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Potential environmental impacts of marine renewable energy due to the release of microplastic particles from synthetic mooring cables

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Abstract

The large-scale exploitation of offshore renewable energy in floating platforms will increase the use of synthetic mooring cables to secure them to the sea-bottom, because of the need to employ low-cost and lightweight materials to ensure economic viability. The degradation of these cables will release microplastic particles to the ocean, causing environmental impacts that have so far received little attention. Here, we try to raise awareness to this potential problem, by explaining the fundamental differences between offshore renewable energy structures and traditional ones, such as oil platforms, in what concerns their economics and layout at sea, listing the most relevant materials for mooring cables, and discussing potential problems and solutions. These impacts have not yet materialised because offshore renewable energy technology is only now reaching commercial viability, but are likely to become an issue in the future.

Keywords: microplastics, ocean, mooring cable, marine renewable energy, floating structure

1. Introduction

One of the methods of installing structures to operate at the sea is to design the structures to float, and then prevent them from drifting on the sea by securing them to the sea floor by means of cables, called mooring cables. This technology is widely used to anchor ships; however, it is also used to install large structures for the extraction and processing of offshore Oil and Gas (O&G) – commonly known as oil platforms – navigational buoys, and scientific equipment. In the 2000's, these installation solutions started being used to deploy structures for offshore renewable energy exploitation, such as offshore wind, ocean waves, and tidal currents; and, in late 2010's, also floating solar photovoltaic panels.

The most common type of mooring cable is a simple steel chain, similar to those used to anchor ships to the seafloor. With the development of synthetic materials in the early 1900's, polymers were soon applied in the manufacture of cables in the marine industry. The first application was in the 1950's, when nylon cables were used for towing [1]. The application of synthetic materials in cables for mooring floating structures soon followed, with an increase in the variety of available materials, as described in Section 3. Until the mid-2010's, issues related to the environmental impact of synthetic materials for mooring cables received little attention. The main environmental impact associated with offshore structures was mostly the spillage of hydrocarbons and their impact on marine wildlife. Knowledge of plastic pollution in the environment was still limited when compared with the present awareness. Moreover, these floating O&G structures cannot be installed in the proximity of others; thus, any deployment location was only affected by a relatively small number of cables. However, their mission-critical application in marine renewable energy structures, combined with the particular nature of these structures, has the potential to increase their environmental impact owing to the release of microplastic particles.

Microplastics are generally defined as synthetic polymeric particles smaller than 5 mm [2] derived from the degradation of larger plastic items (secondary microplastics) or purposely manufactured in these size ranges (primary microplastics). At present, they are considered an emerging pollutant and their presence has been widely documented in the marine environment, as well as in other water bodies and environmental compartments [3][4]. Microplastics are ingested by several marine organisms, and can potentially enter the food chain, eventually exposing humans via food consumption [5][6].

Although there are several studies analysing the environmental impact of marine renewable energy structures, surprisingly, none could be found that accounts for the potential release of microplastics from mooring cables due to their degradation mechanisms. Some studies, such as [7][8] or [9] do not account for the impact of mooring systems. In [10], the environmental impact of floating wind turbines was analysed only in terms of CO_2 emissions when compared with other sources of energy. Yet again, in [11], in the life cycle assessment of a floating wind turbine, acknowledgement was made of the mooring system, but not of its impact. However, it is mentioned that at the end of the life of the floating wind turbine, the mooring system is expected to be abandoned on the sea floor. It is also referred the potential ecotoxicity posed by the floating wind turbine, but it was not studied.

Most of the studies that do account for mooring systems focus on the physical barriers posed to marine life, or temporary impacts on the seafloor caused by the installation of anchors. For example, in [12] a list of different expected impacts caused by the deployment of wave energy converters (WECs) is presented, including the impacts caused by mooring systems. However, mooring systems are judged to cause mostly temporary impacts owing to the installation and removal of the anchors. It is mentioned that wave energy parks in general might interfere with the migration routes of large sea species, and a comment is made that mooring systems might impact water column species, but no details on this are given. [13] studied the impact of WECs on sea-bottom macrofauna offshore Lysekil, Sweden. The impact of suspended particles is only considered in terms of the temporary effects of suspended sediments caused by the installation of WEC foundations. There was no mention of the release of particles from the WEC itself. A similar assessment was made in [14], analysing the environmental impacts of wave energy parks across Europe: the mooring system is judged to have impacts only during construction and in causing an increase in suspended sediments. In [15], the possible impacts of mooring systems on topography and hydrodynamics were mentioned, but no other impacts were referred.

