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Shared moorings for floating offshore renewable energy technologies: A review

Shaswat Saincher [a,*], V. Sriram [b], Thorsten Stoesser [a]

[a] Department of Civil, Environmental & Geomatic Engineering, Faculty of Engineering Science, University College London, Gower Street, London, WC1E 6BT, United Kingdom

[b] Department of Ocean Engineering, Indian Institute of Technology Madras, Chennai, 600 036, India

HIGHLIGHTS

- Scope for adoption of shared moorings in floating offshore renewables is reviewed.
- Historical wisdom gained from conventional offshore industries is contextualized.
- Shared anchors and mooring line configurations are presented for canonical devices.
- Shared moorings in floating wind, solar and wave sectors are separately evaluated.
- Industrial thrust areas are discussed separately for shallow and deep water systems.
- Corresponding state-of-the-art in academic research is presented along with research gaps.

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ABSTRACT

The next frontier in the floating offshore renewable energy (FORE) industry is the development of large-scale farms comprising arrays of devices. With the goal of reducing the CAPEX and installation costs, shared mooring systems where anchors (and a part of the mooring line) are shared between adjacent devices, have been proposed. However, the industry is prudent towards adaptation of shared moorings and anchors due to a number of challenges which manifest differently in shallow and deep water. Shared moorings/anchors in shallow waters are susceptible to snap loads stemming from complex environmental conditions whilst the deep-water counterpart is, in and of itself, structurally complex and susceptible to peak anchor loads. The aim of this paper is to present a comprehensive review of shared moorings/anchors within the FORE industry with particular emphasis on the floating wind, solar and wave energy sectors. The advent of shared moorings is traced back to the wisdom perceived from conventional offshore industries such as O&G and/or aquaculture, respectively. In addition, an appraisal of the types of shared mooring systems for canonical FORE technologies installed in shallow and deep water is provided. A detailed presentation of device-specific configurations which brings forth the scope for adoption of shared moorings in each FORE sector is provided. This is followed by a comprehensive summary of various thrust areas identified by the industry, the corresponding academic research effort and the emerging knowledge gaps. Based on the findings, the present review identifies the need for developing higher-fidelity futuristic design tools to accelerate the application of shared moorings and anchors by the FORE industry.

1. Introduction

The umbrella term “renewables” used in the common lexicon includes electricity produced from renewable sources, renewable fuel, as well as geothermal, solar thermal, and ambient heat. According to the Renewables 2024 report by the International Energy Agency (IEA), renewables are poised to contribute up to 20 % of the global energy demand by 2030 [1]; a sizable chunk of this contribution would be derived from offshore renewable energy. Over the past two decades, there has been a major push to harness offshore renewable energy in the form of wind, wave, solar and tidal from the world’s oceans. According to the

* Corresponding author.
Email address: shaswat.saincher@gmail.com (S. Saincher).

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Renewables 2022 report by the IEA, global offshore wind installations are expected to increase by 50 % to 30 GW by 2027 [2]; more than a third of the 30 GW would be contributed by Europe (11.56 GW) of which 3.82 GW is expected to come from the UK [3]. The IEA report also predicts solar photovoltaics (PV) to grow by 1500 GW by 2027 [2] of which 10 GW would be floating solar (FPV, also known as "floatovoltaics") by 2025 [4]. Although not yet realised at the commercial scale because 95 % of the proposed >1000 concepts not having progressed beyond a technological readiness level (TRL) of 3 (small-scale model tests in the laboratory) [5], a recent study theorises the global wave power potential to be 23 PWh (which is comparable to the gross hydropower potential of the entire southern hemisphere) of which 21.5 PWh is contributed by offshore areas [6] and may be harnessed by floating wave energy converters (WECs). According to a recent study, the annual harnessable tidal power is 1200 TWh globally of which 98 % accounts for tidal barrage concepts [7]. According to another recent study, tidal current energy converters (TCECs) constitute a total installed capacity in excess of 10 MW globally [8]; TCECs may be either fixed or floating energy harnessing devices. Thus, in terms of total commercial installed capacity, the offshore renewable energy market is led by floating offshore wind turbines (FOWTs) followed by solar PVs and finally by TCECs. Although several floating WEC concepts have been proposed (cf. [5] for a comprehensive listing), the technology still remains to be commercially implemented.

Offshore renewable energy technologies employ either fixed (monopile [9], jacket [10,11] or gravity-based structure (GBS) [12]) foundations in shallow/transitional water ($d \leq 60$ m) or floating (spar [13], semi-submersible [14] or tension-leg platform (TLP) [15]) foundations in deep ($d \geq 60$ m) water [16,17]. According to a recent white paper by Det Norske Veritas (DNV) [18], there is a need to focus the R&D effort towards developing renewable energy devices that employ floating foundations. Floating renewable energy technologies offer the following advantages over fixed concepts:

