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Mooring System Considerations for Renewable Energy Standards

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Abstract

Marine renewables have made great strides in recent years. The IEC, ABS, and DNV GL continue to generate standards and recommended practices in an effort to formulate approved processes as the renewable products make their way offshore and into the market. There are many similarities in some of the processes and designs when compared to oil and gas structures, especially when it comes to moorings. However, many design areas are uniquely related to renewables, even within the same field of energy conversion (e.g. multiple types of wave energy converters). As more renewable systems are installed, the standards will continue to transition from philosophical to more prescriptive recommendations.

One area in which the lines are blurred between oil and gas and renewable industries is mooring systems. The interdependency between the mooring and power generation systems plays a crucial role early in the design phase. Modeling marine energy converters and the mooring system can be complex due the variability of moving parts, and without proper attention, it may be easy to underestimate the loads and fatigue cycles to which moorings will be exposed. Moorings for these structures should incorporate existing standards and recommended practices to ensure safety and reliability. Inspection, maintenance, repair, and replacement should also be considered.

As the renewable industry continues to move forward from scaled prototypes to farms of devices, the oil and gas supply chain will contemplate when to become involved from a financial and resource perspective. However, there are still hurdles within the US authorization bodies like BSEE, BOEM, FERC, NOAA, USCG, etc. to overcome. This paper addresses the existing mooring related standards and delineates areas that need further refinement or conservatism as the renewable industry moves forward with the installation of offshore energy converters.

Introduction

Many standards with regards to mooring marine energy converters (MECs) and offshore wind energy are currently in development or first publication stage. The IEC, ASCE, ABS, and DNV GL are all in the process of generating standards and recommended practices. The IEC TC 114 has issued a technical specification for mooring MECs and is awaiting feedback from practical applications for further revisions. There are not many full scale MECs that have been installed to get a representation of moored behavior, and most specifications are using standard practices for oil and gas industry as a basis for defining safety factor and limit state values. Activity in the marine renewable industry creates an ongoing need for further review of mooring standards and practices utilized for oil and gas structures to determine if these practices are suitable and when or if modifications should be made.

The complex nature of existing mooring applications is amplified by the multitude of unique MEC designs and the geographical diversity of renewable energy installation sites. Mooring specifications and a system's interaction with single rigid body floating structures is more thoroughly understood than the multi-body moving part interaction configurations typical of the renewable energy sector. Therefore, it is easier to underestimate the time and cost needed for design, analysis, fabrication and installation of MEC mooring systems. Additionally, the harsh environmental conditions (i.e. high current and large waves) that these MEC systems operate in, to maximize energy output, may impose additional constraints for suitable mooring equipment and installation requirements.

While there are similarities within mooring design processes used in oil and gas compared to those used in MECs, some attributes are unique to the renewable sector. This paper addresses the current status of MECs, mooring requirements related to design and installation of MECs, regulatory bodies and agencies, existing standards, and areas needed for future development.

Overview of Current Development of MECs

MECs use any of the following type of natural sources to generate power:

- Ocean Waves
- Ocean Current
- Tidal Currents
- Tidal Range
- Ocean Thermal GradientSalinity Gradient

Technologies to capture energy from each type are in various stages of development and there are examples of full scale operational wave energy, tidal current, and tidal range devices. Presently, several countries have installed MECs, consisting primarily of scaled prototypes, for proof of concept. Some countries with more advanced concepts have used these prototypes to produce power to a utility grid. Following the completion of full scale testing, of which many are performing at test facilities such as the UK's EMEC and Canada's FORCE, many have agreements in place to install arrays. A non-exhaustive sample of recent open sea testing and an approximate summary of installed capacity is presented in Table 1, as indicated in Ref 1 unless otherwise specified. In terms of installed capacity, the UK leads in wave energy conversion (WEC), Korea leads in tidal range energy and Ocean Thermal Energy Conversion (OTEC), and France leads in tidal currents [31]. Compared with other countries, the United States lags in prototype development and testing.

Table 1 – 2015 Global MEC Testing Status

Country	Recent Open Sea Testing [1]	Installed Capacity[1] (kW)
Australia	• Three units completed operations and were decommissioned offshore Garden Island in 2015 [11].	-
Belgium	• A scaled prototype was tested near Harbour of Ostend.	-
Canada	• Four <100 kW turbines were tested the Winnipeg River in 2015. • Two 2 MW turbines began testing in Cape Sharp in 2016 [10].	Wave: 9 Tidal Range: 20,000
China	• Tidal power plant in Jiangxia was upgraded from 3.9 to 4.1 MW. • A 100 kW wave energy converter was installed in the off Wanshan Island in the South China Sea [20].	Wave: 450 Tidal Currents: 170 Tidal Range: 4,100
France	N/A	Tidal Currents: 2,500 Tidal Range: 240,000
Germany	• As of 2015, a scaled prototype began powering the grid in Nissum Bredning, Denmark. • A modular designed WEC was installed in 2015 in Crete, Greece.	-
Korea	• A wave energy pilot plant was installed off the coast of Jeju. • A 20 kW scaled OTEC prototype continues to operate [1].	Wave: 500 Tidal Currents: 1,000 Tidal Range: 254,000 OTEC: 220
Netherlands	N/A	Tidal Currents: 1,300 Salinity Gradient: 50
Norway	• Prototype testing at Stad in Sogn og Fjordane was completed.	Wave: 200