A few studies have focused on the risks posed by the release of plastic particles by cables and ropes in general, such as [16]or by the abandonment of synthetic fishing gear in the sea [17]. And some studies have addressed the issue of microplastics in aquaculture in particular, such as [18]. Aquaculture structures can be a good model for renewable energy installations given that they usually comprise several moderate sized structures installed in parks, somewhat close to each other, where fishing activities are not expected. And, as found in [18], the microplastics released by the different types of equipment do pose ecological and health risks, although further studies are encouraged.

The most complete analysis of the impact of mooring systems from marine renewable energy devices was presented in [19]. It analyses in detail the disruption of benthic habitats by the mechanical action of mooring cables dragging and rubbing against the seafloor. However, as in other studies, no analysis has been conducted on the possible dangers posed by the release of chemicals and microplastics from synthetic mooring cables.

Although not directly related with mooring cables, or cable-like structures like fishnets or fish-pens, some studies have focused their attention on microplastics generated by the erosion of wind turbine blades. This phenomenon is caused by fatigue damage on the leading edge of the blades after repeated impacts with rain droplets. Studies in this field are recent, and their results, just like the ones mentioned above, are far from conclusive. It is clear that the operation of wind turbines releases microplastic particles [20][21]; however, estimates for the amounts and effects are uncertain. [20] estimates values around 0,24 kg per turbine per year, while [21] estimates values between 0,080 kg and 1,000 kg per turbine per year. Both studies, however, conclude that the load released into the ocean might be small compared with other sources, such as road tires, and might be negligible. And both studies highlight that the methodologies to estimate the microplastic load need to be better developed and improved, highlighting, in past studies, that have these estimates have not been properly conducted. Moreover, it is not easy to pinpoint the effects of such a load. [22] tried to measure the microplastic load from eroded wind turbines in the vicinity of their installation, but was not able to detect particles originating from the blades (only from other sources). It is hypothesized that that wind and current might carry the microplastic load away from the turbine location before they settle on the ocean floor or even on the water column.

2. Importance of synthetic cables

Mooring cables can be made from three types of materials, in order of historic application: natural fibres, steel, and synthetic materials/polymers, also called high-technology fibres [23]. Natural fibres were disused because their mechanical properties are not as reliable as those of other materials [24].

Steel is used either in the form of chains or as stranded steel cables, which are also called wire ropes. Steel is a reliable material for mooring cables, but because it is relatively dense, steel mooring cables become very heavy when the floating structures are installed in deep waters, and the length of cable required becomes larger than tens of meters [1]: some offshore O&G platforms are anchored at depths close to 2500 m.

Because of the large weight of mooring cables in deep water, the offshore industry has started using synthetic cables, which can provide a similar load-bearing capacity with a smaller weight [25]. The materials and processes used to manufacture synthetic cables are cheaper than those used to manufacture steel cables. This, in combination with the possibility of using lighter vessels for transport and installation of the lighter synthetic mooring cables, makes their use more affordable than the use of steel ones [1].

The mooring system for a typical O&G platform is only 2% of the investment, so there is no significant drive to optimise its costs. The change from steel to synthetic materials in the O&G sector was mainly due to the need to reduce the loads transferred by the mooring cables to the floating structure. The situation is different for floating renewable energy platforms. These structures are not expected (at least not yet) to be installed in deep waters; therefore, the weight of the cable is not a major problem. However, in contrast to O&G, the mooring system can represent between 18% and 30% of the total investment [26], [27]. Moreover, the levelised cost of energy is greater for offshore renewable energy than for offshore O&G, to the point that offshore renewable energy is still dependent on subsidies for viable exploitation [28]. Estimates for the levelised cost of energy for offshore wind have a wide variation, but if we take a lower estimate, as reported in [29], it will be around 95€/MWh. With a barrel of oil at approximately 75€/barrel and an average energy content per barrel of 1,7 MWh, we have a levelised cost of energy for oil of about 44 €/MWh. These conditions impose the need for intensive cost optimisation for the deployment of marine renewable energy. Representing such a high percentage of cost, the mooring system is a prime target for optimisation, leading to the use of synthetic cables even at shallow and moderate water depths [30][31]. And, in fact, both in early studies for prototype installations [32], [33], or actual deployments, such as the Windfloat prototype in Northern Portugal [34], synthetic materials were the main choice.

