

Review

Review of Wave Energy Converter and Design of Mooring System

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Abstract: In recent decades, the emphasis on renewable resources has grown considerably, leading to significant advances in the sector of wave energy. Nevertheless, the market cannot still be considered as commercialized, as there are still other obstacles in the mooring system for wave energy converters (WECs). The mooring system must be designed to not negatively impact the WEC's efficiency and reduce the mooring loads. Firstly, the overview of the types of wave energy converters (WECs) are classified through operational principle, absorbing wave direction, location, and power take-off, respectively, and the power production analysis and design challenges of WECs are summarized. Then, the mooring materials, configurations, requirements, and the modeling approaches for WECs are introduced. Finally, the design of mooring systems, including the design considerations and standards, analysis models, software, current research focus, and challenges are discussed.

Keywords: ocean wave energy; wave energy converter; mooring system; design analysis

1. Introduction

The sea surface waves provide a large amount of green energy and could make an enormous difference to global energy demands going toward the sustainable world. One of the factors that makes waves desirable for harvest is that they have tremendous power density compared to many renewable energy sources [1]. Wave energy seems to have the second-highest potential of all ocean clean energy sources [2,3]. The theoretical potential of wave energy is shown in Table 1. Wave energy sources have been evaluated at global [4–6] and regional [7–10] levels and the volume of wave energy available is high enough to stimulate significant interest in exploitation. The estimated worldwide demand in 2014 for electrical energy reached 19,800 TWh/year [11] with a worldwide wave energy reserve of the same extent [12]. However, estimates of theoretically usable wave energy capacity on a worldwide scale are widely recorded between 2000 and 4000 TWh/year [13]. Environmental problems, including air pollution, global warming, and severe weather, due to colossal fossil oil use are gradually being discussed. For electricity generation in 2040, fossil fuels are expected to account for greater than 35% of the total energy consumption [14]. In this sense, it is much more essential to harness renewable energy sources such as wind, solar, and ocean wave energy.

China, America, India, and European countries are on the frontline of establishing strategies for incorporating the wave energy of the ocean into their systems [15]. Government agencies within these countries funded studies to carry out resource assessments [16] and provided test sites and laboratories for the development and planning of energy conversion systems [17–19]. Apart from state-funded studies, some studies are conducted by universities [20], private organizations [21], research centers [22], and individuals who are all involved in an attempt to promote ocean energy into

the public consciousness of a renewable energy sector. Due to the immense potential of wave energy [1], a wide range of wave energy converter (WEC) ideas has been formed to capture energy from waves. It is noted that now there are more than 1000 WEC prototypes [23,24]. Different studies have identified challenges resulting from the volatility of the properties of ocean waves and the sustainability of energy converters of the waves in a severe ocean environment [25].

The stability of the wave energy converter requires a mooring system. Present mooring systems and design specifications cannot completely fulfill the demands of the offshore WECs. It is according to the four properties of the wave energy converters which place them apart from the other offshore installations: function, operation, investment/revenue relationship, and the consequences in the event of failure. In the case of offshore WECs, the failures of a mooring system seem to be minor compared to offshore platforms. As such, strict safety requirements are not required. However, recommended offshore standards are needed for the implementation, and this results in the total investment between 18% [26] to 30% [27] in mooring systems. To optimize the energy efficiency of the wave energy converters, they need to be deployed to high-energy zones. Those are areas where the wave condition is high and, as a result, where a converter and also its mooring mechanism would be under extreme loading. Some of the WEC types are motion-dependent that require oscillations in waves, mostly in resonance, to obtain energy. Such oscillations will cause a mooring system to make high amplitude motions at a high frequency, causing higher dynamic tensions in mooring lines, mainly when it is in resonance. The performance of the motion-dependent devices is affected by the mooring system, because as mooring lines adding their mass (added mass), damping, and stiffness it changes the dynamic responses of WECs. The mooring system mass and stiffness are not detrimental and may also increase the performance of the converter, as stated in reference [28]. In addition, the additional mooring damping, contributing to the stabilization of floating structures [29], dissipates energy that may be exploited by WECs that are motion dependent.

An excellent mooring system for floating WECs will consider not only the possible consequences of the power take-off and device motions and but also ensure stability, be easy to maintain and monitor, and reduce installation and material costs. In this paper, the overview of the types of WECs and their mooring configurations, components, requirements, modeling approach, design consideration, suitable software, and challenges are discussed.

Table 1. Global resources of wave energy [30].

World Regions	Wave Energy Potential (TWh/y)
Asia	6200
New Zealand, the Pacific Islands, and Australia	5600
South America	4600
North America and Greenland	4000
Africa	3500
Western and Northern Europe	2800
Central America	1500
The Mediterranean Sea and Atlantic Archipelagos	1300
Total	29,500

2. WECs

The conversion of wave energy into useful energy, such as electricity, is performed through WECs.

2.1. Historical Background

The prospect of conversion of wave energy to useful energy has encouraged various inventors: by 1980, more than 1000 patents were already registered [31] and since then, the number had risen considerably. In 1799, Girard filed the earliest best known such patent in France [32]. By the late-twentieth century, several patents relating to the conversion of wave energy were in existence [33].

Former Japanese naval chief Yoshio Masuda can be called the founder of advanced wave energy development. He developed a navigation buoy equipped with a wave-driven air turbine. Such buoys are the components of the oscillating water column (OWC) [34]. The revival of wave energy work within the 1970s–1980s was mainly a result of oil crises in 1973, and the crises generated recognition of the spatial and temporal importance of the reserves of fossil fuel to policymakers and governments [35,36]. Governments [37,38] and intergovernmental associations, thus, spearheaded several developments and research activities. The 1973 oil crisis sparked a significant shift in the scenario of renewable energies and increased interest in wave energy generation on a full scale. In 1974, Stephen Salter introduced wave energy to the community of researchers and had become a landmark [39].

Several articles on the conversion of wave energy were written as books, journal papers, reports, and conference papers, such as McCormick's pioneering book [31], released in 1981, and the books of Shaw [40], Justus and Charlier [41] (finished wave energy long chapter in 1986), Cruz [42], Ross [32], and Brooke [43]. In 1999, a report prepared by the Energy Department of the UK [2] and final report on wave energy (2003) [44] from the Thematic Network of European (European-Commission-funded project) provide a wide variety of data. Shorter reviews are available [45–47].

2.2. Wave Energy Converter Classifications

To date, numerous different methods have been developed to convert the wave energy to electrical energy. Around 53 different technologies of wave energy were reported in reference [48] in 2006. Typically, they are classified as per conversion type. The classifications of WECs are more in detail in references [49–51].

2.2.1. Operational Principle

The operating principle describes how the wave energy converter interacts and absorbs energy from incoming waves. Falcão has proposed classification by operating principle [52].