Portugal	• An oscillating water column continues to power the grid in Azores. • A WEC demonstration project was completed in Peniche.	Wave: 400
Singapore	N/A	Wave: 16 Tidal Range: 5
Spain	• After 4 years, 1 GWh was completed off the Amintza-Lemoiz coast. • Off the Canary Islands, two WEC prototypes were tested.	Wave: 296
Sweden	• Tidal turbines near Söderfors were tested. • In 2015, 36 tidal and wave energy converters were tested off the west coast at Sotenäs, powering the national grid [28].	Wave: 200 Tidal Currents: 8
United Kingdom	• One 1.5MW turbine of a 4 turbine array was installed in Pentland Firth, Scotland and grid connected in 2016 [26]. • A tidal turbine was installed in the Ramsey Sound.	Wave: 960 Tidal Currents: 2,100
United States	• A WEC was tested in Kaneohe Bay, Hawaii. • A turbine was tested in the Kvichak River in Alaska.	-

NOTE: [1]*Information that is not explicitly referenced was obtained from Annual Report Ocean Energy Systems, [31]*

Mooring Considerations for MECs

Overview

The primary objective of the mooring system for a MEC is to maintain some form of stationkeeping without unduly inhibiting energy extraction. Indeed, some WECs are designed to optimize power generation by leveraging the mooring performance characteristics. Unlike the floating structures in oil and gas where one of the main objectives is to minimize offsets, the desired range of motions for MECs differs widely depending on the type of device and the required optimal performance characteristics for power production. Mooring systems can be designed to facilitate small or large allowable offsets or allow for weathervaning into the predominant environment heading. Fundamentally, MECs require harsh ocean environments to maximize electricity generation. Operating in strong wind, wave, and current conditions, and the potentially distributed nature of these locations, creates many challenges to the industry in terms of the mooring design, fatigue design, anchoring, installation, inspection, and maintenance.

Oversimplification of the mooring system can lead to underestimating schedule and costs of the overall mooring scope. The design of mooring systems requires evaluation and consideration of:

- Metocean conditions and environmental assessment, site geological data
- Mooring components type and length
- Anchor type and size
- Dynamic analysis
- Installation requirements and procedures

Furthermore, long term maintenance and replacement requirements are often inadequately considered. In some cases, the design and evaluation of the mooring system can trigger an iterative process that in-turn affects the design of the MEC device. Consequently, the MEC structure may need to consider mooring survivability at the expense of performance [25].

The scope of work and costs for designing and installing a mooring system can be significant compared to the MEC device cost. In the past, some MEC developers have used the most readily available vessel and personnel that fit within their limited budget to install systems. As a result, the underestimated costs and subsequent overruns have limited the forward progress of a project as any delays or failures during installation can quickly consume small budgets [25]. It is critical to the success of MEC design and development that power capture, mooring, installation and maintenance requirements are all properly considered and accounted for due to their interdependence and impact on the lifetime cost of the system.

Metocean conditions and environmental assessment

Establishing the specific wind, wave, and current conditions and design conditions may be straightforward but no less challenging. In an effort to outline areas most suitable for MEC devices, the Department of Energy funded several resource assessments for offshore wind, wave, river current, tidal current, ocean current, and OTEC [23]. However, while this may help to highlight potential installation sites, more thorough site information is required. Many prime locations for energy production are in remote locations with limited historical data. Numerical modelling tools and expertise can be used to extrapolate historical conditions but these techniques have larger uncertainty than direct measurements at or near the site. Initial studies may reasonably assess the resource, but longer duration data may be required to realize statistically meaningful data for day to day operations, extreme design, and energy capture predictions. Acquiring this data is expensive and requires time. For WECs, initial measurements typically cover the wave spectra, while directionality and combined associated effects with local currents may not be covered in the initial assessment and may require additional longer term measurements.

Localized efforts produce valuable information on different resources available. For example, the University of Victoria's West Coast Wave Initiative [34] has for several years used a combination of existing Navigational Aid metocean data, nearshore wave measurement weather buoys, and numerical wave propagation capabilities to map the wave energy resource along the coast of British Columbia, Canada. This information provides useful input for both energy capture predictions and extreme design conditions for MECs in this region.

Currently, there are no cumulative lists of required environmental load cases for specific types of MECs. Wind energy has several references to environmental criteria that may be applicable, though the cases are structured towards offshore wind. There are several references for determining relevant metocean parameters in oil and gas references that could be applied for MEC applications. The onerous task to determine the required load cases falls to the MEC designer, especially with regards to adequately assessing fatigue. ISO 19901-1 has general guidelines for determining relevant metocean data [21]:

- Evaluation of extreme and abnormal metocean parameters - used to check ultimate limit states (ULS) and accidental limit states (ALS),
- *"Long-term distributions of metocean parameters, in the form of cumulative conditional or marginal statistics."* - used to define the fatigue limit state and to define operability based on structural or equipment limitations
- *"Normal environmental conditions, which are required"* - to determine safe working criteria for installations, workovers, maintenance, etc.

In addition to the metocean assessment, the geotechnical conditions of the site location need to be addressed. Soil conditions will drive the anchor selection as well as the presence of any seafloor anomalies and environmentally sensitive exclusion zones (i.e. faults, reefs, biological habitats, etc.). Incorrect installation due to or because of insufficient soil data can affect anchor holding capacities through cyclic loading or changes in tensile loads [21].

Return Period Selection and Associated Safety Factors

A tradeoff exists between the return period and safety factor selection of the mooring design of MECs. Uncertainties associated with the metocean data may be a result of historically unreliable data for the area or lack of long term data. For cases with more uncertainty, higher safety factors or redundancy are often incorporated into the design. Return period selection, or the likelihood of a storm event, should exceed the expected design life. Table 2 indicates oil and gas standards' return period requirements of 100 years and floating offshore wind requirements of 50 years. The reduced return period for floating wind systems highlights an increase risk tolerance that could apply to MEC systems as well.