- **lower foundation costs:** according to a recent study, tension-leg buoys (TLBs) are cheaper than monopiles and jackets in water-depths exceeding $d = 50$ m [19].
- **access to a greater fraction of energy resources:** about 58 % and 80 % of the USA's and Europe's offshore wind resources (respectively) exist in deep water ($d \geq 60$ m) [20,21] whilst about 80 % of the global technical potential lies in deep water [22]. A recent wave-energy resource classification identifies waves in open seas in the lower and lower-middle latitudes (wave power in the range: 10 – 40 kW/m) as having the largest Wave Exploitability Index (WEI) [23].
- **lesser intervention in human activities:** a recent survey carried out in Japan indicates that social acceptance of offshore wind turbines was largely driven by their low visibility from the shore [24] and this is a widely-accepted advantage offered by FOWTs [17,25]. Similar concerns surrounding visual pollution brought about by WEC arrays may primarily govern the selection of the depth of installation [26]. In context of solar PV, the issue of visual pollution is also mitigated by shifting the panels offshore where nature-based bamboo floating solutions have been proposed in the literature [27].
- **opportunity to co-exist in harmony alongside other industries:** beginning from the coast up to 200 km offshore, the ocean space is shared by a number of industries/stakeholders such as shipping, defense, fisheries, recreational activities and nature conservation. In this scenario, deployment and subsequent operation of floating renewable energy devices would inevitably necessitate space-sharing with said industries [17,22]. According to a recent technical report by Ørsted A/S, this presents an opportunity for the floating renewable energy industry to work alongside other "ocean users" wherein a successful co-existence would boost the perception of floating renewables in the maritime sector [22].
- **possibility to upscale through larger devices:** once established at the commercial scale, the Levelised Cost of Energy (LCOE) associated with renewable energy systems can be primarily reduced through the deployment of larger devices (economies of scale) [2,17,18,21] which is realisable through floating concepts in offshore areas.
- **possibility to upscale through device arrays:** the Levelised Cost of Energy (LCOE) can also be reduced through very large-scale deployment in the form of offshore wind/wave farms and solar PV plants [2,18,22,28] which is only realisable in offshore areas.
- **positive influence on biodiversity:** according to a recent study carried out by University College Cork (Ireland), FOWT foundations would double as fish aggregating devices (FADs) to attract ocean-going pelagic fish and boost habitat complexity in the process [29].
- **positive influence on marine primary productivity:** the aforementioned study also states that flow separation occurring around FOWT foundations as well as the turbine wakes would jointly cause upwelling/downwelling flows akin to Langmuir circulation which would in turn boost the vertical mixing of nutrients across adjacent clines [29,30].

From the above, it is evidenced that the merits of floating renewable energy systems are not only confined to savings in capital expenditure (CAPEX) or gaining accessibility to more energetic resources. The merits rather extend to promoting co-existence with other ocean users as well as boosting marine productivity and biodiversity which would help consolidate the overall acceptability of floating renewables as an alternative energy resource within the public. As a consequence, a multitude of floating renewable energy projects have been commissioned or are currently in the deployment/planning stages globally. An exhaustive listing is provided in Tables A1–A4 for floating offshore wind turbine (FOWT), floating solar PV (FPV), floating wave energy converter (FWEC) or floating tidal current energy converter (FTCEC) concepts, respectively. It is seen that the commissioning of FWEC concepts predates the other technologies by at least 1.5 decades which is attributable to a major push towards developing wave energy following the 1970s oil crisis [31]. However, it is also seen from Table A3 that a majority of the FWEC projects have since been decommissioned as more well-proven technologies such as FOWT, FPV and FTCEC have emerged. In case of the latter three, a re-imagining of the (century-old) harnessing technology was unessential; the first solar panel was invented in 1881 closely followed by the first hydroelectric power plant in 1882 in turn followed by invention of the first wind turbine in 1887. In contrast, the overabundance of proposed WEC concepts (>1000) has been responsible for the field being branded as a "zoo of solutions" [32] leading to a waning of industrial interest. As argued by [33] in context of the Indian coast, wave-energy development should be approached from the standpoint of selection and sizing of already proven technologies for a given site in lieu of perpetual inventing and reinventing of "novel" concepts. The dwindling commercial interest in wave energy is underlined by the fact that the term "wave" cannot be found in the "Renewables 2022" report published by the IEA [2]. On the contrary, FOWTs, FPVs and FTCECs are rapidly dominating the floating renewable energy sector in terms of installed capacity, cross-industrial collaborations as well as the number of multi-megawatt projects being planned globally (cf. Tables A1–A4). Currently, the UK is the global leader in offshore wind. According to the Renewables 2022 report by the IEA [2], the UK is poised to increase its total renewable energy capacity to 36 GW over 2022–2027 out of which 18 GW (50 %) would be contributed by offshore wind [2]. According to the report, offshore wind projects worth 7 GW were contracted through Contract for Difference (CfD) auctions where, for the first time, a 32 MW floating foundation won a contract. Commissioned in 2017, Hywind Scotland is the world's first FOWT farm with 5 FOWTs each rated at 6 MW. In late 2021, the world's largest FOWT farm became fully operational at Kincardine, Scotland with 5 FOWTs each rated at 9.5 MW (cf. Table A1). Referring to Table A2, the FPV market is currently dominated by emerging economies such as China, India and Thailand despite the fact that the projects have solely been commissioned in inland reservoirs/waterways. Nonetheless, the possibility of developing offshore FPVs is being explored through small-scale pilot projects in Europe and Japan. It is worth noting from Table A4 that at least 10 FTCEC projects have either been commissioned or are in the deployment/planning stages globally with the sector currently led by Scotland's Orbital Marine Power and Sweden's Minesto AB.

The importance of floating devices in the marine renewable energy sector cannot be overstated; neither can the importance of mooring systems, which form an integral component of said devices. Mooring systems serve the following purposes for floating renewable devices [34]:

- station-keeping of the device,
- limiting excursion of the floater (especially important in device arrays),
- balancing environmental as well as operational loads.

Looking at floating renewables as a whole, the industry employs a multitude of different types of mooring systems, a sizeable chunk of which have been adopted from conventional offshore industries such as O&G and aquaculture. Whilst the pioneering developments are described in detail in Section 2, the same are briefly presented here for the sake of completeness.

Referring to Table A1, spar, semi-submersible (also known as semi) and moonpool-type (also known as barge-type) floating platforms have been extensively adopted in commissioned/upcoming FOWT projects. In this regard, tension-leg platforms (TLPs) and tension-leg buoys (TLBs), although touted as one of the key platform designs for FOWTs [18,34,35], have seen limited application. This is because the stability of the TLP/TLB substructure during mooring lines/power cable connection/disconnection and towing is believed to have major implications for project feasibility [16]. In case of FOWTs, a catenary arrangement of the mooring lines is generally adopted for spar [13], semi [36] as well as barge type [37] foundations.