Oscillating water column (OWC): The OWC is a floating hollow or fixed device that compresses and decompresses compressed air using the change in wave induced in the water level within the chamber [53], as shown in Figure 1. The pressure difference in the chamber forces air to move via a turbine that is coupled with the generator. If built near the shore, OWCs will act like breakwater structures to secure the coastline [54]. Some OWC devices have a natural installation advantage when installed close to the shore. Some examples are Energetech [55], OceanLinx [56], WaveGen Limpet [57], Yongsoo Power Plant [53], and Pico OWC [58]. Some examples of floating OWCs include Mighty Whale [59], the Spar Buoy [60], and Backward Bent Duct Buoy [61].

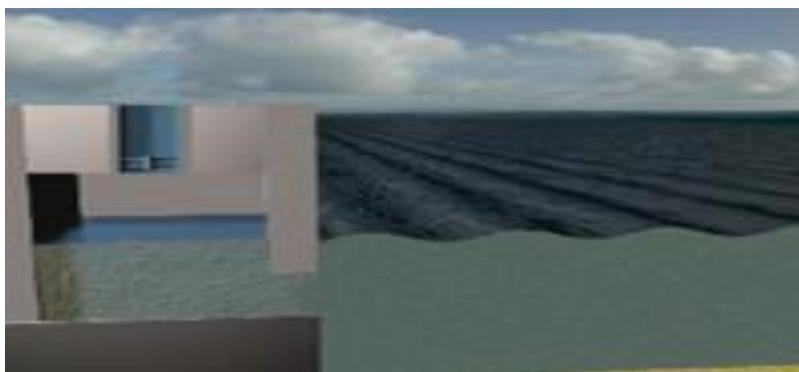


Figure 1. Oscillating water column [62].

Oscillating bodies: Oscillating body is a generic term used to identify WECs that derive power from wave-induced oscillations of submerged or floating structures primarily in surge or heave.

Heaving type devices are commonly constructed as axisymmetric buoys just below or on the surface of the water, extracting power from the wave's vertical motion. A total of 74 listed companies of wave energy by the Marine Energy Centre in Europe [63] concentrate on the production of heaving type point absorbers. These include Cor Power WEC (floating WEC of bottom-referenced connected to pneu-mechanical drive) [64], Power Buoy [65] (floating system of two-body self-referenced with hydraulic power take-off (PTO), as shown in Figure 2), the CETO system [66] (submerged converter of bottom-referenced with hydraulic PTO), and Sea-based wave energy converter [67] (floating system of bottom-referenced coupled with linear generator).



Figure 2. Power buoy [65].

Oscillating wave surge (OWSC) converters are made up of the flapping structure, for example, as a plate, hinged on the seafloor or submerged reference base, as shown in Figure 3. There are currently 14 different oscillating wave surge converters developed around the world [63], including BioWare, Langlee, and Oyster. The (OWSC) power output is lower compared to bottom-fixed because the reference base that is built to be stable always tends to pass in waves and often does not have an appropriately high reaction point of impedance [68].

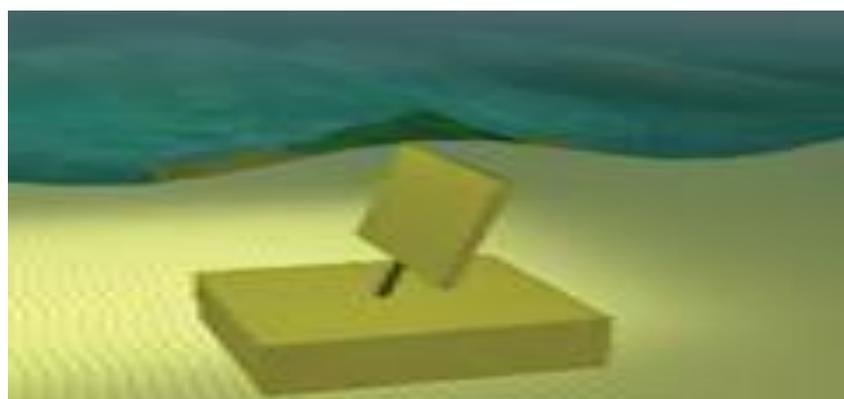


Figure 3. Oscillating wave surge converter concept [62].

Submerged pressure differential: In general, this device's position is near the shore and anchored to a seabed [62]. They usually are submerged point absorbers fixed and located near shore [69] and are comprised of one or more chambers that are air-filled in which the pressure fluctuates based on the incident wave phase (trough or crest). The changing pressure in the presence of deformable chambers results in a continuous airflow within the device, which is converted by air turbine into electricity. This concept is found in the Bombora WEC [70]. The air chamber for rigid structures consists of one constant and one rotating component where there is a variation for chamber volume due to the

changing pressure. The moving component down and up motions transform into electricity by the linear generator; it is applied in Archimedes Wave Swing [71], as shown in Figure 4.



Figure 4. Archimedes Wave Swing [62].

Overtopping: The overtopping mechanism consists of a water reservoir above the surface level of the ocean, which causes the water of the reservoir to transfer to the sea through the turbine structure. The overtopping earliest devices in Norway are the wave power tapered channel devices (Tapchan) [72]. They have a 350kW nominal power. Wave Dragon is another conventional device and is a floating device designed in Denmark [73], as shown in Figure 5. The design of the slope Seawave Cone Generator [74] is similar to the Wave Dragon. Wave Dragon is a universal application that uses as overtopping devices, and the Wave Dragon structure is shown in references [73,75]. Wave Dragon is a multiple MW plant of production with maximum power take-off performance and fast maintenance. Moreover, because of its large size, it is costly. Wave Dragon covers a vast region of the ocean and has an environmental impact.



Figure 5. Wave Dragon [73].

Since these WECs have substantially different performances, the estimated hydrodynamic efficiency is shown in Table 2, and WECs' breakdown by the principle of operation is shown in Figure 6.

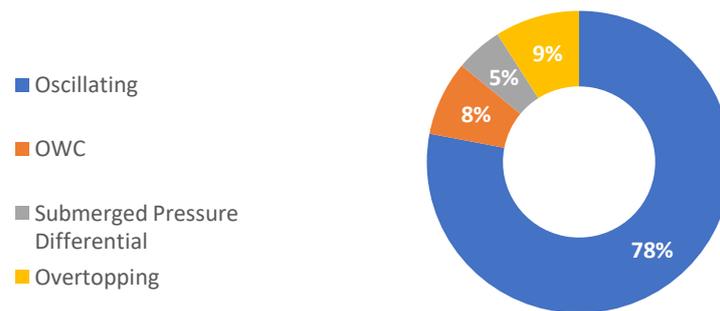


Figure 6. WECs, based on the operational principle [78].

Table 2. Different wave energy converters' (WECs') efficiencies [76,77].

WEC Device Type	Efficiency %
Pressure differential	38
Oscillating water column (OWC)	29
Overtopping	17
Oscillating body—Heaving	16
Oscillating body—Surging	37

2.2.2. Direction

The WECs, according to the wave propagation direction, are classified as follows:

Attenuator: Usually, the attenuator is a flexing device, mounted parallel with the direction of propagation of the wave. An attenuator works by absorbing the energy from their two arms' relative motion when the wave moves through them. This device is also a floating-type device that acts in parallel with the path of the wave and drives the waves efficiently [62]. The Pelamis [79] is a typical example. Three Pelamis units formed the commercial world's first wave-farm of Portugal's coast in September 2008 [80], as shown in Figure 7.