Table 2 – Safety Factor and Return Period Referenced in Mooring Standards

Standard Documents & Version	Design Return Period		Safety Factor		Notes
	Section Addressed	Return Period (years)	Section Addressed	Intact Safety Factor	
ISO 19901-7: 2nd ed, 2013-05-01	6.4.2.2.1	100	10.2	1.67	Offshore oil and gas
API RP 2SK: 3rd ed, May 2008	3.1.1.1	100	7.2	1.67	Offshore oil and gas
BV NR 493 DTR03 E: Dec-15	2.1.2	5 X deployment life, min 5yrs	11.1.3	1.67	Offshore oil and gas
BV NI 572 DT RO1 E: Oct-15		50	2.7.2	1.67	Offshore floating wind
ABS FOWT installations: Jul-14	4.3.7	50	8.3.8	1.67	Offshore floating wind • Non-redundant intact safety factor: 2; • 'Survival' check at return period of 500 years (no safety factor requirement)

DNV GL OS E301: Jul-15	1.2.4	100	-	See notes	Offshore oil and gas; • Partial safety factors are applied to mean tension (1.1 or 1.4) and dynamic tension (1.5 and 2.1) depending on consequence class.
DNV GL OS J103: Jun-13	5.2.5	50	-	-	Offshore floating wind; same partial safety factors as DNV GL OSE301
IEC 62600-10: 2014	9.6.1	100	9.6.2	1.67	Design Factors are based on consequence class • Consequence Class 3 = SF *1.5 • Consequence Class 2 = SF *1.3 • Consequence Class 1 = SF *1.0

Offshore oil and gas safety factors for mooring components illustrated in Table 2 indicate a typical value of 1.67 for the intact design case. In addition, API RP 2SK and ISO 19901-7 specify safety factors for different anchor types. The nascent marine renewable and floating wind industries lack the extensive operational experience of offshore oil and gas, and this is reflected in the similarity of floating wind and marine renewable safety factors to the oil and gas stationkeeping standards. However, these safety factors are inherently calibrated for offshore oil and gas systems. The reliability tolerances and associated design and cost implications for marine renewables may be very different than offshore oil and gas systems.

For non-redundant portions of the mooring system, application of higher safety factors helps to address the risk associated with failure of equipment within this portion of the system. For oil and gas, DNV GL describes Consequence Levels, whereby Class 1 refers to cases "*where mooring system failure is unlikely to lead to unacceptable consequences such as loss of life, collision with an adjacent platform, uncontrolled outflow of oil or gas, capsize or sinking*". While it is likely Class 1 would cover most MECs, consideration of mooring failure and the risk it poses to nearby structures should be incorporated into the reliability of the mooring design and considered in the array spacing.

The IEC 62600-10 has further assigned a consequence class with design factors based on the most limiting of the described consequence class scenarios. It defines the three consequence classes as [18]:

- *"For consequence class 3, possible outcomes of a mooring system failure may include loss of human life, significant damage to marine environments, blockage of high traffic navigable waterways, and substantial financial or third party property damage."*
- *"For consequence class 2, possible outcomes of a mooring system failure may include serious injury, damage to marine environment, blockage of navigable waterway, and financial or property damage."*
- *"For consequence class 1, possible outcomes of a mooring system failure may include minimal human injury, minimal environmental impact, minimal navigable waterway impact, and minimal financial or property damage."*

The adjusted factor of safety increases with consequence class due to the unknown variables within the MEC design and possible severity of the consequence. The quantitative value of damage to the marine environment or financial loss is not defined as it is based on the developer's risk tolerance and ability to prove to a certifying body that they have chosen the correct consequence class. Consequently, higher design factors of safety can impact the overall project costs as it may lead to larger equipment, anchors, etc.

As an illustrative example, anchors are a small component for deep water oil and gas systems and increasing reliability with higher specification anchors does not have a big impact on project costs. In contrast, anchors are a dominating component for tidal energy systems that can operate in comparatively shallow water with scoured rocky seabeds. Increasing reliability with larger gravity anchors can have a significant impact on project due to material cost and vessel requirements. A detailed investigation to assess the associated reliability implications and tolerances for marine renewables is critical to further standards and industry development.

The calculated design maximums, or ultimate loads, come from a combination of the selected design environmental conditions and the associated factors of safety. Unlike offshore wind platforms and oil and gas platforms, the wide variety of MEC mooring designs constrains the learning curve of the device behaviors. With greater operational experience, MEC designs may begin to converge whereby they can be categorized and acceptable return periods with associated safety factors can be reevaluated accordingly.

Mooring Components and Anchors

Anchors

MEC site selections, in particular for WECs and in-stream hydrokinetic turbines, are installed in harsh environmental conditions to maximize power production. These locations, whether in fresh water or located off the coast, can be installed in relatively shallow water when compared to installations in the oil and gas industry. When looking at the shallow water location and the geotechnical effects from the environment, it leads to locations where typical anchor installations (i.e. drag anchors, suction pile, or driven piles) are not ideal as the soil conditions can be rocky, sandy, have large slopes, or contain obstructions such as coral reefs. Particularly in shallow areas exposed to high tidal currents, gravity based anchors may be required instead of embedment anchors, since the soil for embedment is not present. Drilled and grouted piles may provide another option for rocky bottoms or shallow water designs utilizing taut leg systems.

In many applications, the anchor type selected for a given location will drive the rest of the mooring system design (e.g. component type and length). Since the performance of some MEC designs is affected by the mooring system response characteristics, it is important to determine suitable anchor options very early in the MEC design stage. In addition, anchor foundations like driven and suction piles require additional geotechnical design checks, engineering and fabrication as these are not off the shelf items. The ability to install a MEC in a particular location can play an important part in the total installation costs. Typically, the harsher the soil conditions are, the higher the cost for design engineering and installation of the anchor.