As already mentioned in Table A2, almost all FPV projects have been commissioned over inland reservoirs in shallow waters. Inland FPV platforms are generally modular and constructed from several (million) individual floats made of High Density Polyethylene (HDPE) [38,39]. Nonetheless, several innovative platform designs have been proposed for future offshore FPV installations. These include [40]: (a) thin floating panels, (b) semisubmersibles, (c) platforms with air cushions, (d) cylindrical floaters, (e) platforms connected by cubic floaters and (f) porous pontoons and cylinders. It should be noted that an inland FPV installation does not necessarily preordain tranquil conditions in comparison to offshore sites. This is substantiated by a recent mishap [41,42] in which a sudden gale (wind-speeds of $\sim$14 m/s) induced by a summer storm tore mooring lines and toppled over sections of the Omkareshwar Floating Solar Power Park (cf. Table A2) which is currently the largest FPV plant in the world [43]. The incident has brought forth concerns regarding the susceptibility of inland FPV installations to climate-change-induced extreme weather events [44]. Such events would be characterized by high winds causing significant variations ($\sim$10 m) in the water-level within the reservoir. Such variations are extreme, even if compared to offshore sites, and necessitate innovative mooring and anchor designs to withstand large variations in water-depth.

In case of FWECs, mooring systems may resemble those employed in FOWTs in that a single taut or three/four catenary-profiled mooring lines may be directly connected to a WEC (cf. [45] for the "Sharp-Eagle" WEC, [46] for the "Uppsala buoy WEC" and [47] for a hybrid FOWT-FWEC concept involving the integration of "Wavebob" and "Wavestar" into the "DeepCwind" platform). However, more often than not, large FWECs are attached to a moored buoy and allowed to weathervane about it [48] which resembles single-point-mooring (SPM) systems popularly employed in O&G offloading operations. In such cases, the catenary anchor leg mooring (CALM) and single anchor leg mooring (SALM) systems have been extensively recommended for station-keeping [5,48,49].

Similar to FOWTs, the mooring systems adopted for FTCECs are dictated by the type of floating foundation to which the tidal turbine is attached. It is evident from the literature that most FTCECs employ a horizontal axis tidal turbine (HATT) [50–54] with catenary spread moorings in an $a \times b$ configuration where a is the number of clusters and b is the number of mooring lines per cluster [34]. In this regard, some of the key mooring systems include: (a) barge-type platform (using 4×1 [50] or 6×1 [53] configurations), (b) semisubmersible (3×3) [51], (c) catamaran-type platform (4×1) for modular tide generators (MTG) [54] and (d) central buoyancy tube turret-moored to the seabed (employed in Orbital Marine's O2 project; cf. Table A4) with fore/aft mooring lines in a 1×2 configuration. In addition to the above, the HATT may also be directly moored to a gravity base using a single mooring line [52] or tension-moored to the seabed using tendons (as for instance employed in Nautricity's CoRMaT system [7]). The next frontier in floating offshore renewable energy technologies (abbreviated as "FORE" henceforth) is the development of larger "farms" comprising arrays of single devices. In this regard, shared mooring systems have been proposed where adjacent devices would share anchors and a section of the mooring line [16,55]. Shared mooring systems are inevitable from a CAPEX and installation cost point of view. However, the offshore industry is only cautiously considering such shared mooring systems due to their many challenges [16].

The challenges for shared moorings manifest differently in shallow (50–100 m) and deep (800–1000 m) waters [16]. In deep water, both the anchor and mooring lines may be shared. The deep-water mooring system is susceptible to motions of the platform being amplified over the water column thus leading to large displacements in the mooring line [56] in turn resulting in peak anchor loads. In shallow water, sharing of the mooring lines would be largely inconsequential to the CAPEX, however, considerable cost reduction can still be achieved through sharing anchors [16]. Chain catenary moorings in shallow water are susceptible to snap loads (also referred to as snatch loads or shock loads in the industry [16]) which occur when there is a momentary slack and the mooring line re-engages suddenly causing a spike in tension [57]. The industry is considering developing axial load-reducing mechanisms such as replacing part of the mooring chain with highly elastic components (say nylon ropes) to mitigate snap loads. However, the technological viability of these solutions is yet to be proven at the commercial scale [16]. Thus, the development of shared mooring systems has been recognized as a major thrust area demanding innovation in the offshore renewable energy industry [16,55,58], yet their development is hindered due to a lack of understanding of the peak loads in such systems.

Whilst the mooring systems for FWECs have recently been reviewed in [5], to the best of the authors' knowledge, a review on shared mooring systems is yet to be attempted. The goal of this review is to consolidate the existing pool of knowledge on shared mooring systems in FORE so that a thorough understanding of the state of the art from both industrial development as well as academic research perspectives can be attained. This is achieved through the following objectives: (i) review of the historical wisdom on mooring systems bequeathed to floating renewables from conventional offshore industries (namely O&G and aquaculture) in Section 2 and (ii) reporting of the strategies adopted for sharing of mooring components and how said strategies differ in deep and shallow water in Section 3, and (iii) discussion of the scope for and feasibility of adopting shared mooring systems in floating renewables (FOWT, FPV, FWEC and FTCEC) in Section 4 and (iv) outlining of the major thrust areas of R&D in shared moorings identified by the industry in Section 5 and (v) detailing of the accompanying academic research effort in the aforementioned thrust areas in Section 6 and (vi) identification of gaps in the existing research effort in Section 6.3. Conclusions are then drawn in Section 7.

2. Historical wisdom gained from conventional offshore industries

The mooring systems in FORE have been largely developed based on the technological advancements pioneered by conventional offshore industries such as O&G (particularly in deep water) and aquaculture (particularly in shallow water). The influence of advancements in O&G on the development of FOWT platforms has been recently discussed in [59]. The historical wisdom gained from pioneering developments in O&G mooring systems is summarized in the following sub-sections.