3. Cable materials

Synthetic mooring cables are made, most commonly, of the following materials [35][36]:

i. Nylon, technically a polyamide;
ii. Polyethylene terephthalate (PET), usually called polyester, although polyester is a class of materials;
iii. Polyolefins, such as polyethylene and polypropylene;
iv. Liquid crystal fibres, which include the fibre commercially known as *Vectran*, and aramids, such as the one commercially known as *Kevlar* (poly-para-phenylene-terephthalamide (PPTA)).

Some properties of the synthetic fibres are listed in Table 1, reproduced from [37].

Table 1- Properties of synthetic fibres when compared with steel.

Property	Nylon 6	Polyester	Vectran	Aramid	HMPE	Steel
Density (kg/m3)	1140	1380	1400	1450	970	7850
Melting point (ºC)	218	258	400 (chars)	500 (decomposes)	150	1600
Modulus (N/tex)	7	11	54	60	100	20
Tenacity (mN/tex)	840	820	2286	2000	3500	330
Break extension (%)	20	12	3.8	3.5	3.5	2 (yield point)
Moisture (%)	5	<1	<0.1	1-7	0	0

Polyolefins include a class of polyethylene known as high-module polyethylene (HMPE), high-density polyethylene (HDPE), or High-Performance Polyethylene (HPPE), all equivalent designations. Two particular fibres in this category are the commercially branded *Spectra* and *Dyneema,* which have been rather successful [38] in the nautical and offshore industry. Fibres made from HMPE, PPTA (Kevlar), or Vectan, are also classified as High Modulus, High Tenacity (HM, HT) fibres.

Nylon exhibits good elastic behaviour; however, its resistance to abrasion decreases when wet, which can be a disadvantage in marine applications [35]. PET is very similar to nylon even in the manufacturing process; the most significant difference is that it shows better abrasion resistance than nylon when wet [35]. Compared with steel cables, polyester cables demonstrate better fatigue behaviour (fatigue is a degradation mechanism described in Section 4). Both Nylon and PET are preferred for applications requiring "moderate high strength and ductility" [1].

Polyolefins are similar to Nylon and PET; therefore, they are applied in similar situations. However, they are less resistant to degradation by ultraviolet (UV) light and fatigue damage [37].

Liquid crystal polymers are advantageous in applications requiring good dynamic behaviour, because of their resistance to abrasion [35]. High Module, High Tenacity materials (liquid crystal polymers and the sub-class of polyolefines of HMPE) are useful for applications requiring similar strength to steel, but lower weight [37]. These materials also exhibit better fatigue behaviour than steel.

4. Cable degradation mechanisms

The wear and the degradation of mooring cables depend strongly on the material, although some mechanisms are common to all cable types. Common mechanisms are i) loading exceeding the cable strength, ii) fatigue, and iii) abrasion and wear. All cables break if the load applied to them is greater than the load they can resist. This is a significant problem because, although there are design guidelines that should ensure that mooring systems have very low probabilities of failure, mooring cables break much more often than expected [39], [40][41], releasing material particles and cable sections into the ocean. Fatigue is the damage caused to cables by repeated cycles of loading and unloading and is the same process that is instinctively used to break metal wires by bending them back and forth. Fatigue damage increases with the amplitude and frequency of the loading; the greater the stretch on the cable and the more often it happens, the faster the cable will deteriorate. Wear and abrasion are caused by cable scraping against surfaces such as the sea bottom or components of the structure.

In addition to what was described above, synthetic mooring cables have particular degradation mechanisms [42]. When cables are stretched and released, their fibres rub against each other, causing fibre-on-fibre abrasion damage [25][30]. This friction action also generates heat within the cable. Together with the heat generated by the nonlinear hysteresis behaviour of synthetic fibres when strained, the internal temperature of the cable can reach values as high as 260ºC [25][24][42], resulting in melting or charring of the cable. Synthetic cables are also susceptible to the damage caused by sand ingress [42]. Sand suspended in the water column can become lodged inside the cable and rub against the fibres, worsening abrasion damage. Similarly, hard-shell animals, such as mussels, can become attached and grow on the cable and, because their shells are hard and sharp, cause damage to cables [37]. To mitigate abrasion and heat problems, mooring cables can be fitted with protective sleeves to prevent sand ingress and lubricants to reduce abrasion and internal heat [30]. Abrasion is also caused by wet-dry cycles. When portions of mooring cables are repeatedly submerged and exposed to air, dissolved salts will crystallise within the cable, straining the fibres on the one hand, and increasing abrasion damaged, on the other.