Many MEC locations are characterized by shallow water with hard soil or sand. In addition, some MEC designs require vertical resistance for power capture operations and this can create a significant anchor uplift requirement. The combination of hard soils and high uplift loading requirements significantly reduces anchor selection. It is also important to recognize that some high uplift capable anchors (e.g. VLAs) are not designed to be loaded in a purely vertical manner.

The tradeoffs between anchor types should be well understood for each MEC design and location. Table 3 is an example anchor selection using a weighted exercise for a shallow water location characterized by sand for a long-term MEC deployment that requires a high uplift anchor capable of high testing loads. The table presents some factors that should be considered to select the most appropriate anchor type for each application. The weights and scores for each factor and anchor type are application specific. In the example, a score of 3 is most favorable and 1 is least favorable for the application. The list is not intended to be exhaustive or prescriptive and is intended to give an example of the types of factors to consider in anchor selection. A mooring specialist should be consulted early in the MEC design stages to help identify a suitable anchor.

Table 3 – Anchor Selection – Relative Factors to Consider for Example Application

Anchor Type	Soil Suitability	Holding Capacity Suitability	Uplift Suitability	Physical Size	Anchor Cost	Installation Cost	Efficiency (capacity/ weight)	Usage History	Overall Design Reliability	Weighted Score
Factor Weight	*N/A*	*N/A*	*N/A*	*0.05*	*0.15*	*0.25*	*0.05*	*0.25*	*0.25*	
Deadweight	Y	**N**	Y	1	3	3	1	3	2	**2.55**
Suction Pile	Y	Y	Y	1	1	2	3	3	3	**2.35**
Driven Pile	Y	Y	Y	1	2	1	2	2	3	**1.95**
Drilled/Grouted Pile	Y	Y	Y	2	2	1	3	1	1	**1.30**
Drag Embedment HHC	Y	Y	**N**	3	3	3	2	3	2	**2.70**
Drag-Installed VLA	Y	Y	Y	3	3	2	3	2	2	**2.25**
Gravity-Installed VLA	**N**	Y	Y	2	2	3	3	2	2	**2.30**
Driven VLA	Y	Y	Y	3	3	1	3	2	2	**2.00**

The choice of the appropriate anchor for a location can drive the design and engineering related to installation. During the design phase, the budgeted costs for the mooring design and installation can be underestimated by MEC designers due to oversimplification of the mooring design and cost of components and anchors. While most standards, both in renewable and offshore, make note of common anchor types, the impact of the selection on the system design is often not thoroughly understood.

Mooring Lines and Components

Like anchors, the mooring components selected are required to satisfy the design specifications of the MEC for optimal power generation and reliability. Mooring components for the system design are typically selected based on the following considerations [18]:

- Component strength
- Component fatigue properties
- Component or system stiffness requirements [1]
- Redundancy
- Installation requirements
- Cost and availability
- Anchor requirements

Other typically less considered aspects in regards to mooring lines components/design are:

- Repair, inspection and maintenance
- Decommissioning and retrieval
- Long Term Behavior (i.e. creep)
- Clearance/line clashing (i.e. arrays or systems moored close to each other)

[1]*In addition to station keeping, the stiffness of some mooring systems can play a part in the power generation of MECs which can benefit or adversely affect power generation depending on the intention of the mooring system [32].*

Traditional mooring lines may be composed entirely of steel (e.g. chain/wire systems or fully chain systems), commonly used in shallow water mooring for ship shaped vessels and offshore platforms. Typical small chain and wire sizes are off the shelf items and easily procured. For catenary systems, chain is typically used as the grounded component as it does not have the abrasion issues along the mudline that synthetics or wire mooring line types may experience. Chain is often used for anchor types with uplift angle limitations because of the higher weight per unit length.

In the oil and gas industry, for deep water mooring applications where weight of the mooring becomes an issue, the use of synthetic mooring lines are common. Synthetic ropes are attractive options as they are typically lighter weight and have good fatigue performance. Currently, polyester is the most common and well understood synthetic in permanent moorings. Polyester for deepwater oil and gas applications is attractive due to its creep resistance, stiffness characteristics, and restoring force efficiency, in addition to its lighter weight and fatigue performance. Other synthetics may have similar characteristics, but with variation in fatigue or creep performance.

For MECs, the use of synthetics is attractive for similar reasons as it is used in oil and gas. The required physical properties of the synthetic may drive the selection process. While polyester is used predominantly for deepwater oil and gas moorings, the higher stiffness compared with other synthetic options may not be suitable for some MEC applications. For example, synthetics with lower stiffness may be attractive to WEC designs [25].

While synthetics can be attractive to MEC developers, systems installed in relatively shallow water may pose challenges. The practice for oil and gas structures has traditionally been to avoid installing synthetics in marine growth zones, or depths exposed to sunlight. In general, this can include the first 200 ft of the water column depending upon the temperature, as warmer temperatures facilitate hard marine growth. Jackets may provide protection, but they do not necessarily restrict hard shelled marine organisms from growing within the jacket, which may cause abrasion to the rope's core. Some synthetics may incur damage due to UV exposure; however, jackets are typically used to account for those limitations [6]. In addition, permanent elongation from construction stretch or creep over the rope's lifetime will affect the length and may require pretension adjustments in the field.

In oil and gas, for regulatory approvals, it is up to the operator to provide the proper documentation showing that the synthetic fiber rope selected has followed all the design, testing, and manufacturing standards. For oil and gas, the following standards typically used to design, test and/or certify the different synthetic types are listed in Table 4. Testing and certifying requirements have currently not been outlined for synthetic ropes used for mooring MECs. New requirements may be needed based on the unique operational behavior of MEC devices.