2.1. Oil and gas (Deep water)

In order to completely describe moored systems employed in the offshore industry, the following aspects need to be considered: (a) type of floating platform, (b) type of mooring system and (c) components of the mooring system. These aspects are listed in detail in Fig. 1. The substantial variety existing in the various components of the floating system is readily evidenced from Fig. 1. The O&G industry deserves credit for the development of these technologies during the latter half of the 20^{th} century. The developments were driven by the need to explore resources in waters deeper than 550 m which is the maximum depth in which (bottom-fixed) compliant towers could be deployed [34]. The chronology of these developments is briefly presented.

Floating offshore structures in O&G were traditionally referred to as “Mobile Offshore Drilling Units” (or MODUs) [34]. The first MODU was the semi-submersible barge “Mr. Charlie” developed in 1954 for 12 m deep water followed by the first floating drilling vessel “Western Explorer” in 1955. The first jack-up MODU was “Gus I” developed in 1956 for 25 m deep water; the operational depth had increased to 120 m by the 1990s. In 1961, Shell Oil integrated a mooring system into a semi and developed “Bluewater I” which was followed by “Ocean Driller” in 1963 which was rated for 90 m water-depth. Mooring systems in the 1960s comprised of chain and wire-rope connected to 6–8 anchors [34]. However, large water depths, vessel motions and the weight of long mooring lines posed challenges. O&G semis evolved from their first generation (in 1960s) to their fifth generation (in 1990s) with the latter platforms capable of operating in a depth of ~ 1 km. Owing to the large water-depth, the fifth generation semis used dynamic positioning (DP) systems for station-keeping and weathervaning. Over the course of the development of semis emerged the ship-shaped Floating Production Storage and Offloading (FPSO) platform (cf. Fig. 1(a)); the first FPSO was the “Shell Castellon” which was built in Spain in 1977. The evolution of semis was also interspersed with the advent of Tension-leg Platforms (TLPs) which were vertically moored and could be deployed in water depths ranging between $300\,\text{m} \le d \le 1600\,\text{m}$; TLPs were first applied in 1984. This was followed by the development of the (highly stable due to their deep-draft) spar-type platform; first being the “Neptune spar” installed in the Gulf of Mexico in 1997. The above development chronology could be summarized as: Semi → FPSO → TLP → Spar. By the turn of the millennium, floating O&G platforms had moved up to 2500 m deep water.

Initial mooring components in the 1980s comprised wire-ropes and chains (cf. Fig. 1(c)). Nowadays, O&G vessels employ DP systems in > 3500 m deep water. DP systems in drillships are used *in place* of physical moorings where the latter is not feasible due to very deep water ($\gtrsim 3.5$ km). Thus, DP systems act as digital moorings/anchors of sorts. Standalone DP systems are different from *thruster-assisted* mooring systems (cf. Fig. 1(b)) wherein DP systems complement passive moorings [34]. Synthetic fiber ropes (developed in the 1990s; cf. Fig. 1(c)) have enabled physical mooring-based O&G operations in deep water. For instance, polyester moorings were used in the Red Hawk and Mad Dog platforms in the Gulf of Mexico in 2004; polyester is now the most widely used mooring line material in the world.

Foundational mooring systems employ drag anchors which a limited capability of withstanding vertical loads [34]. In order to withstand very high vertical loads, nowadays, vertically-loaded and suction-pile anchors (cf. Fig. 1(c) and Fig. 2) are widely used in deeper waters and harsher environments. The various types of anchors developed by the O&G industry along with their suitability requirements and applications are showcased in the form of a mind-map in Fig. 2. These innovations in anchor design and development have now been inherited by the FORE industry. As alluded to previously, thruster-assisted mooring is essentially a hybridisation of DP and physical mooring systems. Semis are sometimes equipped with such hybrid systems to enable drilling in shallow as well as deep water [34]. On the other hand, drillships have become very large and thus function in ultra-deep water exclusively using DP systems.

The contributions of the O&G industry towards development of offshore floating platforms, requisite mooring systems and mooring components are substantial. Owing to their very large size, O&G platforms are standalone structures and are (almost) never deployed in arrays. And even if an array of O&G platforms were to be hypothetically deployed, it would not be possible to share mooring system components between adjacent platforms, simply because of the magnitude of loads acting on said components. Having said that, the concept of sharing mooring lines and anchors is inherent to offshore aquaculture wherein a typical farm may be comprised of tens of fish cages and the associated loads on the mooring system are substantially less in comparison. The advancements in offshore aquaculture moorings adopted by FORE are discussed next.

2.2. Offshore aquaculture (Shallow water)

The term aquaculture refers to the cultivation of marine organisms for food either in littoral waters (inshore) or in the open ocean (offshore; $20\,\text{m} \le d \le 150\,\text{m}$). By moving to the open ocean: (a) conflicts with other marine users as well as nearshore pollution have been avoided and (b) it is possible to deploy larger fish-farms (in-line with increasing demand for seafood). As a result, offshore aquaculture is currently one of the fastest developing food industries in the world as farming is being increasingly preferred over conventional capture/wild fisheries [61,62]. In offshore areas, fish cages can reach volumes of up to $30,000\,\text{m}^3$ [63] (rigid standalone cages can be much larger at $250,000\,\text{m}^3$ [64]) and their design philosophy is dictated by the ability to withstand harsh environmental conditions that are predominantly driven by waves and currents. Recently, Nasyrlayev et al. [65] have identified stressors that influence the cage system:

- high current speeds:
  - excessive strain on the cage
  - reduction in cage volume
  - fish expend more energy eventually leading to feed loss
- excessive wave-action:
  - damage cage structure
  - damage mooring system
  - injure fish
- seabed quality and water-depth (impacts mooring design and anchor selection).

