savings can be found concerning previously presented synergies, other categories still present high costs, such as insurance, development time, technologies, etc.;

- Marine environmental constraints: floating systems should undergo severe conditions when they are placed offshore, such as weather (storm, hurricane), strong waves, salinity, biofouling, corrosion, etc.;
- Mooring and anchoring system reliability, which should be able to resist local environmental conditions.

Several projects have encountered issues either at an early stage of development or during the operational test phase, sometimes involving the premature project end. However, little information is available concerning the reasons of the end of a project. The following points can be highlighted, according to several publications:

- Damage or failure during the installation or operation phases, as happened for the SKWID wind/tidal hybrid system [80]. For example, failure can concern the structure, the power take-off technology, or the mooring and anchoring systems [122];
- Project ended prematurely due to high costs and lack of funding. This aspect has been seen at different steps, and it is thought that some companies cease to exist since there is a lack of information concerning recent activities. Also, some concepts appeared to be ambitious and thus costly. This could explain the lack of further development.

#### 4.3. Feasibility and Design Methodology

To overcome some of the obstacles previously listed and make a system sustainable, feasibility aspects should be carefully studied. Thus, design methodologies and recommendations have been proposed by J.S. Martinez et al. [11] and B. Zanuttigh et al. [122] for the integration of energy converters in multipurpose platforms. The following methodology has been proposed previously [11] during the MERMAID project:

- Resource assessment according to the selected site;
- Power take-off technology selection allowing the power production to be maximized;
- Offshore structure technology selection (fixed or floating);
- Technology integration, by either platform sharing or area sharing (offshore energy farms);
- Environmental impact assessment, concerning pollution, recycling, etc.;
- Feasibility of combining with other activities.

Thus, the feasibility of such hybrid systems should start by a local evaluation, as the available resources can differ significantly [10]. Moreover, it has been advised [10] to use mature technologies, to avoid technology failure during the operational phase. Social acceptance must be considered by involving all the actors concerned in the project, including industries, political groups, investors, local communities, etc. Some authors advised developing individual renewable energy systems in the same area (this was for offshore wind farms) [123–125], then developing hybrid platforms that share the same structure [10,11].

## 5. Conclusions

Ocean energy can provide sufficient energy for the electricity supply of remote maritime areas, since the worldwide resources are major. Thus, combined systems including photovoltaic, wind, tidal current, and wave energies, which harness several kinds of energy, are a possible solution to replace the traditionally used genset-based systems to supply islands or floating systems. These four resources currently demonstrate the best maturity levels among all existing renewable energy sources, even if tidal kinetic energy and wave energy are still earlier in their development process than photovoltaic and wind energy converters.

After an overview of these four energy resources, this paper reviewed the industrial and academic hybrid systems based on marine energies. It appears that the development of such systems is still at an early stage in the development process, as shown by the number of projects that have remained at

concept status. Several projects are currently close to full-scale mega-watt operational tests, such as the Poseidon P80 device [58,59] and the W2Power device [74]. Other projects have reached sea tests with small-scale prototypes. This review has also shown a lot of concepts that are more or less realistic given the limited amount of available information concerning further development. On the one hand, concerning possible obstacles for the development of hybrid systems based on marine energies, the required long development times and high costs, especially of insurance, can explain this situation. Moreover, the severe marine environment constraints make the design of hybrid systems more complex, especially for the mooring system which requires a high reliability level. On the other hand, the review of research dealing with energy management aspects and sizing optimization shows the promising aspects of such systems. Indeed, combining different renewable energy resources reduces the output power variations as their temporal characteristics differ, so less storage capacity is needed and Diesel generator use can be reduced. Other positive points have been listed in this article, such as sharing area, equipment, infrastructure, etc. The process engineering synergies should help the development of hybrid systems based on marine energies, with respect to all possible combinations with other sectors and activities: desalination, aquaculture, transport, oil and gas, etc. As a result, a development of hybrid systems based on marine energies is expected in forthcoming years, following the improvement of both tidal kinetic current and wave energy converter maturity levels.

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