Table 4 – Synthetic Rope Guidelines and Specifications

Doc No.	Document Name
NI 342 DTO R01E	Certification of Fibre Ropes for Deepwater Offshore Services, Guidance Notes
DNVGL-OS-E303	Offshore Fibre Ropes, Offshore Standard
DNVGL-RP-E305	Design, Testing and Analysis of Offshore Fibre Ropes
DNVGL-OS-E301	Position Mooring, Offshore Standards
-	Guidance Notes on the Application of Synthetic Ropes for Offshore Mooring, ABS
API RP 2SM	Design, Manufacturing, Installation, and Maintenance of Synthetic Fiber Ropes for Offshore Mooring
ISO/PDTS 14909	Fibre Ropes for Offshore Stationkeeping – High Modulus Polyethylene (HMPE)
ISO 18692	Fibre Ropes for Offshore Stationkeeping – Polyester
ISO 17920	Fibre Ropes for Offshore Stationkeeping – Aramid
NTL No. 2009-G03	Notice To Lessees and Operators of Federal Oil, and Gas Leases in the Outer Continental Shelf (OCS), Gulf of Mexico OCS Region – Synthetic Mooring Systems
CI 1500	Test Methods for Fiber Rope

For polyester and other synthetic ropes, it has been noted that several oil and gas mooring designs use the dynamic safety factor (SF) limits in the ABS guidelines [4] for design limits of the synthetic systems, Table 5. These SF are more conservative than those currently defined in API RP 2SK, [5], which are the common values used for typical all steel systems. It is assumed that the higher requirements are to compensate for the unknown behaviors of a synthetic mooring system.

Table 5 - Tension Limit and Factor of Safety for Dynamic Analysis for Synthetic Mooring Lines, [4], [5]

Analysis Type	ABS		API-RP 2SK
	Tension Limit (% MBL)	Equivalent Factor of Safety	Factor of Safety
Dynamic Intact	55	1.82	1.67
Dynamic Damaged	70	1.43	1.25

Subsea Connectors

Subsea mooring connectors and quick disconnect devices have been introduced into some oil and gas mooring designs for a few decades in order to provide a method for disconnecting the hull from its mooring lines, for example to evade ice, storm or emergencies [19]. These devices utilize acoustic signals, typically by an operator on the rig for oil and gas, to trigger hydraulic releases to disconnect from the anchors. A similar technology though employed for device maintenance purposes, the Pelamis WEC introduced a quick release and connection system in order to readily disconnect the device from its moorings for maintenance purposes [27]. This type of technology may be attractive to developers with similar maintenance needs in addition to other subsea mooring connectors that may be triggered near the anchor by an ROV.

Device Dynamics

Compared with offshore oil and gas platforms, WECs aim to operate with lower natural periods, typically below 15 seconds, to maximize energy capture via the most frequently occurring waves. Some WECs have additional structures intended to maximize motions during waves that fall within the operational range. For longer wavelengths, the devices' structures essentially heave and pitch in unison. Figure 1 illustrates the variation in the heave response for traditional ship shaped structures, spars, and semisubmersibles when compared with a generic WEC point absorber [15]. This characteristic dynamic response of a generic WEC, with larger motions than ships in smaller periods and a natural period significantly less than the spar and semisubmersible, implicates fundamentally different mooring design requirements compared to established offshore systems.

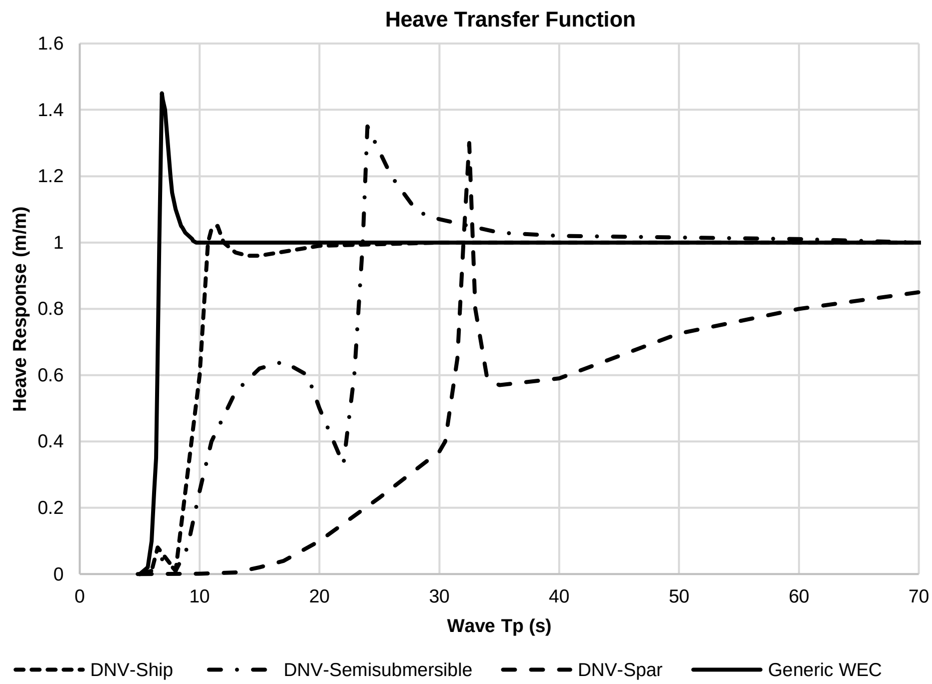

Figure 1 - Heave Response Comparison for Ships, Oil and Gas Structures and Renewables, [15]

The operational mode for any device can produce large loads that affect the motion of the system and must be included in the analysis for accurate mooring design. For wind and water current devices, this produces a large thrust and torque load and, as a result, additional load cases should be considered to account for the effect of waves in combination with wind or current. Different operational control modes such as activation or emergency stop may also introduce transient loads that can be important to consider.