Based on the above stressors, station-keeping, weathervaning and minimizing deformation of the cages are some of the key elements central to the design of offshore aquaculture systems. A mind-map depicting the various constituents of a floating offshore fish-farm is shown in Fig. 3. Many floating fish-farms employ grid-mooring which is considerably different from conventional spread-mooring employed by the O&G industry (cf. Fig. 1(b)). In aquaculture, a “grid” of mooring lines is formed around the fish-cage using frame-lines and the cage itself is connected to the frame-lines using so-called “crowfoot cables” or bridle lines [65]. The reader is referred to Park et al. [66] for a detailed investigation into the design of bridle line connections. A typical aquaculture grid-mooring system is illustrated in Fig. 4. Fish cages may be deployed as standalone or in the form of arrays wherein the cage itself may be comprised of flexible (grid-mooring) or rigid (multi-module platform) structural members. Following Jin et al. [68], the need to upscale fish

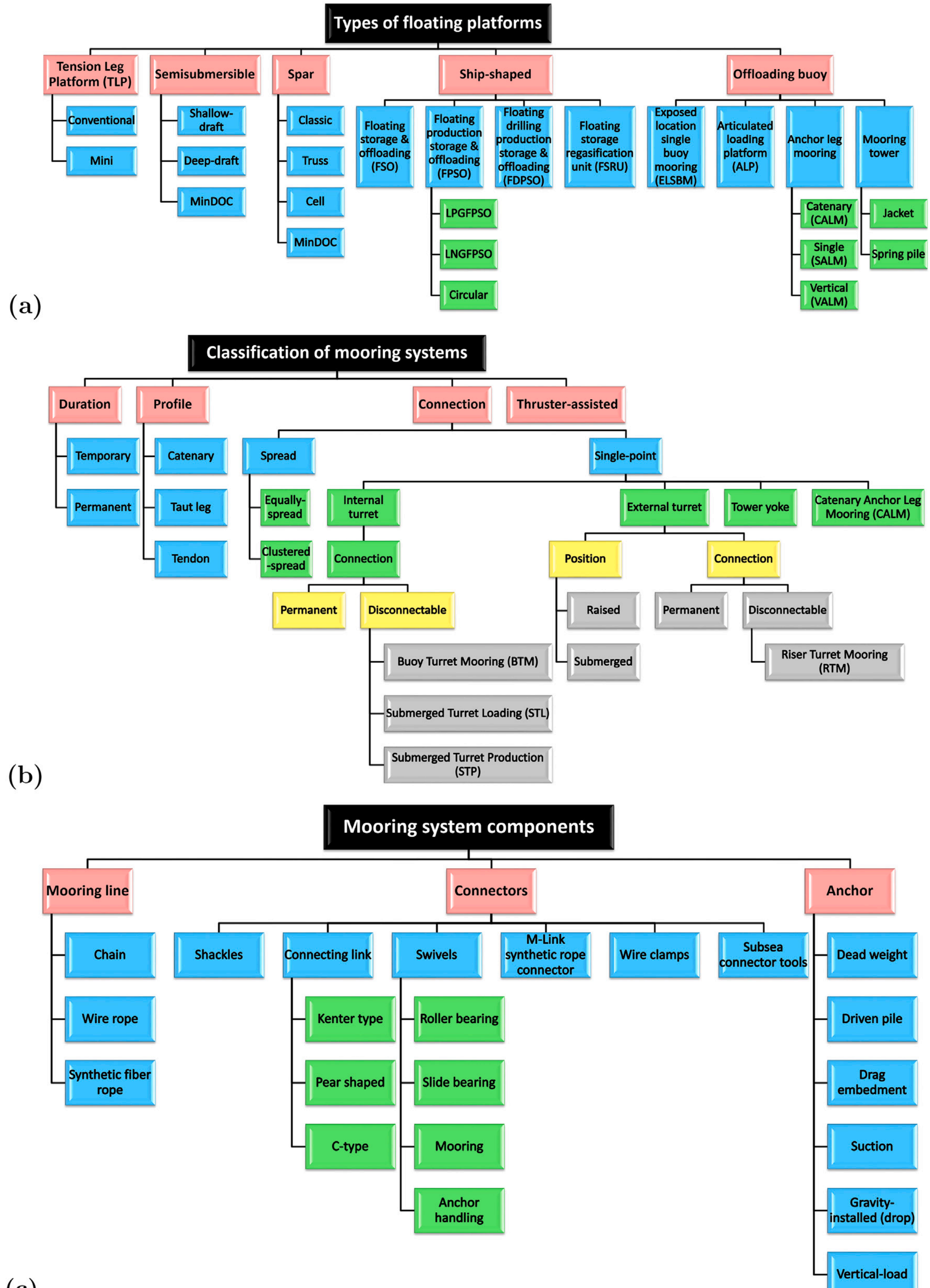

Fig. 1. Various descriptors of an offshore moored system. The superstructure is supported by a suitable (a) floating foundation which is "station-kept" by an appropriately chosen (b) mooring system that is comprised of various (c) components [34,60].

farms for deployment in more energetic offshore locations has led to the development of rigid standalone cage as well as multi-module platform designs (cf. Fig. 3). In this regard, the ovaloid "Egg", the circular semi-submersible "Arctic Offshore Farming" as well as the dodecagonal "Ocean Farm 1" concepts pertain to the standalone category whilst the vessel-shaped "Havfarm" concept belongs to the multi-module category