Figure 7. Pelamis wave farm [81].

Terminator: This device intercepts waves by standing perpendicular to a prevailing direction of the wave [82,83]. The device Salter's Duck, invented by Dr. Stephen Salter at Edinburgh University in 1978, is probably the most known of this kind, as shown in Figure 8.



Figure 8. Salter's Duck [65].

Point absorber: Point absorber has considerably smaller dimensions than a wavelength and can produce power independently of the direction of the wave propagation. The buoy can oscillate to one degree of freedom or more, as shown in Figure 9. A motion of the buoy damping extracts energy, and a generator converts it into electricity. A pitching type point absorber is the example of the Salter's Duck [39]. Wave Star [84], FO3 [85], and Manchester Bobber [86] are heaving type multipoint absorber devices.

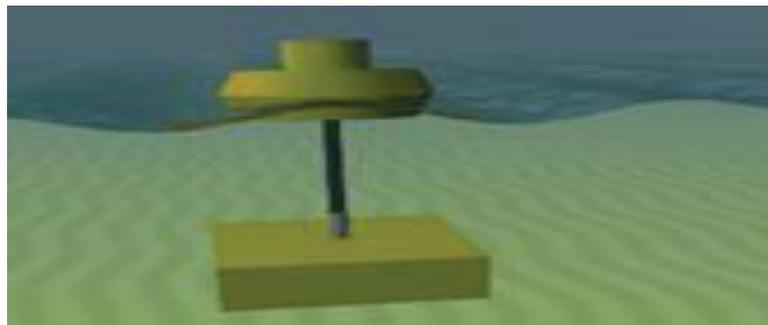


Figure 9. Point absorber [62].

Quasi-point absorber: Presented by Hals and Falnes [87], quasi-point absorbers characterize axisymmetric WECs, which are unresponsive to the direction of wave (like point absorbers) but have fairly broad dimensions comparable to wavelengths (like terminators).

A summary of WECs based on orientation is shown in Figure 10.



Figure 10. WECs based on orientation [78].

2.2.3. Location

Wave energy converters are classified based on the location as offshore, nearshore, and onshore.

Offshore locations: A higher energy level of waves in deep water makes the offshore devices more impressive for the production of wave power [83]. Offshore devices, due to the severe climatic conditions, can sustain larger loads; however, they are much more challenging to deploy and operate.

Nearshore: These devices are referred significantly to as lower water in which converters are attached commonly to an ocean floor. The example of a nearshore type device is WaveRoller [88].

Onshore: Onshore devices are fixed on the shoreline, with the benefit of being easy to maintain and install. Furthermore, moorings of deep water are not required, and the risk of storm damage to onshore devices is minimal, but the wave regime is less efficient.

A summary of WECs based on location is shown in Figure 11.

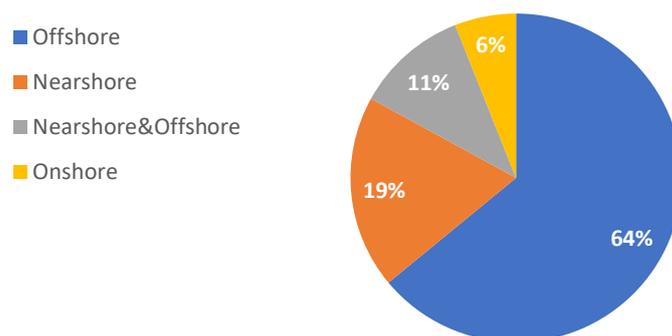


Figure 11. WECs based on location [78].

2.2.4. Power Take-Off

Typically, recognized power take-off (PTO) is the process where energy passed between the WEC and the waves, directly or subsequently, turns into a usable form [89]. The types of PTO include hydraulic, hydro, pneumatic, and direct-drive, and their efficiencies are shown in Table 3. The critical challenge of the development of PTO is that the machines must work at lower speeds and higher forces, whereas typical electrical generators are planned for low torque and higher speed motion. Although the efficiency of the hydraulic system is relatively low (see Table 3), it is most suitable for extracting wave energy, as seen in Figure 12 and further WEC examples with their (PTO) systems presented in Table 4.

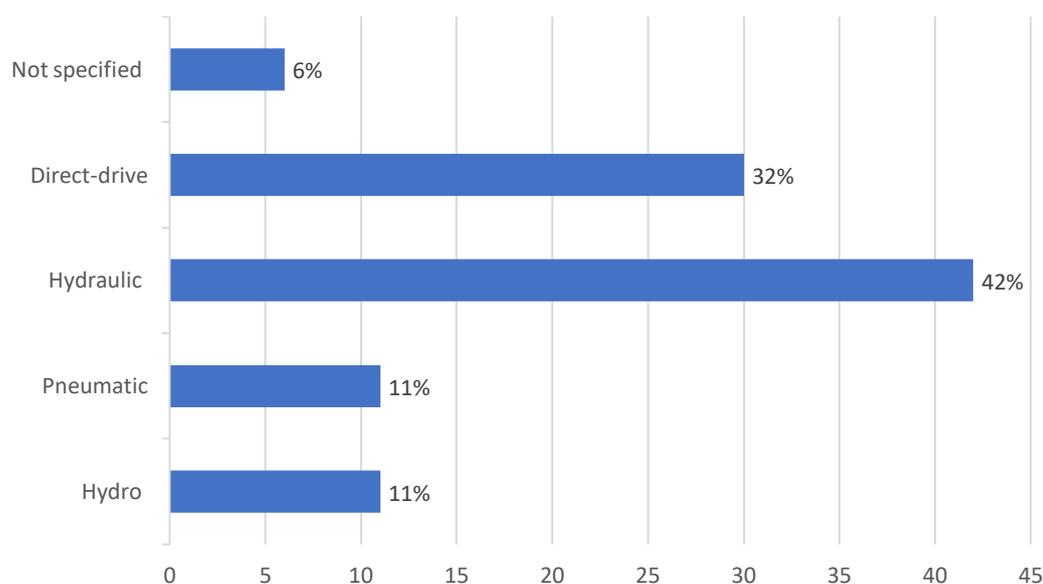


Figure 12. WECs based on PTO principle [78].

Advancements and improvements continued in the wave energy sector, and a detailed assessment of power take-off is provided in reference [90].

Table 3. Power take-off (PTO) systems' efficiencies [91].

WEC Device Type	Efficiency %
Hydro	85
Pneumatic	55
Hydraulic	65
Direct mechanical drive	90
Direct electrical drive	95

Table 4. WEC examples with their (PTO) system.

Name of WEC	Type of WEC	PTO	References
Pelamis	Pitching system	Hydraulic system	[92]
Wavebob	Heaving body	Hydraulic system	[93]
SEAREV	Pitching system	Hydraulic system	[94]
REWEC3	OWC	Wells turbine	[95]
Sakata	OWC	Wells turbine	[96]
AquaBuoy	Heaving body	Impulse turbine	[97]

2.3. Power Production Analysis of WECs

Table 5 shows the systems-based power production analysis of WEC. The power values produced varies, which may well not be consistent and depend on the device's size and location.