Another degradation mechanism particular to synthetic cables is fish bite [42][43]. Sharks seem to be responsible for a large portion of fish bites and certainly for the most damaging ones [43]. The reasons for this are not well understood, but it appears that the low-frequency oscillations of the cables attract sharks. As will be explained in the next section, renewable energy deployments will have a larger density of mooring cables; this higher density will likely be more attractive to sharks than a small number of cables in large areas, as is currently the case in traditional O&G installations.

Other factors that attract both sharks and other species include the bioluminescence of marine organisms attached to the cables, colour and geometry of the cables, and odours released by organisms attached to the cables and from the cables themselves. Depending on the structure, electromagnetic fields caused by generators or galvanic protection also attract fish to the area where the structure is deployed [43].

The final major degradation mechanism is chemical and photochemical attack. Ultra-violet radiation quickly degrades some types of synthetic cables unless they are protected by special sleeves, chemical coatings, or additives [44]. Substances dissolved in water, such as SO_2, corrode the cables [43][44], and even sunlight, in the presence of oxygen, degrades the synthetic materials in mooring cables [44].

The degradation of cables through different mechanisms leads to the release of plastic particles, cable breaking, and, eventually, to the need of cable replacement. Although this problem exists from the day synthetic cables started being used, their impact should become larger with the installation of floating structures for renewable energy. This magnification comes from the fundamental differences between the O&G and renewable energy structures, as explained in the next section.

5. The problem of synthetic cables in renewable energy

O&G platforms have dimensions of around a hundred meters, are relatively isolated from other structures, and are moored by approximately 15 sets of cables [23]. Therefore, in a relatively large area, there is a small number of cables. In contrast, floating renewable energy structures have much smaller dimensions, only around tens of metres. As the consequences of the failure of renewable energy devices are relatively mild, they are moored by as few as three cables [45][46][47]. Because of this and because a large number of devices is needed to generate reasonable amounts of power, they will be installed very close to each other in relatively small regions in large numbers. Studies predict figures between 25 [48] and 100 devices [46]in regions as small as 17 km × 18 km [40]. With three cables per device, using the lower estimate for the number of devices – 25 – there will be 75 cables in this area; with 100 devices, the figure is 300 cables.

Another issue that is particular to renewable energy devices is how they are meant to work. Unlike O&G platforms, which need to be as stable as possible even in rough seas, some wave energy technologies need to move with the waves to activate their electrical generators. These motions increase the amplitude and number of load cycles in the mooring cables, which contributes to faster degradation and to the need to use more material in the cables, when compared with other structures of the same size.

6. Expected impact of synthetic cables

The increased use of synthetic mooring cables for renewable energy devices is expected to result in new sources of microplastics to the ocean, as a result of the degradation of synthetic materials. This increases the pollution load in the oceans. However, in addition to the release of microplastics, the degradation of the cables will also release lubricants and additives applied to increase the resistance of the synthetic materials to UV and to lubricate the fibres, creating another source of contamination (delustrants (e.g. (TiO_2), photostabilisers (e.g., 2-hydroxy-benzophenones and 2-hydroxybenzo-triazoles, ZnO, MgO, $CaCO_s$, iron oxides, chromium oxides), thermal stabilisers), and anti-oxidants)[35]. Some studies, such [49], indicate that TiO_2 increases the oxidative stress in seawater, demonstrating citotoxicity. Other studies, such as [50] have analysed the impact of additives released by PVC components used in aquaculture structures; however, this material is not used in mooring cables. In general, the impact of the release of additives from synthetic mooring cables to the marine ecosystem is not fully understood and research on the topic is scarce.

Because of the restrictions on navigation and fishing in and around renewable energy parks, these locations will work as marine sanctuaries for a large variety of marine species [51]. This is mostly portrayed as a positive impact of the creation of marine renewable energy parks. However, as described above, these same areas will be a source of microplastics and, by drawing a parallel to what has been recorded at marine aquaculture installations [18], we can expect this to enhance the transfer of microplastic particles into the food chain. This can happen through feeding on microplastic particles that are mistaken by food, but also by accumulation via the gills through respiration. And if even the particles are deposited on the sea floor, they will pose a risk to demersal species.