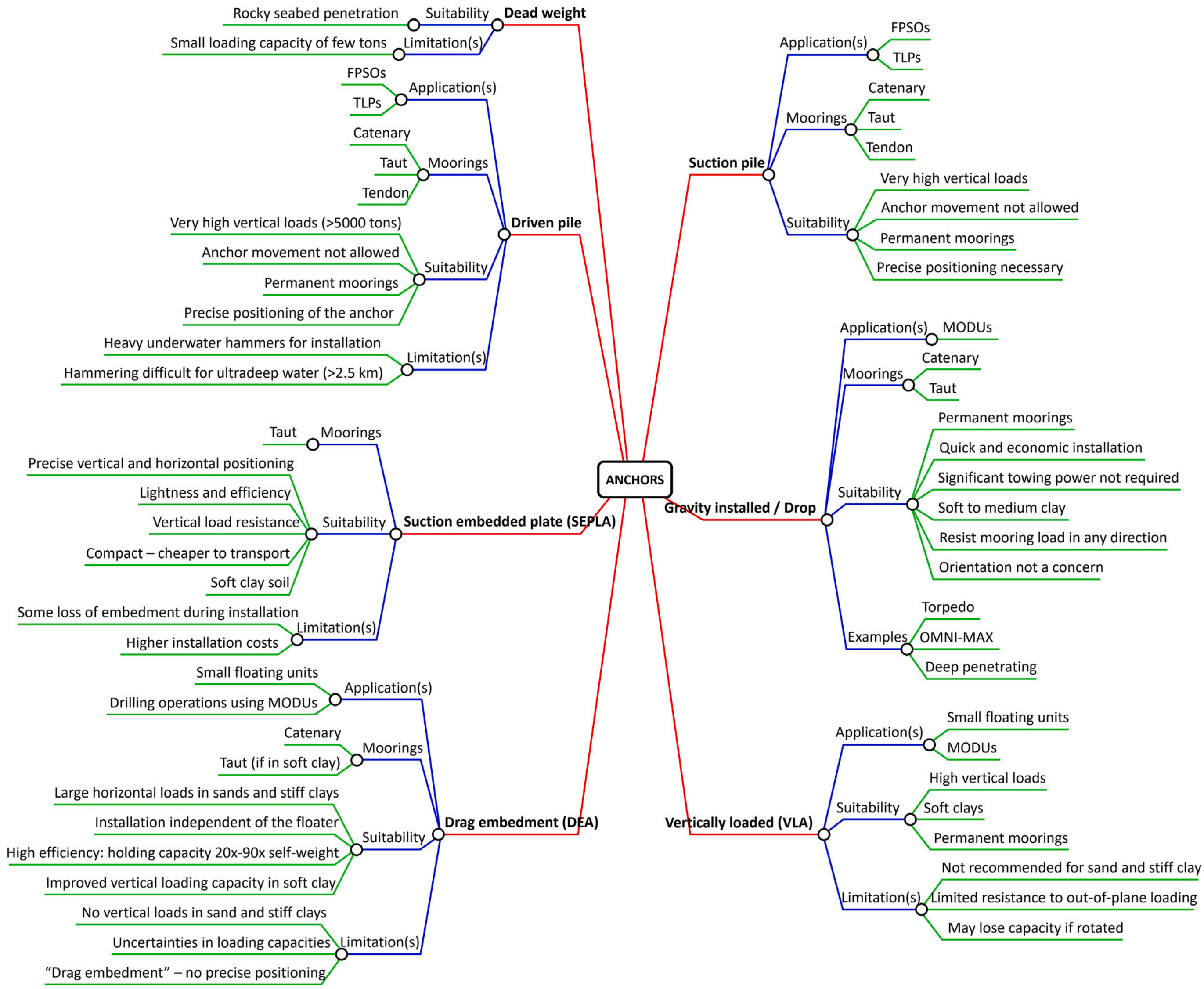

Fig. 2. Mind-map showcasing the various types of anchors developed by the O&G industry alongwith their applications, suitability in terms of site/application/mooring requirements, sub-categories and limitations [34,60].

[68]. It should be noted that standalone cages may also be grid moored without sharing of mooring components between adjacent cages (cf. Fig. 4 and Fig. 5(c)).

Nonetheless, deployment in the form of cage arrays has now become the industry standard in offshore aquaculture. A multi-module arrangement is beneficial in terms of:

- more efficient space utilization [72],
- reduction in wave-loads as different modules would be acted upon by different phases of the wave [72] (cf. Fig. 5(c)),
- reduction in current-loads on downstream cages that fall in the wake of upstream cages [61],
- increased productivity (cultivation volume) due to a reduction in the overall environmental loading on the farm [61],
- simplification and ease of management [65,72] and
- cost minimisation due to shared mooring systems [65].

Amongst the above advantages, it's particularly worth noting that modular fish cages provide an opportunity for the deployment of shared mooring systems. Referring to the schematic of a standalone cage in Fig. 4, the mooring system components which may be shared include: (a) anchors [62,72], (b) anchor lines [61,65], (c) frame lines [61] as well as (d) connectors (in case of modular platforms) [69,70]. Shared mooring systems adopted in offshore aquaculture are illustrated in Fig. 5 with detailed specifications of prototype-scale systems listed in Table 1. Two distinct shared mooring scenarios are illustrated in Fig. 5. In the first case, adjacent grid-moored cages only share anchors (cf. Fig. 5(a)) whilst in the second case, both anchors and mooring lines (anchor-lines and frame-lines) are shared (cf. Fig. 5(b)). In the latter case, it is evidenced that shared mooring systems can decrease the total number of anchors and mooring lines by as much as 50 % which represents a substantial reduction in CAPEX. By directly reducing the number of lines and anchors, shared moorings also help reduce the overall complexity/DOFs of the offshore aquaculture farm. Interestingly enough, shared moorings aren't the only means by which the total number of anchors/mooring lines may be reduced; the same result can be achieved by transitioning from multi-point mooring (MPM) to single-point mooring (SPM). The SPM concept has been adopted directly from the O&G industry (cf. Fig. 1(b)) and involves the floating fish-farm moored to the seabed using a single anchor-anchor line pair (cf. Table 1). The key advantage of SPM