Table 5. Systems-based WEC power production analysis.

Ref.	System	Power	Remarks Advantages/Disadvantages
[98]	Wave Dragon	11 MW	It is portable, the installation process is easy, but it operates in limited places, and also is expensive
[98]	Power Buoy	11 MW	Continuous electricity produced from all of the directions, but their installation required in far and deep sea
[82]	Oyster	800 kW	It creates no pollution and maintenance process is easy, but it requires a large area for operation
[98]	Pelamis	750 kW	It is portable, and the maintenance process is easy, but it is expensive
[99]	Penguin	500 kW	It is reliable and durable for extreme environments, and the maintenance process is easy, but it requires a large area
[82]	LIMPET	500 kW	It is installed nearshore and has a low maintenance cost, but their initial costs are high

2.4. WEC Design Challenges

The design of an effectual and sturdy WEC faces several challenges.

(1) Some of the biggest challenges for WECs are the design and implementation because the technology is still in its infancy compared to other solar and wind [100–103] matured renewable technologies, despite numerous patents and prototypes published in several kinds of literature.

(2) The extraction of sea wave energy not only needs to be sustainable but efficient, because it may not be the sole accessible offshore clean energy option. In addition, to increase the WECs' energy generation from the rate of current production, the power production cost needs to be decreased; at the same time, the efficiency of the system also needs to be improved as a whole.

(3) The WECs facing challenges vary from technological issues to operating and maintenance problems [104], extreme weather, and ocean salinity conditions in an extreme marine environment [105].

(4) The challenge is to extract energy from lower motion frequency and larger and variable displacement.

(5) The waves of the ocean change in periods and heights, and it is challenging to transform the waves' kinetic energy into electric energy.

(6) The energy converters for ocean waves are typically located in extreme offshore climates. The appropriate mooring system, as well as the anti-corrosion perfect design, are dangerous.

(7) Wave energy converter optimized design is also a concern, as its design could impact the performance.

Some recent research [106,107] investigates the potential for the collaboration between the offshore wave power converters and wind turbines in a similar geographic region in order to maximize energy production and to minimize the costs of installation. It will provide a range of significant synergies and benefits, such as a reduction of the cost of installation integrating the electrical services, foundations, development and planning, operations, and maintenance expense.

3. Mooring System for WEC

WECs are essentially moored with cables and anchored to the ocean floor, generating electricity by using wave energy. As with most moored offshore structures on the ocean floor, a distinctive WEC mooring device may consist of three components: mooring lines, anchors, and connectors.

Based on their importance to WEC action, mooring systems are divided into three classes [108–110]: reactive, passive, and active.

Reactive mooring: The mooring mechanism is an essential part of a transformation system and is particularly appropriate as the PTO takes advantage of the associated motions between the seabed and WEC.

Passive mooring: When station holding is the primary aim of a mooring, the WEC's power extraction from waves is unaffected.

Active mooring: The mooring system has an essential effect on the WEC's power extraction and dynamic response, additional to offering station keeping.

3.1. Mooring Materials

Synthetic fiber rope, chain, and wire rope are three primary types of mooring lines used for offshore structures that may be used in WECs [111–113]. A comparison of various materials of the mooring line is provided by Harnois [114]. The material preference will affect factors, including the elastic stiffness, inertia, and mooring line damping. Chains are resistant to abrasion and offer decent catenary stiffness. However, some WECs cannot find the chain restraining stiffness appropriate. They can hinder the motion of oscillation needed to transfer energy. In addition to high costs, it is difficult to maintain a catenary line, since the chain embedded into the seabed is exceedingly long for much of a service period.

Synthetic ropes become beneficial along with their buoyancy properties, which can reduce the impact of mooring weight and are ideal options for applications in deep water [115]. Synthetic ropes such as polyester, High Modulus Polyethylene (HMPE), aramid, and nylon are typically used with mooring lines. A detailed review of the evaluation of several synthetic ropes for ocean renewable energy can be found in reference [116], in which it is confirmed that nylon and polyester are the appropriate materials for the compliant mooring structures.

A summary of the materials of mooring lines is shown in Table 6. The table compared different mooring lines like a chain, synthetic ropes, and wire ropes. The importance of a line's features relies on the configuration of a mooring.

Table 6. Summary of the mooring line.

Mooring Lines	Installation	Remarks
Chain	Easy	High abrasion, intermediate fatigue resistance, low elasticity, and low cost
Wire Rope	Intermediate	High abrasion, high fatigue resistance, low-intermediate elasticity, and intermediate cost
Synthetic Rope	Hard	Polypropylene nylon: Low fatigue resistance, low abrasion, high elasticity, and cheap cost Polyester: High fatigue resistance, abrasion, and elasticity, and costs are intermediate Aramid HMPE: Very high fatigue resistance, intermediate abrasion, low elasticity, and expensive cost

Anchors are like terminals that pass the entire forces of the system to the seafloor. The primary considerations for the anchor should be the capability of withstanding high horizontal and vertical (some cases) loads in certain seabed forms, soft to hard, and, further, be readily installable and cost-effective [114]. The mooring structures, in general, are subjected to strongly cyclic, nonlinear loading conditions, primarily caused by incident waves. There are several types of anchors available: drag anchor, dead weight, plate anchor, and pile anchor. Discussions are provided about anchors for wave energy converter systems in references [117,118]. The summary of different types of anchors is shown in Table 7. Numerous types of connectors are used in marine structures and WECs [111,119].

Table 7. Summary of anchors.

Anchors	Ultimate Holding Capacity (UHC)	Load Direction		Cost	Remarks
		Omnidirectional	Horizontal		
Deadweight	Lowest	-	Good	Expensive for UHC	Useful for all soil types
Drag-embedment Anchor	Highest	Good	Good	Cheapest	Perform well for all soil types, except hard rock
Piles	Low	Good	Good	Expensive	Perform well for soft and medium clay, but not suitable for hard clay and rock. For sand, only driven pile performs well
Vertical Load Anchor	High	Good	Good	Expensive	Perform well for soft and medium clay, but not suitable for sand, hard clay, and hard rock

3.2. Mooring Configurations

Mooring systems may be divided appropriately for WECs into two primary configurations: single point mooring and spread mooring.

Spread mooring prevents the horizontal movement of the WEC and, thus, does not allow it to weather-vane. These mooring could be ideal for the non-directional energy converters. Single point mooring enables weather-vaning for a WEC [120,121]. Configurations of moorings are also categorized as slack/catenary and taut mooring. Taut mooring depends on whether cables are tightly stretched under pretension, and catenary/slack mooring depends on whether the cables hang slack. If the mooring system's impact on the WEC's vertical motion is to be reduced, the upper portion of the mooring cables must remain as horizontal as possible and connected directly to the WEC. In this condition, a buoy is connected horizontally to a WEC and anchored to the bottom of the sea. When mooring system

compliance has to be improved, then the mooring lines must be attached with clump weights and subsurface buoys.