The expected intense generation and release of microplastic particles, connected to the increase in marine activity, can increase the likelihood of these particles absorbing pollutants and entering the food chain before dispersing in the ocean or settling down on the seafloor.

The increase in the use of synthetic cables will also lead to an increase in the number of synthetic cables that break during operation and are wholly or partially abandoned at sea. It is documented that cables designed using current standards break more often than expected [52], [53], [54], and this will also happen to marine renewable energy devices.

The potential impacts described here were deducted on a logical basis, accounting for the type of material, its expected use, and the experience gained from the degradation and impact of synthetic materials in the ocean. It clearly needs to be expanded by appropriate research to assess the magnitude of these impacts and the possible existence of others that have not been foreseen.

7. Suggested solutions

The problem that we point out in this work has not yet fully materialised, and there is sufficient time to develop solutions to prevent it. Some of the possible solutions could be the return to the use of natural fibers, using advanced technology and engineering to control the quality of the raw material from the initial cultivation of the plants, to extracting and selecting the fibres, and ending in manufacturing the cables. An example of this is the paper industry, which nowadays is currently a high-technology field with rigorous quality control, almost fully based on natural fibers. Other solutions could be the envelopment of cables in environmentally safe jackets or sleeves, designed to trap particles released by the cables. These sleeves or jackets could be exchanged or maintained whenever the device is shut down for maintenance. Additives, lubricants, and similar components used to improve the performance of the cable can be developed to bond and trap particles that break away, preventing their release.

Another solution is the recovery and recycling of cables instead of abandoning them in the sea. Although this does not fully prevent the impact of cable degradation, it helps mitigate it by preventing abandonment at sea or in landfills. According to [29], the cable manufacturer Lankhorst Euronete has a recycling program for mooring cables. However, this process is difficult because of cable contamination, which necessitates research to improve this process.

8. Conclusions and future work

To sustain current energy needs and support the transition to less environmentally harmful energy sources, several technologies for marine energy converters are being developed and deployed. Most of these devices float in the ocean and require cables to anchor them to the seafloor to keep them in place. To reduce the cost of these marine energy converters, it is expected that cables will be made of low-cost and lightweight synthetic materials. Because a large number of devices are required to produce reasonable amounts of power, and because they will be installed in small areas, the usage of synthetic mooring cables is expected to increase significantly when compared with the current situation. The known processes of degradation acting on the mooring cables of renewable energy devices will increase the load and concentration of microplastic particles released to the sea and the amount of synthetic cables abandoned at sea. These will be taken up by the food chain, with the potential to cause serious environmental impacts. Although the impact of mooring cables for renewable energy devices has been investigated in different studies, none has accounted for the issue of microplastics.

Some suggestions to mitigate this problem include: i) returning to the use of natural fibres in mooring cables, using advances in technology since they were last used, to achieve higher quality cables; ii) development of sleeves to envelop mooring cables and trap particles or fibres that break away; iii) development of sticky additives to mooring cables, to bond with and trap released particles or fibres; iv) encouraging efforts to recycle synthetic mooring cables and improve recycling methods.

The actual impact of mooring cables used in marine renewable energy devices is not fully known because, to date, only a few prototypes have been deployed in the sea. On the one hand, this provides the research community with time to analyse this problem in detail and to develop appropriate solutions. On the other hand, this urges the need for research into the long-term degradation of synthetic cables in marine renewable energy applications, including byproducts of cable degradation, impacts of particles on the food chain, absorption of pollutants by microplastics, impacts of cable lubricants, and additives released by mooring cables, etc.

It is our hope that by raising this issue and proposing possible solutions, future studies will investigate the severity of this problem and, if necessary, develop preventive measures instead of remedial ones. We do not want to portray renewable marine energy as an environmentally damaging use of resources. We simply aim to encourage more in-depth research on this topic and the development of solutions to mitigate this problem.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

[1] S. D. Weller, L. Johanning, P. Davies, and S. J. Banfield, "Synthetic mooring ropes for marine renewable energy applications," Renew Energy, vol. 83, pp. 1268–1278, Nov. 2015, doi: 10.1016/j.renene.2015.03.058.

[2] J. P. G. L. Frias and R. Nash, "Microplastics: Finding a consensus on the definition," Mar Pollut Bull, vol. 138, pp. 145–147, Jan. 2019, doi: 10.1016/J.MARPOLBUL.2018.11.022.