Furthermore, to accurately incorporate the effects of the MEC device power capture, more complex analysis tools are required when compared to established mooring design tools. This may include new numerical software tools or the coupling of multiple tools to appropriately account for the additional operational loads. For instance, DNV GL has launched a JIP to address coupling analysis tools for floating offshore wind turbines [17]. Frequency domain tools may be advantageous for preliminary design and the quick identification of critical load cases; however, for permanent systems time domain analysis involving multiple sea state realizations, or seeds, for each load case is often required to ensure the loads are properly captured. The IEC marine renewable mooring standard specifies the effect of power capture must be included in the design of mooring systems [18].

One observation worthy of note in the wind energy sector is that wind turbine dynamic excitations were underestimated using modeling methods to quantify dynamic loading [35]. Additionally, for wind turbines and some current turbines, the presence of downstream structural elements such as towers or other moored structures may also introduce cyclical loading into the system. The added cyclical motion and load effects due to power capture may introduce additional fatigue cycles that should be accounted for in the permanent mooring design for MECs.

Installation, Operational, and Decommissioning Considerations

The oil and gas industry has developed many industry best practices and standards with relation to installation, operations, and decommissioning such as DNV-OS-H101 and DNV-OS-H102 [12], [13]. These best practices and standards provide a framework that the marine renewable industry needs to consider and will form the basis for establishing safe procedures for their unique needs.

Some locations for MEC installations are remote with limited local infrastructure to support larger scale operations. This limits available vessels for towing, lifting, or installing and may place design constraints on the size and capacity of individual MEC units, or may require mobilizing vessels from other regions. Insufficient planning or knowledge of installation practices can lead to failures during the transport and installation of the devices adding to delays and costs. Installation planning generally includes the following:

- Equipment Procurement (i.e. installation aides, lifting slings, etc.)
- Vessel Selection (Capabilities)
- Mobilization
- Tow Out

- Mooring Installation
- MEC Hook-up

Vessel Criteria and Considerations

A critical cost consideration for MEC mooring is a capable installation vessel(s). In the oil and gas industry, a standard Anchor Handling Towing Supply (AHTS) vessel capable of handling Mobile Offshore Drilling Unit (MODU) sized mooring equipment would typically include basic level specifications such as:

- 50 - 250 tonnes bollard pull
- Dynamic positioning (DP2) system
- 2 x 500 tonne drum winches
- Additional 1 or 2 x storage reels (for wire rope or synthetic line components)
- Chain locker(s) below deck
- 2.5-meter minimum diameter stern roller (single or split)
- 500 tonne shark jaws or karm forks
- 15-tonne deck tuggers for handling equipment on deck
- 150 horsepower work-class ROV with manipulator (if required)

AHTS vessel capability and onboard equipment can vary greatly by region and vessel. The vessel onboard equipment and capability can significantly impact mooring installation efficiency. The AHTS may be larger than what is needed for a typical renewable installation; however, the vessel’s functions have been geared toward offshore operations and mooring installation, making the installation phase more efficient. System reliability can also be affected by installation vessel capabilities (e.g. anchor proof loading).

While most mooring service providers typically deal with large oil and gas floating structures, the knowledge and expertise of mooring design and installation is transferable to the renewable energy sector. Mooring service providers have found that installations are more efficient when vessel capabilities which can influence the mooring design and installation are considered early on and incorporated into the mooring system design. Consulting with mooring experts is recommended to plan an efficient operation as well as establishing a mooring installation budget prior to detailed design. Mooring service providers do not typically own the AHTS vessels, but are familiar with the capabilities of vessels available in their respective regions.

Table 6 provides estimated day rates for standard AHTS vessels in various regions. All rates are in US dollars and are intended to provide a range for budgetary planning purposes. AHTS rates can vary greatly based on current market conditions, vessel availability, and vessel capabilities. The estimated ranges are based on project experience from mooring service providers for recent market high (circa 2012) and market low (2016) values. Fuel, supplies, and ROV crews are typically charged in addition to these rates. In the Gulf of Mexico region, specialized anchor handling crews are also charged in addition to these rates. The AHTS vessels in most other regions typically use the boat crews for anchor handling operations which are included in the vessel day rate.

Table 6 - Standard AHTS Installation Day Rate Estimations

Budgetary AHTS Day Rates (USD)		
Region	**Market Low (2016)**	**Market High (2012)**
Gulf of Mexico	$35,000 - $75,000	$150,000 - $225,000
NW Shelf Australia	$35,000 - $45,000	$50,000 - $75,000
North Sea	$15,000 - $35,000	$75,000 - $100,000

Smaller and cheaper installation vessel options (e.g. Multicats) may be attractive from an economics perspective. Availability of Multicats or equivalent vessels may also be more favorable than AHTS vessels depending on location. These vessels have been used as alternatives to the more costly AHTS vessels for pilot projects or prototype testing of new MECs. However, these vessels provide much less capability for handling large moorings and have less component storage, bollard pull, heavy deck handling equipment, winch capacity, etc.

Whereas most installations could all be handled with a single AHTS, multiple smaller vessels may be required for an installation to encompass the equivalent capabilities of an AHTS. As an example, a wave tidal device installed in EMEC’s wave test site facility in 60 m of water used four (4) different vessel types in the installation of the device [33]:

- Survey Vessel - ROV Operations
- Tug Installation - used as an assist for towing, installation, decommissioning and unplanned maintenance.