There are many subtypes of mooring systems, so it is hard to identify which is better without taking into account the safety, type, location, and cost of the WEC [122,123]. However, in spread mooring, Catenary Anchor Leg Mooring (CALM) appears to be more accessible, and in single point mooring (SPM), Single Anchor Leg Mooring (SALM) appears to be more prominent in realistic projects [117,124]. The summaries of mooring lines and anchors are shown in Tables 6 and 7, respectively.

3.3. Mooring Requirements

In order to achieve a reasonable mooring of floating WECs, several designs and materials are proposed. It must be built as an essential part of the complete structure, which contributes to the efficiency of power extraction [125–127]. Nevertheless, the list for mooring requirements is lengthy and complicated, and it is not an easy task. A summary of primary design criteria for WECs' mooring systems (collated mainly from Harnois [114], Fitzgerald [128], and Harris et al. [115]) is as follows:

(1) The moorings have to keep the system to a specified tolerance on the station. For WECs, the distance to adjacent machines in such an array or maximal offset permitted by the electrical power cable usually determines this.

(2) To mitigate the forces exerted on to the system itself, anchors and mooring lines must be appropriately compliant with the environmental loads.

(3) Under load criteria from classification rules [129], the moorings should remain intact, under ultimate, accident, and fatigue limit states.

(4) The mooring system's horizontal footprint should be lessened for purposes of array performance.

(5) Conditions of slack-snap must be avoided.

(6) In arrays, feasible inter-moorings should require removal for the operation and repair of the individual system without disrupting neighboring devices.

(7) Moorings must not be harmful to power absorption under operating conditions.

(8) The mooring system installation should be decided to make it as simple as practicable. Inspection, repair, and possible removal of components of the mooring must be required within a standard weather timeframe.

(9) The design should consider marine growth, corrosion, and longer-term aging.

(10) It should be adequate to include the tidal scope at the position of installation.

Consequently, the design of a mooring is a crucial part of the project of a WEC because of wind, waves, and current; the structures are usually considered for use in regions with challenging environmental loads. Existing offshore guidelines, such as the DNV-OS-E301 [129], resolve these survivability challenges.

4. Modeling Approaches for WECs

The dynamic behavior of floating structures and waves, whether offshore platforms or ships, is usually modeled with a linear potential theory that is clearly illustrated in references [130,131]. These structures' requirement to include small movements fits well with the small movement supposition of the linear potential theory. In addition to its clarity and reliable performance, the linear potential theory is often admired for the prospect of using it in simulations of time or frequency domains. As floating structures, it can be probable that linear potential theory could be used for modeling of floating WECs. For some, this may be valid, but others depend on large resonant motions' amplitude to harvest energy and the linear potential theory's small motion supposition does not apply.

More suitable approaches for these kinds of devices will be computational fluid dynamics (CFD) as in reference [132] or nonlinear potential theory as in reference [133]. CFD simulations are increasingly computationally affordable, as stated in the study in reference [134], and are becoming highly competitive with physical models. Nevertheless, both the simple nonlinear theory of potential and CFD

are still challenging for useful engineering purposes. The most popular chosen method for applications of wave energy in CFD has been the use of totally nonlinear simulations of Reynolds-averaged Navier–Stokes (RANS) along with the method of the volume of fluid (VOF) for the interface of air–water [135].

The benefit of ocean basin experiments is that under managed environmental conditions they allow a thorough study of the system of WEC responses and can also be updated regularly. For different purposes, multiple ocean basin experiments of the systems of WECs have been performed, such as design evidence, power efficiency evaluation, analysis of hydrodynamic response, parametric analysis, and measurements of mooring and structural forces. Implementing a WEC model relies on simulation and numerical modeling because it offers the versatility to evaluate at a comparatively low cost with a wide range of WEC design choices. In order to evaluate scale results, Dai et al. [136] validated a computational model of the fixed OWC against physical experimental testing. When measurement variance was included, deviations up to 15 percent were reported while analyzing the amplitude operators' (RAOs') response and the power captured between numerical and experimental performance. Xu et al. [137] conducted a numerical and physical experimental analysis of the type of WEC as a floating point-absorber. Independent experimental research campaigns were undertaken in separate test facilities and with varying sizes under both survival and operational conditions. Windt et al. [138] verify the Wavestar WEC 1/5th NWT scale model for the output of power evaluation, detecting inconsistencies between numerical and physical results for the body motion, surface elevation, force of power take-off, and hull pressure. It is emphasized that the validity of a physical complex system needs extensive knowledge about device features in the computational model for the formulation's assumptions.

In Table 8, numerous computational design techniques and experimental methods have been mentioned.

Table 8. Publications of different modeling approaches for WECs.

Type of Approach	References of Publications
Numerical Modeling	[139–143]
Numerical and Experimental	[144–148]
Physical Experiment	[149–153]

Consequently, the simulations of the floating WECs still need to rely on the linear potential theory. Time-domain simulations were performed to integrate nonlinear adverse effects with the aid of the methods of convolution like van Oortmerssen [154] or Cummins [155]. However, as Mårtensson and Bergdahl [156] had already recognized in 1995, floating WECs need specific methods to design.

5. Design of Mooring System

The mooring system design of WECs is a complex comprehensive system design, including design specifications; design sea states; structural characterization; mooring system data; selection of calculation and analysis methods; analysis, comparison, and verification of results; etc. The overall design flow chart is shown in Figure 13.

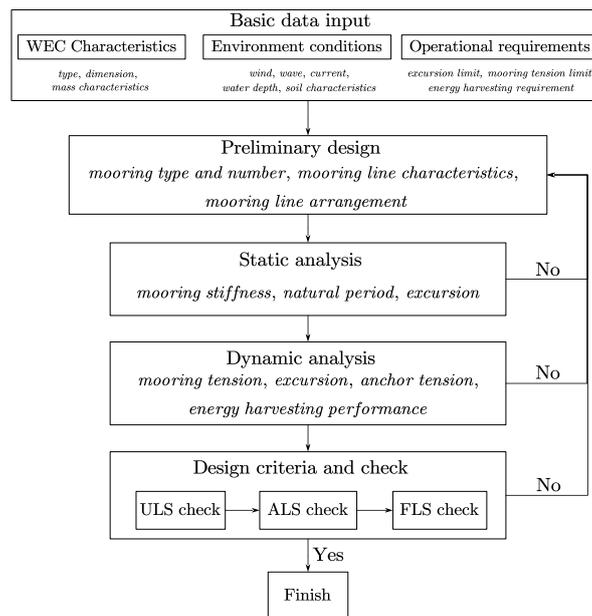


Figure 13. Flow chart of mooring design. ULS—ultimate limit state, ALS—accidental limit state, and FLS—fatigue limit state.

5.1. Mooring Design Considerations and Standards

The design contemplation for mooring structures comprises design loads, design criteria, design life, maintenance, and operation. The criteria of the design are specified concerning limit states like the ultimate limit state (ULS), accidental limit state (ALS), and fatigue limit state (FLS). Offshore design standard [157] describes these limit states as follows.

The ultimate limit state must assure that the independent mooring cables have enough strength to survive the load impacts caused by severe environmental behavior.