[3] M. J. Stapleton and F. I. Hai, "Microplastics as an emerging contaminant of concern to our environment: a brief overview of the sources and implications," Bioengineered, vol. 14, no. 1, Dec. 2023, doi: 10.1080/21655979.2023.2244754.

[4] H. Yang, G. Chen, and J. Wang, "Microplastics in the Marine Environment: Sources, Fates, Impacts and Microbial Degradation," Toxics, vol. 9, no. 2, p. 41, Feb. 2021, doi: 10.3390/toxics9020041.

[5] D. Marmara, S. Katsanevakis, M.-V. Brundo, F. Tiralongo, S. Ignoto, and E. Krasakopoulou, "Microplastics ingestion by marine fauna with a particular focus on commercial species: a systematic review," Front Mar Sci, vol. 10, Sep. 2023, doi: 10.3389/fmars.2023.1240969.

[6] "Presence of microplastics and nanoplastics in food, with particular focus on seafood," EFSA Journal, vol. 14, no. 6, Jun. 2016, doi: 10.2903/j.efsa.2016.4501.

[7] C. Frid et al., "The environmental interactions of tidal and wave energy generation

devices," Environ Impact Assess Rev, vol. 32, no. 1, pp. 133–139, 2012, doi: 10.1016/j.eiar.2011.06.002.

[8] F. Guerra, C. Grilo, N. M. Pedroso, and H. Cabral, "Environmental Impact Assessment in the marine environment: A comparison of legal frameworks," Environ Impact Assess Rev, vol. 55, pp. 182–194, Nov. 2015, doi: 10.1016/j.eiar.2015.08.003.

[9] E. Loukogeorgaki, D. Vagiona, and M. Vasileiou, "Site Selection of Hybrid Offshore Wind and Wave Energy Systems in Greece Incorporating Environmental Impact Assessment," Energies (Basel), vol. 11, no. 8, p. 2095, Aug. 2018, doi: 10.3390/en11082095.

[10] M. Kausche, F. Adam, F. Dahlhaus, and J. Großmann, "Floating offshore wind - Economic and ecological challenges of a TLP solution," Renew Energy, vol. 126, pp. 270–280, Oct. 2018, doi: 10.1016/j.renene.2018.03.058.

[11] J. Weinzettel, M. Reenaas, C. Solli, and E. G. Hertwich, "Life cycle assessment of a floating offshore wind turbine," Renew Energy, vol. 34, no. 3, pp. 742–747, 2009, doi: 10.1016/j.renene.2008.04.004.

[12] L. Margheritini, A. M. Hansen, and P. Frigaard, "A method for EIA scoping of wave energy converters—based on classification of the used technology," Environ Impact Assess Rev, vol. 32, no. 1, pp. 33–44, Jan. 2012, doi: http://dx.doi.org/10.1016/j.eiar.2011.02.003.

[13] O. Langhamer, "Effects of wave energy converters on the surrounding soft-bottom macrofauna (west coast of Sweden)," Mar Environ Res, vol. 69, no. 5, pp. 374–381, Jun. 2010, doi: 10.1016/j.marenvres.2010.01.002.

[14] D. Greaves et al., "Environmental Impact Assessment: Gathering experiences from wave energy test centres in Europe," International Journal of Marine Energy, vol. 14, pp. 68–79, Jun. 2016, doi: 10.1016/j.ijome.2016.02.003.

[15] L. Lin and H. Yu, "Offshore wave energy generation devices: Impacts on ocean bio-environment," Acta Ecologica Sinica, vol. 32, no. 3, pp. 117–122, Jun. 2012, doi: 10.1016/j.chnaes.2012.02.007.

[16] N. A. Welden and P. R. Cowie, "Degradation of common polymer ropes in a sublittoral marine environment," Mar Pollut Bull, vol. 118, no. 1–2, pp. 248–253, 2017, doi: 10.1016/j.marpolbul.2017.02.072.

[17] V. Moschino et al., "Is derelict fishing gear impacting the biodiversity of the Northern Adriatic Sea? An answer from unique biogenic reefs," Science of the Total Environment, vol. 663, pp. 387–399, 2019, doi: 10.1016/j.scitotenv.2019.01.363.

[18] L. Lin, C. C. Chen, X. Zhu, K. Pan, and X. Xu, "Risk of aquaculture-derived microplastics in aquaculture areas: An overlooked issue or a non-issue?," Front Mar Sci, vol. 9, Jul. 2022, doi: 10.3389/fmars.2022.923471.