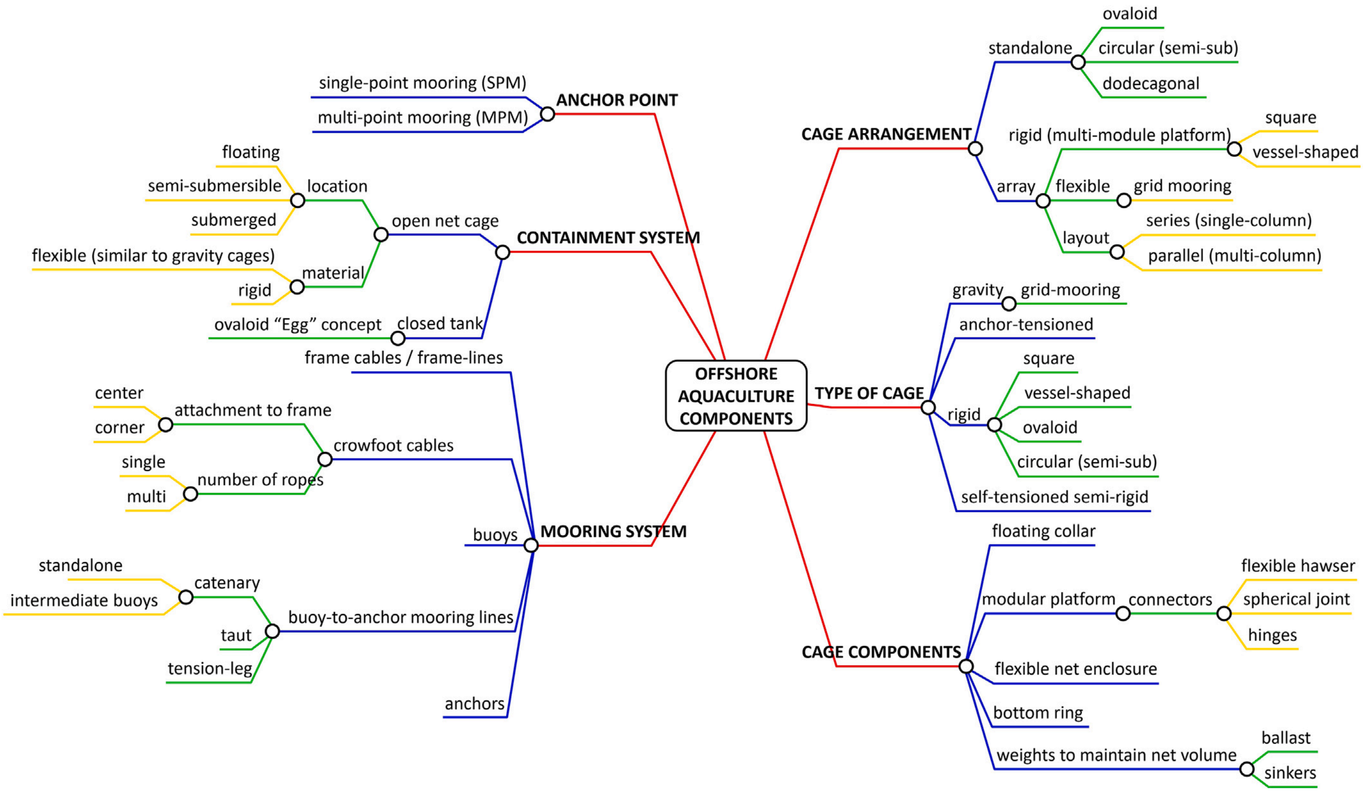

Fig. 3. Mind-map showcasing the various components constituting the cage and mooring systems employed in offshore aquaculture alongwith their classifications (developed based on [65–70]).

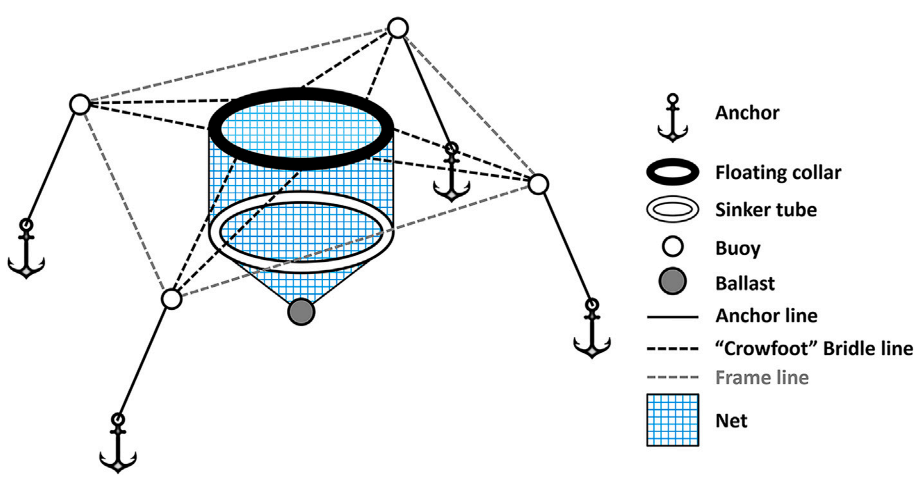

Fig. 4. Standalone aquaculture cage with grid mooring (developed based on [65]).