Accidental limit states assure that a mooring mechanism has enough ability to tolerate the collapse of the one mooring cable.

Fatigue limit states assure that the independent mooring cables have enough ability to survive cyclic loading.

The evaluation of a mooring structure is carried out by these kinds of three types of limit states. The design of the mooring cables for a permanent mooring should address all these three types of limit states [157]. The evaluation of the mooring structure consists primarily of two categorizations of the environmental conditions: the maximum operational and maximum design conditions.

The maximum design condition is determined by the conjunction of wind, current, and waves for the design of mooring structures. This condition is characterized as an intense conjunction of the waves, wind, and currents that cause excessive loads within the design environment [158]. The environmental loads are stated as wave height, wave period, wave spectrum, wind direction, wind speed, the function of wind spectrum, current direction, the current speed of surface, and current profile over the depth [157].

The maximum operational condition is described as a conjunction of wind, currents, and waves under which the device is capable of continuous operation, for example, drilling, offloading, or sustaining a gangway connection. This condition does not surpass the overall specification limit [158].

There is a range of certified companies globally in order to guarantee the offshore structures' safe and practical design. The structure can be accredited and installed in the preferred destination by meeting the requirements of these companies. All these specifications are defined in several design guidelines that cover the methodology of analysis, safety factors, and specifications for materials. Table 9 provides the design standards documents for the mooring of WECs.

Table 9. WECs' mooring documents of design standards.

Documents	Scope	References
DNVGL OS E301	Details of mooring processes	[159]
ISO/TS 14909	Offshore station fiber ropes with a high polyethylene modulus	[160]
IEC TS 62600-10	Details of mooring practices	[161]
DNVGL OS E304	Wire ropes details	[162]
DNV-RP-H103	Details of marine operations	[163]
DNV OS J103	Environmental loads	[164]
DNVGL RP F205	The method of dynamic analysis for floating structure	[165]
CIRIA C666	Metocean data	[166]
DNVGL RP N103	Marine operation analysis and modeling	[167]
DNV RP C205	Environmental loading calculations details	[168]
API RP 2SM	Synthetic rope details	[169]
DNVGL RP E302	Plate anchors installation and design information	[170]
API RP 2I	Mooring hardware inspection	[171]
ISO 18692	Polyester mooring ropes details	[172]
DNVGL OS E303	Fiber ropes information	[173]
ISO 19901-7	Detailed of mooring practices	[174]
DNVGL OS C101	Details of steel structures in offshore	[175]
Nearshore Position Mooring	Environment loads	[176]
DNVGL OS E302	Mooring chain details	[177]

5.2. Analysis Model Types

Mathematically explaining the mooring system's behavior with associations among parameters, variables, and environmental inputs may be applied with various types of models, differing in complexity. These different types of models can be categorized as static, dynamic, or quasi-static. Static models only recognize constant loads, including buoyancy, gravity, varying non-time current and wind, and mean forces of wave drift. A static analysis considers the equilibrium between the means environmental or constant loads and the mooring lines restoring force upon on a WEC. A quasi-static technique suggests that the system's motion is continuous and linear among two static locations over a particular time phase in which the device loads are considered to be constant [178]. This approach lacks dynamic effects upon the mooring system, ignoring the system's motion reliance on damping, fluid acceleration, and mass [179]. In general, the petroleum and gas industry mooring systems are mostly modeled using a quasi-static technique, because of their large structures and correlating inadequate responses with low velocity.

The structures are usually of lesser masses, in the market of WEC, so there may be an acceptance or even a need for higher displacements. Thus, a more distinctive response with more significant velocity, but lower loads, is generally reported; usually, the quasi-static technique ignores all of the dynamic effects from fluids, mass, and damping and considers just horizontal displacements, whereas dynamic analysis resolves motion's equation across all of the degrees of the freedom and incorporates all of the dynamic effects [180].

Considerable non-linearities into the mooring system are present that must be adequately modeled by a software program. Non-linearities comprise, for example, nonlinear lines stretching, geometry changes, fluid effects, and the bottom effects. When resolving the motion equations, a time or frequency domain approach can be used. In the approach of the frequency domain, the series of linear motion equations handle the motions, measure, and integrate the values of the statistical peak for various motion inputs. The frequency domain demands that all of the non-linearities must be linearized. This linearization is inappropriate in the approach of a time domain, where the problem can be solved by direct mathematical integration. Therefore, the analysis of a time domain also includes time history of line tensions and WEC displacements.

Two different approaches could be used, uncoupled or coupled, when resolving the motion's equation [1]. In the method of uncoupled, initially, the motions are resolved by ignoring the mooring lines' effect after that WEC's fairlead motion then is fed it into the cable, and tensions manage to be solved throughout the mooring lines. In the coupled method, the total equations of the system both for

mooring lines and WECs are solved simultaneously. In addition, to accurately model the mooring line's effects on WEC motions as well as the mooring system's full nonlinear actions, design guidelines specify that the coupled method must be adopted. Comparably, a simulation of the time domain with all of the non-linearities and the dynamic effects is required for this.

5.3. Research Status

The mooring system must be designed to not negatively impact the WEC's efficiency by lowering mooring loads and motions behaviors. In addition, the mooring system costs must also be taken into account. The research status is described as follows.

5.3.1. Mooring Design Concept

Fitzgerald and Bergdahl [181] and Martinelli et al. [27] describe in-depth many essential parts of WEC mooring design. The authors concluded from the findings of the study by reference [181] that the usage of the synthetic cable through more significant elasticity can significantly reduce the total load of the structure. Thomsen et al. [108] assess the existing state of mooring system design with a variety of Danish WECs, including a clear description of the mooring design approaches and assessments.

The design of mooring for WECs is available in reference [182], and the probable WEC design requirements can be seen in reference [183]. The evaluation of mooring structures in Denmark for large WECs was researched in references [184–186], where the expenses of the numerous mooring structures have been approximately measured. A comprehensive explanation of the cost expenditures of mooring structures for larger WECs is discussed in reference [187].

5.3.2. Static Approach for Initial Mooring Design

Monarcha and Fonesca [188] propose an analytically static approach for the initial design of multi-line mooring for offshore floating structures. Fonesca et al. [189] firstly proposed a static analysis to determine possible mooring designs, and then further refined and improved them with dynamic analysis. For preliminary design, Johanning et al. [179] suggest that a static approach should be used to measure the maximum stress and tensions on the mooring components of the WEC due to severe environmental factors by which initial dimensions of the components of material can be determined for more analysis. The static analysis is incredibly simple, producing results in fewer seconds, whereas the dynamic analysis may take hours to produce relevant results, relying on the complexities of the system [189].

5.3.3. Dynamic Approach for Mooring Design

A dynamic analysis is needed to determine the maximum tension within a mooring system. Models of dynamic mooring cables are different from models of quasi-static since they can accommodate the effects of drag, inertia, and internal damping. Dynamic mooring cables, in particular, transmit both transverse and longitudinal vibrations. In models of quasi-static such vibrations are neglected. The mooring initially was built using a quasi-static modeling process, and dynamic simulations then followed. Then, the calculations of dynamic may be performed in the frequency domain to enable the execution of several cases, from which some crucial cases must be run in the time domain.