[19] V. Krivtsov and B. Linfoot, "Disruption to benthic habitats by moorings of wave energy installations: A modelling case study and implications for overall ecosystem functioning," Ecol Modell, vol. 245, pp. 121–124, Oct. 2012, doi: 10.1016/j.ecolmodel.2012.02.025.

[20] M. Caboni, A. E. Schwarz, H. Slot, and H. van der Mijle Meijer, "Estimating microplastics emissions from offshore wind turbine blades in the Dutch North Sea," Dec. 19, 2024. doi: 10.5194/wes-2024-175.

[21] L. Mishnaevsky, A. Tempelis, Y. Belahurau, and N. F. J. Johansen, "Microplastics Emission from Eroding Wind Turbine Blades: Preliminary Estimations of Volume," Energies (Basel), vol. 17, no. 24, Dec. 2024, doi: 10.3390/en17246260.

[22] S. Piarulli, L. Sørensen, S. Kubowicz, H. K. Vrålstad, K. M. Murvoll, and A. M. Booth, "Assessment of microplastics in the sediments around Hywind Scotland Offshore Wind Farm," in Journal of Physics: Conference Series, Institute of Physics, 2024. doi: 10.1088/1742-6596/2875/1/012050.

[23] N. D. P. Barltrop, "Mooring systems," in Floating Structures - A Guide for Design and Analysis, Volume Two, Oilfield Publications Limited, 1998, ch. 9, pp. 9-1-9–125.

[24] S. Weller, P. Davies, L. Johanning, and S. Banfield, "Guidance on the use of synthetic fibre ropes for marine energy devices - Deliverable 3.5.2 from the MERiFIC Project," RDT CSM 13-232, 2013.

[25] J. F. Beltran and E. B. Williamson, "Investigation of the Damage-Dependent Response of Mooring Ropes," J Eng Mech, vol. 135, no. 11, pp. 1237–1247, Nov. 2009, doi: 10.1061/(ASCE)0733-9399(2009)135:11(1237).

[26] J. Fitzgerald, "Position Mooring of Wave Energy Converters," Chalmers University of Technology, 2009.

[27] L. Martinelli, P. Ruol, and G. Cortellazzo, "On mooring design of wave energy converters: the Seabreath application," in Proceedings of the 33rd International Conference Coastal Engineering (ICCE), P. Lynett and J. McKee Smith, Eds., Santander, 2012, pp. 1–12.

[28] C. E. Clark and B. DuPont, "Reliability-based design optimization in offshore renewable energy systems," Renewable and Sustainable Energy Reviews, vol. 97, pp. 390–400, Dec. 2018, doi: 10.1016/j.rser.2018.08.030.

[29] A. Martinez and G. Iglesias, "Mapping of the levelised cost of energy for floating offshore wind in the European Atlantic," Renewable and Sustainable Energy Reviews, vol. 154, Feb. 2022, doi: 10.1016/j.rser.2021.111889.

[30] S. D. Weller, P. Davies, A. W. Vickers, and L. Johanning, "Synthetic rope responses in the context of load history: The influence of aging," Ocean Engineering, vol. 96, pp. 192–204, Mar. 2015, doi: 10.1016/j.oceaneng.2014.12.013.

[31] G. M. Paredes, L. Bergdahl, J. Palm, C. Eskilsson, and F. T. Pinto, "Station keeping design for floating wave energy devices compared to floating offshore oil and gas platforms," in Proceedings of the 10th European Wave and Tidal Energy Conference, Aalborg, Denmark: European Wave and Tidal Energy Conference, 2013.

[32] N. Fonseca, R. Pascoal, T. Morais, and R. Dias, "Design of a mooring system with synthetic ropes for the FLOW wave energy converter," in Proceedings of the ASME 2009 28th International Conference on Ocean, Offshore and Arctic Engineering, Honolulu, HI, United states: American Society of Mechanical Engineers, 2009, pp. 1189–1198.

[33] Jonas Bjerg Thomsen, "Mooring Solutions for Large Wave Energy Converters," Aalborg Universitet, Aalborg, 2017.

[34] Z. Jiang, "Mooring design for floating wind turbines: A review," Apr. 01, 2025, Elsevier Ltd. doi: 10.1016/j.rser.2024.115231.

[35] H. A. McKenna, J. W. S. Hearle, and N. O'Hear, Handbook of fibre rope technology. Cambridge: Woodhead Publishing Limited and The Textile Institute, 2004.