- Multicat(s) - main vessel(s) for towing, mooring and device installation, decommissioning, and unplanned maintenance.
- Rigid Hull Inflatable Boat (RHIB) - assisted with mooring and device installation, decommissioning, planned maintenance, and crew transfers.

Currently, there have been individual full scale prototype MEC installations, yet no full scale floating arrays or farm deployments. As a result, there is limited real-world cost data, since the cost amortization with additional units cannot be adequately assessed without array deployments. An economic analysis done in 2012 was extrapolated to estimate that it would cost between $300,000 and $700,000 for deployment of each WEC device. As with the oil and gas industry, as the MEC industry matures, there may be better fit for purpose vessels built to assist with MEC installations and may reduce costs over time [25].

Installation and Decommissioning Planning Considerations

Mobilization, transit to location, anchor pre-setting, mooring line connection, transit back to dock, and de-mobilization times should all be considered in schedule and budgetary planning. Multiple trips may be required depending on the volume and physical size of mooring equipment that needs to be installed. Allowances for weather down time (e.g. systems requiring ROV operations) and potential anchor installation difficulties (e.g. locations where soil properties are uncertain) should be considered in the cost estimates. Pre-setting a single anchor and mooring line can take anywhere from a few hours to a full day depending on the type of anchor, length and type of line component, water depth, and vessel capabilities. Connecting a single preset mooring line to a MEC could also take between a few hours to a full day depending on the method of connection and tensioning that is required. The onboard equipment of the MEC needs to account for proof loading requirements and pretensioning adjustments that may be needed throughout the design life.

Furthermore, at the end of the design life, the MEC hull, mooring, subsea cabling, and converters will require decommissioning. The renewable industry needs to consider decommissioning early on, particularly with relation to farms and arrays as it could reduce overall decommissioning costs. For example, arrays/farms will involve many anchors and retrieval costs may be high, for some anchor types, if complete anchor removal is required.

Weather windows should also be taken into account, especially in areas dominated by high winds, waves or currents. In some cases, yearly forecasts of currents (e.g. loop current in the GOM) or other weather related data can postpone installation. Timing for operations in some locations is determined by seasonal data, meaning there are times of the year that the probability of waiting on weather is high. Typically, operators will wait for a more favorable time of year to avoid incurring additional vessel costs associated with weather downtime.

Additionally, it should be noted that environmental operating criteria and installation criteria are two different specifications. For instance, ocean current turbines are typically installed in locations with high currents for power generation [32]. It is particularly challenging for vessels to deploy mooring equipment in these locations as it can be hard to maintain station. A well-designed mooring system that optimizes installation efficiency can reduce the total project costs significantly.

Inspection, Maintenance, Repair, and Replacement (IMRR)

A detailed IMRR plan helps to budget for scheduled inspections, maintenance, and repair/replacement intervals to ensure the reliability of the moorings. The critical aspects of an inspection should investigate corrosion rates of steel components, assess marine growth, ensure shackle pins are secured and in place, check that twist of line chain, wire, and synthetic rope are within design limits, observe if there is any damage to mooring components, and verify that scour or trenching near the anchor is within recommended guidelines. Guidelines for inspection include API RP 2I In-service Inspection of Mooring Hardware for Floating Structures and DNV-OSS-101 and DNV-OSS-102. The most common form of in-place inspection is visual using ROVs or divers. For permanent oil and gas floating structures, the visual inspection is carried out at least annually and after any major storm or other damaging event. For MECs, a more frequent inspection may be required due to the dynamic nature of the desired operating environment. If visual inspection identifies an anomaly, the system designer, installer, operations team, and mooring component manufacturer can determine whether structural damage has occurred, and if immediate or future repair or replacement is needed.

For the shallow water MECs, the use of ROVs for visual inspection can be challenging due to propulsion and maneuverability constraints in strong currents and inadequate cooling capabilities in warmer waters near the surface. The strong currents can also pose risks for diver inspections. In all cases, visibility in shallow, turbulent, or murky water can be a complication for visual inspections. Inspection operations therefore need to be planned around optimal weather windows based on inspection equipment availability and capabilities. It should also be noted that visual inspections cannot identify the condition of the anchor or the mooring component below the mudline near the anchor. It is important that adequate consideration be given to the type and size of components selected to allow for the design life of the system knowing that minimal inspection will be possible in some areas of the system.

Arrays

Array spacing for MECs and floating wind systems will generally require much tighter spacing than traditional oil and gas structures to minimize leasing and the grid connection costs associated with subsea cabling. Conversely, advantages for wider array spacing include reduced risk for clashing, wake effects for downstream turbines, and reduced shielding effects for WEC arrays. Also of note for array design are mooring spacing requirements for anchor installation, mooring line hookup, inspection, operations, maintenance, and considerations for broken-line conditions. The IEC standard is currently applicable to individual units and not arrays. DNV-OSS-901 Project Certification of Offshore Wind Farms also does not address farm spacing requirements.

Authorizing Bodies

United States

Within the United States, several regulating bodies exist for approval of offshore installations. Traditionally, offshore installations have most often applied to the oil and gas industry. For MECs, regulating bodies will also need to approve these installations. While many of the authorizing bodies are the same as those that approve offshore oil and gas installations, subtle differences in renewable energy devices may change the required jurisdiction. Currently, there is not a defined outline for getting a renewable device installed offshore. To assist with defining a clear path for approval, a workshop was held in 2015 to outline the responsibilities by inviting regulating bodies including [7]:

- US Coast Guard (USCG)
- Bureau of Ocean Energy Management (BOEM)
- Bureau of Safety and Environmental Enforcement (BSEE)
- Department of Energy (DOE)

The main objective was intended to outline the approval process for floating wind; however, the process should be applicable to MEC devices.