Brown and Mavrakos et al. [190] compared experimental data with the outcomes from many frequency and time domain methodologies. Differences in the measurement of the mooring damping were found. Liu [191] focused on the response of the dynamic analysis of moored floating structures and extreme value difficulties. The standard method of calculating the extreme tensions of the mooring line is to run multiple time-domain simulations that are computationally costly. Consequently, Liu [191] suggests that in order to estimate the tension of extreme mooring lines, just fewer simulations, and the extreme theory value therein, are needed. Liu determines the predicted extreme tensions of mooring cable, utilizing statistical techniques, on time-domain nonlinear simulations [192], and afterward extreme responses through combined Low Frequency-Wave Frequency (LF-WF) excitation for floating

moored platforms [193]. Masciola et al. [194] studied the different theories of dynamic line modeling, which are currently being used in offshore simulation applications. The benefits of each model were assessed, and even though every model had merit, the lumped mass (LM) model was selected for inclusion in the mooring analysis program (MAP). Bergdahl [195] addresses the number of environmental factors that should be considered when developing a mooring system for WECs. An overview of how to build a mooring system with the help of static, dynamic, and quasi-static models is present in various design stages.

5.3.4. Optimization Approach for Mooring Design

Design optimization of mooring systems of offshore floating structures is a challenging task, partly because of the large number of design variables, complicated design constraints, nonlinear system behavior, and time-consuming numerical simulations.

Shafieefar and Rezvani [196] introduced the optimization of the floating platform mooring design, which reduces platform responses. A genetic algorithm (GA) had been applied, and they explain precisely how to create a GA code to solve mooring configuration optimization problems. The optimized model of moorings was tested for varying environmental factors, and conclusions were presented, with the time expected to run. Pillai et al. [197] described a method for optimizing mooring structures in renewable offshore energy systems. This methodology examines the positioning of the anchors along with the length, diameter, and material of the mooring cables to reduce the tension in the cables, mooring system costs, and the risk of fatigue into the system at the same time—the multi-objective strategy used for these objectives instead of limiting to a single target optimization problem. Pillai et al. [198] proposed a new method for multi-objective optimization of mooring systems that used a randomized forest-based surrogate methodology combined with the genetic algorithm—minimizing mooring system costs as well as cumulative fatigue risk. Li et al. [199] introduced an integrated methodology for optimizing mooring system design. The methodology incorporates screening analysis, time-domain simulations, experiment design, and metamodel-based procedures of optimization, where the Kriging metamodels are used as surrogates for simulated time-domain responses. The proposed approach also refers to the design of the optimization of other ocean structures. Wang [200] provides an optimization analysis on the design of offshore mooring structures, describing that the usage of mooring models with the approach of numerical optimization to provide software that helps in the design and to optimize offshore mooring structures.

5.3.5. Experimental Approach for Mooring Design

Sirigu et al. [201] performed an experimental study of the hydrodynamic efficiency of a floater and compared the outcomes of numerical codes. Exploring the various effects of the forces of moorings on the dynamics of a floater, two separate configurations of the mooring were evaluated, and the variations between experimental and numerical findings and the nonlinearities effect on hydrodynamic efficiency were concluded. Sirigu et al. [152] proposed an experimental strategy on an Inertial Sea Wave Energy Converter (ISWEC) scaled prototype 1:20 based on the effect of the mooring configuration on loads in extreme conditions of the wave. The goal was to find the solution of mooring that could ensure the proper operation of the system and the severe sea conditions for load carrying. Yang et al. [202] presented a numerical and experimental analysis of a taut-moored WEC device with a kind of point-absorber WEC. Two realistic models were designed and tested in the 1:20 and 1:36 scale models and motions of the WEC buoy were validated. Yang et al. [203] in another study, validated calculations of the mooring force for the same model [202]. An experimental study on a floating 1:25 scaled OWC model was given in reference [204]. Two kinds of mooring materials considered, nylon rope and iron chain, were used to study their effect on the mooring lines' tensions. It concluded that nylon rope could introduce substantially greater surge motion; no shock loading was found in the measured wave conditions for the iron chain configuration. An experimentally investigated taut-mooring system behavior for floating WEC is available in reference [205]. An experimental

analysis of advantages and effects that various mooring principles of point absorbers might have is available in reference [206].

Table 10 provides some further research publications of different types of mooring system design for WECs.

Table 10. Research work for the design of WEC mooring.

Type of WEC	Mooring System	References
Heaving Point Absorber	Spread mooring with three cables	[207]
Two Body Heaving Point Absorber	Spread mooring with four cables	[208]
Overtopping	CALM	[151,209]
Attenuator	Spread hybrid	[210]
Point Absorber	Submerged buoy floater without and with a slack chain	[211]
Two Body Heaving Point Absorber	Three-point mooring with multiple legs	[212]
Oscillating Wave Surge	Spread taut	[213]
Multi-point Absorbs	CALM	[124]
Point Absorber	Spread slack	[207]
Heaving Point Absorber	Floaters and weights with a slack chain	[214]
Large-size Floating WECs	Taut SALM and SPM	[184]
Overtopping	Five catenary cables attached to WEC	[215]
Attenuator	Single point catenary	[216]
Point Absorber	Spread catenary	[217]
Floating Oscillating Water Column	CALM	[218]

5.4. Software

There is a wide range of software programs for the analysis of mooring floating structures, for example, quasi-static for ports design and offshore petroleum and gas structures, as well as other dynamic modeling tools. For WECs' moorings, only dynamic software is required. The list of some suitable software options is in Table 11.

Table 11. Tools for mooring systems modeling.

Software's	Developer	Used for Modeling
Aqwa	ANSYS Inc. [219]	[220–222]
OrcaFlex	Orcina Ltd. [223]	[217,224–233]
DeepC	DNV-GL [234]	[235,236]
Flexcom	Wood Group Kenny [237]	[238]
ProteusDS	Dynamic System Analysis Ltd. [239]	[212,240]

5.5. Mooring Design Challenge

The mooring system is a core component in the economic viability of wave energy projects. WEC moorings need to meet the same requirements as the other offshore systems. Designing and analyzing mooring systems poses many challenges, some obvious and some subtler. Sections below illustrate some of the main issues that require attention.

5.5.1. Metocean

Firstly, it is not easy to collect quality data within the timeframe needed for the site. Early data collection planning is usually cost-effective and significantly reduces needless design conservatism. Even when there are useful data available, suitable criteria development for floating structures still are challenging.

In order to define the design requirements and assess extreme environmental conditions to be evaluated, a thorough assessment of the dynamic response of the system is necessary. WECs are usually mounted in depths of water <100 m [42]; therefore, the wave height design is technically a

significant component. For that, loads of ocean waves and tidal fluctuations at the site of installation should be incorporated.

The specialist of metocean and the mooring need to collaborate to match the design requirements based on the responses. A permanently designed system, for example, in the North Sea, must be planned to withstand the highest wave predicted in the hundred years and leading to waves over 20 m higher in places [129].