[36] N. D. P. Barltrop, Floating Structures - A Guide for Design and Analysis, Volume Two. Oilfield Publications Limited, 1998.

[37] S. . D. Weller, Lars. Johanning, P. Davies, and S. . J. Banfield, "Synthetic mooring ropes for marine renewable energy applications," Renew Energy, vol. 83, pp. 1268–1278, 2015, doi: 10.1016/j.renene.2015.03.058.

[38] H. A. McKenna, J. W. S. Hearle, and N. O'Hear, Handbook of fibre rope technology. Cambridge: Woodhead Publishing Limited and The Textile Institute, 2004.

[39] A. Kvitrud, "Anchor line failures Norwegian continental shelf: 2010-2014," 2014.

[40] W. Brindley and A. P. Comley, "North Sea Mooring Systems: How Reliable Are They?," in Volume 1A: Offshore Technology, in Proceedings of ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering. San Francisco, California, USA: ASME, Jun. 2014, p. V01AT01A025. doi: 10.1115/OMAE2014-23395.

[41] G. Moura Paredes, C. Eskilsson, and A. P. ; Engsig-Karup, "Uncertainty Quantification in Mooring Cable Dynamics Using Polynomial Chaos Expansions," Submitted to Marine Structures, 2019.

[42] D. T. Brown, "Mooring System," in Handbook of Offshore Engineering - Volume II, First Edit., Subrata K. Chakrabarti, Ed., Amsterdam: Elsevier, 2005, ch. 8, pp. 663–708.

[43] E. J. Softley, J. F. Dilley, and D. A. Rogers, "An Experiment to Correlate Strumming and Fishbite Events on Deep Ocean Moorings," Philadelphia, Pa, USA, 77SDR2181, 1977.

[44] F. J. McGarry et al., "Deterioration of Synthetic Fiber Rope during Marine Usage," R/T-11, 1981.

[45] Statoil, "Hywind Scotland Pilot Park - Environmental Statement," A-100142-S35-EIAS-001, 2015.

[46] C. M. Fontana et al., "Multiline anchor force dynamics in floating offshore wind turbines," Wind Energy, vol. 21, no. 11, pp. 1177–1190, Nov. 2018, doi: 10.1002/we.2222.

[47] G. M. Paredes, J. Palm, C. Eskilsson, L. Bergdahl, and F. Taveira-Pinto, "Experimental Investigation of Mooring Configurations for Wave Energy Converters," in Proceedings of the 11th European Wave and Tidal Energy Conference, Nantes: European Wave and Tidal Energy Conference, 2015, pp. 08B5-2-1-08B5-2–10.

[48] B. Borgarino, A. Babarit, and P. Ferrant, "Impact of wave interactions effects on energy absorption in large arrays of wave energy converters," Ocean Engineering, vol. 41, no. 0, pp. 79–88, Feb. 2012, doi: http://dx.doi.org/10.1016/j.oceaneng.2011.12.025.

[49] R. J. Miller, S. Bennett, A. A. Keller, S. Pease, and H. S. Lenihan, "TiO2 Nanoparticles Are Phototoxic to Marine Phytoplankton," PLoS One, vol. 7, no. 1, p. e30321, Jan. 2012, doi: 10.1371/journal.pone.0030321.

[50] L. T. Fung et al., "Plasticizers released from PVC microplastics in aquaculture environments: leaching behaviors and ecological implications," J

Oceanol Limnol, Jan. 2025, doi: 10.1007/s00343-025-4230-1.

[51] C. Huertas-Olivares and J. Norris, “Environmental Impact Assessment,” in Ocean Wave Energy - Current Status and Future Perspectives, 1st ed., J. Cruz, Ed., Berlin Heidelberg: Springer-Verlag, 2008, ch. 8, pp. 397–419.

[52] A. Kvitrud, “Anchor line failures Norwegian continental shelf: 2010-2014,” 2014.

[53] W. Brindley and A. P. Comley, “North Sea Mooring Systems: How Reliable Are They?,” in Volume 1A: Offshore Technology, in Proceedings of ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering. San Francisco, California, USA: ASME, Jun. 2014, p. V01AT01A025. doi: 10.1115/OMAE2014-23395.

[54] G. Moura Paredes, C. Eskilsson, and A. P. ; Engsig-Karup, “Uncertainty Quantification in Mooring Cable Dynamics Using Polynomial Chaos Expansions,” Submitted to Marine Structures, 2019.