The proceedings outlined that federal authority over the design and construction plans on the outer US continental shelf lie wholly with BOEM. BOEM will collect three documents: Construction and Operations Plan (COP), Site Assessment Plan (SAP), and General Activities Plan (GAP), and is responsible for soliciting feedback and review from other agencies such as BSEE, and USCG. It was determined that the USCG involvement will be limited for unmanned structures such as floating offshore wind, as they are viewed as hazards to navigation, similar to weather buoys or other mooring buoys, falling under 33 CFR. With regards to moorings, BOEM will be the ultimate reviewer; however, it is likely that BSEE will provide feedback.

An independent third party or certification verification agency (CVA) is required to perform a detailed review of the site assessment, design, construction, cable lay, burial, and crossings, as outlined in 30 CFR 585.707; they may engage with a Marine Warranty Surveyor for offshore installations. The CVA reports to BOEM and reviews fabrication and installation phases [7].

Other Regions

Additionally, offshore wind developers, similar to offshore vessels and oil and gas installations, often request the involvement of classification societies, as it eases negotiations with insurance agencies. Recent trends have shown that offshore wind developers are sometimes self-insuring the project, and bypassing use of a classification society. For example, for European offshore wind projects, it has become common to certify the wind turbine and its foundation as opposed to class. The approaches are different in that certification requires confirmation that the design, fabrication, and installation met selected standards, while classification requires regular inspections throughout the design life [7].

Standards Development

Recently, the International Electrotechnical Commission (IEC) published a technical specification for design of mooring systems for MECs [18]. A detailed comparison of a draft version of this technical specification was completed that remains relevant to the published version [30]. As an international organization that brings consensus based standards developed with participation from international stakeholders, the IEC standard was produced with expertise available from many countries.

The IEC standard incorporates consequence classes that introduce design factors when greater risk to the environment, human life, or surrounding infrastructure is present. The equivalent safety factors are similar to offshore oil and gas standards in the least critical consequence class [30],[22] and it is expected that additional experience will refine these factors. Existing offshore oil and gas standards, such as API RP 2SK [5] have had an influence on the development of international standards. However, using them directly for marine renewable applications is not advisable due to the fundamentally different dynamic operational nature of these technologies. Applicable guidance and analysis consideration is required for safe design.

A key differentiating factor of the IEC mooring standard is in the analysis requirements. The effect of power take off systems must be accounted for in the design and the final mooring design must be checked with a fully coupled analysis to ensure the most reliable dynamic load information. The complex response of these machines in a wide range of ocean conditions requires this level of analysis capability for reliable design. The IEC standard applies to individual units and there is no standard for arrays or farms of units at present.

Offshore floating wind standards are also in active development. A developing key concern is on the fatigue effects due to power capture. Lessons learned and information on fatigue design for floating wind will also be directly applicable to tidal energy stationkeeping design problems and also provide insight for fatigue effects in wave energy systems. [2], [3] DNVGL's floating wind standard [14] addresses requirements addressing the differences from the oil and gas mooring standard [16]

Future Development and Conclusions

In many ways, MEC designers are able to capitalize on previous knowledge gained from the oil and gas industry. The oil and gas industry has produced many standards for testing and certifying mooring components and subsea connectors as well as defining procedures and requirements for inspection, maintenance, repair, and decommissioning. In particular, with the marine renewable industry's interest in synthetic ropes due to elasticity and weight advantages, similar certification and inspection requirements are likely. These requirements have been discussed briefly and as the marine renewable industry grows similar requirements must evolve to ensure safe and reliable growth.

Mooring standards from the oil and gas industry are being applied for MEC designs even though the consequences due to line failure can be less catastrophic than for oil and gas systems. However, there are published floating wind and marine renewable mooring standards and others that are in development. Key differences and ongoing developments in these new standards are related to factors of safety, return periods, and system dynamic behavior.

The calculated design maximum, or ultimate loads, come from a combination of the selected design environmental return periods and the selected factors of safety. Most oil and gas standards are pointing towards using 100 year return periods as the design life criteria for permanent systems; however, published floating wind mooring standards use 50 year return periods with the same mooring safety factors as oil and gas. This may also imply a suitable lower return period for MEC systems if the risk tolerance is appropriate.

Furthermore, future work is needed to properly calibrate factors of safety with information from additional installation and operational experience. For example, the anchors of shallow water MEC systems can be a dominating aspect for total project costs unlike traditional offshore oil and gas systems. Installation vessel daily rates are a significant cost in a mooring installation. Small reductions in the factors of safety can lead to smaller equipment, resulting in reduced vessel requirements and potentially large changes in the overall project cost. For the renewable industry, the relationship between these types of acceptable risk tolerance and associated cost implications needs to be better understood.

The dynamic behavior of MECs can be more complex than traditional oil and gas systems. Whether a wind, wave, or tidal MEC, the device's operational behavior can create substantial forces and dynamics in the mooring response. For many WEC designs, the MEC is intended to have a natural period very close to the most commonly occurring wave periods. Wind and tidal rotor thrust and torque loading can dominate mooring loads and introduce extra cyclical loading. Fatigue may be a much greater concern for these types of structures and may even be a dominating mooring design aspect.

Project costs can be reduced significantly through well-designed mooring systems that optimize installation efficiency. Experienced mooring designers brought in early in the design process can help identify suitable anchor types, mooring equipment, and installation requirements. The mooring design cannot be completed in isolation of the MEC design. Mooring designers must also be aware of the complexities of MEC operational behavior as this can introduce loading that is not commonly addressed in traditional mooring software codes.

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