The concept of extreme and related environments can be highly valuable, as well as can have a considerable impact on design. For example, cases of an extreme environment may be described as a return period of 100-year condition. The environment associated may be the 90 percent non-exceedances current and wave condition that must be applied to the design simultaneously. To accurately determine an associated environment, the specialist of metocean needs to consider the responsiveness of the dynamic response of a system in both the direction and magnitude of an associated environment.

5.5.2. Responses

For the response criteria for WEC systems, engineers are confronted with complexity relating to the maximum appropriate mooring configuration as well as long-term durability of mooring components. The concepts of mooring configuration for WECs' progress need analysis from theoretical and experimental studies. The moorings would either need sufficient flexibility to withstand significant displacements or even have adequate capacity to resist their hydrodynamic loads for controlling the motions of the structure. With regards to the retaining flexibility of station, moorings play a significant role in several WECs' designs as they affect the amplitude of the hydrodynamic action.

When designing the mooring systems for WECs, the challenging issues are the environmental inputs' broad range frequency and responses of the mooring system. The time ranges in which physical phenomena arise within the mooring structure cover: static loading that varies according to the tidal influences, WEC Low-frequency motions due to the 2nd order wave drift, WEC Wave-frequency motions, and High-frequency loading that propagates and acts on the line. Although these effects arise at various frequencies, every one of them may be handled independently by one modeling approach to enable the modeling tractable.

5.5.3. Strength and Fatigue

The role of designing a good mooring system for the conditions of design loading may be minimized to choosing the best combination of material strength and compliance. The harsh offshore environment presents a mooring design challenge in established industries like the oil and gas industry. Thus, the design of mooring is closely related to the output of power production [128]; that is why moorings must be considered in a quite early design stage and development of the WEC concept.

Evaluations of failures of the mooring line reveal that the majority of problems arise during the operation of the initial ten years, with the bulk of failures happening in the initial five years [241,242]. Another analysis of incidents of mooring [243], based around 2000 to 2013 on the Norwegian continental shelf, reveals that 54% of the 26 marine accidents reported were owing to breakage of the mooring line. The research highlights the most likely technological reasons for cable failures: line overloads due to snap loads or severe weather conditions, chain fatigue fractures, and fiber lines impaired.

In several areas of the globe, commonly, mooring systems for shallow water are designed to satisfy the requirements of strength and usually meet the fatigue requirements, but it is no longer implemented in the deepwater system. The pretensions for the systems of deepwater are usually higher, and the mooring system of a taut nature results in dynamic tensions, which are considerably higher in normal wave conditions. Fatigue plays a dominant role in deepwater moorings, and it is particularly true concerning the chain of mooring. The prevalent utilization of a studless chain with a shorter lifetime of fatigue, therefore, made the issue more serious.

Modern designs of mooring typically use mooring line groups to keep providing redundancy as in case of a cable failure. The desire for mooring lines' pretension accuracy is strengthened as tension

inequalities in neighboring mooring lines results in a significant reduction in fatigue life on the group's highly loaded line. Sensitivity reviews are highly recommended for realistic deployment tolerances, mainly when the margins of design are small. The sensitivity of pretension fatigue damage stems from the truth that the magnitude of dynamic stress directly increases with the pretension, as well as the damage to fatigue is nearly proportional to the dynamic stress range cube. Thus, pretension imbalances within a group can contribute to reduced performance of fatigue.

5.5.4. Snap Failure

Snap loads appear in cables due to many reasons but are most generally correlated with the slack of cable and the sharp snap that happens as the cable is retightened. In the wave energy research projects [114,244], there are incidents of snap loading that cause severe damage. DNV-GL [129] suggests that conditions of slack-snap must be kept low or avoided by the probability of minimum occurrence. An effective solution to handle snap loads is to analyze them with software that accurately estimates snap duration, magnitude, and occurrence. For appropriate mooring structures of WECs, it would be useful to anticipate and minimize the snap loads in the process of design iteration.

5.5.5. Installation

It is crucial to making sure that the mooring system introduces zero or least twist during hook-up in the stage of final or pre-installation for the long-term mooring integrity. The existence of a wire rope twist may result in action to bird-caging as well as premature failure. The existence of a mooring chain twist can significantly reduce performance in terms of fatigue and strength. Preferably the mooring cables at a hook-up should be twist-free. Additional precautions are needed to prevent the implementation of twist during deployment. A few installation times may need to be invested in removing twist. This stage enhances the time of installation and, thus, the cost, but for the mooring system, optimal performance is essential.

In a mooring structure, the appropriate degree of twist is challenging, and the long-term mooring chain and mooring wire behavior in the existence of differing twist levels cannot be well predicted. There are analytical tools that may be utilized as rough guidance but may not be benchmarked. Reliable tension measuring devices are needed during deployment. Chain separation angle measurement worked practically well for catenary systems of shallow water. For taut systems, the angle resolution measurement maybe not sufficient.

6. Conclusions

Many kinds of research on wave energy are presently ongoing across the globe, especially in China, the United States, and Europe. Advances have been made in experimental research, theoretical, and model design of the prototypes of WEC moorings. The advances in the technologies for prospective characterizations of wave resources have been quite motivating as powerful computer tools and algorithms are now accessible to forecast and to simulate wave environments with spatial resolutions and finer temporal accuracy. The use of wide-scale experiments is recently demonstrated by success in numerical simulations of CFD while integrating dynamic associations between the sea waves and WEC. The use of simulations and experimental experiments in the emerging wave energy sector can contribute to higher performance. Because of the universal need to analyze, optimize, and design moorings for offshore structures, the mathematical simulation for mooring systems of WECs needs to borrow several existing approaches from the other fields of offshore engineering. This paper also provides information related to the suitability of commercial modeling tools for mooring designs of WECs. Most of the software offers some similar features, although some software provides more advanced methods.

Hybrid mooring, consisting of clump weights, buoys, and mooring lines, is an appealing option of station keeping for WECs and demonstrates excellent results in reducing mooring loads and absorbing environmental energy. Due to the capability to reduce environmental loads, it is recommended that the

SPM method must be implemented in large measurements of WECs, and indeed the SALM is a suitable option for floating WECs. Spread mooring works well, in the station keeping of small structures of WECs. For most situations, because of its wide footprint, high stiffness, and significant expenses, the catenary mooring cables are appropriate for shallow water WEC applications. Fiber ropes, particularly for materials that are highly compliant, for example, nylon or other elastic ropes, demonstrate significant benefits in the use of a WEC mooring. However, synthetic rope fatigue and wear issues must be considered.

The mooring system must be designed to not negatively impact the WEC's efficiency by lowering the mooring loads and motion behaviors as much as possible. Additionally, the mooring system costs must also be taken into account, and the energy levelized cost decreases as the efficiency of wave power increases. Moreover, other factors, like water depth, may also be responsible for costs. In comparison to floating structures, the water level would undoubtedly impact fixed structures. If the range of WECs increases further offshore, then the cost of transmission will rise. Transmission expenses can be minimized by sharing deployed facilities in the offshore region, such as wind turbines, if accessible.

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