is the ability of the cage(s) to weathervane about the turret/anchor-point which reduces environmental loads [70] and helps spread out food as well as fish-generated waste over a larger area [67]. Whilst the anchoring/anchor-installation costs for SPM may be 50 % lower than MPM, the inherent "zero redundancy" places SPM systems at a considerably higher risk of failure [67,70]. To this effect, Huang and Pan [67] carried out an in-depth investigation into the various types of mooring line fatigue scenarios as well as the underlying environmental loads responsible for the same. They concluded that cyclic loading induced by ocean waves (especially in deep water) was the major contributor to mooring line fatigue in comparison to axial compression, creep and hysteresis heating. Recently, SPM-based aquaculture systems were studied by Ma et al. [70] using ANSYS®Aqwa in which a vessel/ship-shaped modular platform was considered (cf. Table 1). The platform comprised a triangular floating frame at the anchor point followed by (one, two or three) square floating frames connected in series using hinges. When the response of the modular platform in regular waves was simulated, a sheltering effect was observed in which the heave and pitch motions of the (downstream) square frames reduced by $\gtrsim$ 25 % and $\gtrsim$ 45 % respectively. In addition to the sheltering effect, an increase in the number of frames leads to a reduction in the amplitude of the surge and pitch responses; nonetheless, the inclusion of more frames also leads to an increase in the mooring line tension [70]. It is worth-noting that SPM systems in offshore aquaculture are more akin to single anchor leg

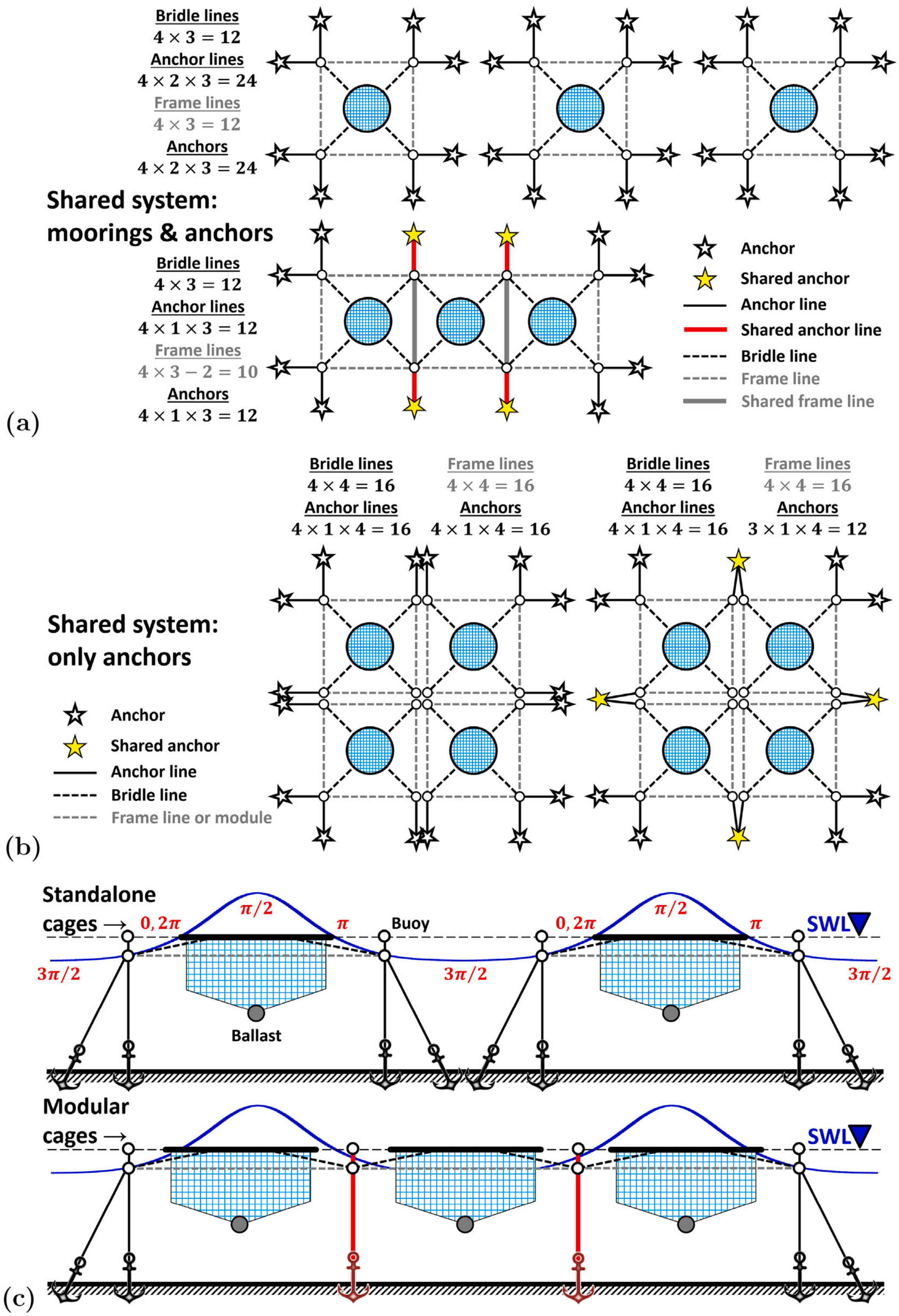

Fig. 5. Shared moorings between tandem cages/modules in offshore aquaculture: (a) sharing of anchors (schematic developed from [62,72]), (b) sharing of both anchors and mooring lines (schematic developed from [61,65]) and (c) differences in the nature of wave-loads across standalone and tandem cages (developed from [72]).

mooring (SALM; cf. Fig. 1(a)) rather than catenary anchor leg mooring (CALM); the latter is more commonly employed in contemporary O&G offloading operations. Nonetheless, the level of risk associated with SPM systems across offshore O&G and aquaculture is the same; the mooring line is the most critical component and its failure has catastrophic consequences.

Table 1
Details of mooring systems employed in prototype scale offshore aquaculture as reported by various studies in the literature. Entries are sorted chronologically and the ones in **bold** indicate sharing of components in the mooring system.

Floating collar/frame	Dimensions		Depth	Mooring system				Mooring layout		Ref.
	Width	Height		Profile	Arrangement	Line	Components	Lines	Anchors	
Circular (1 × 5 array)	11.5 m	6 m	30 m	Taut	Single-point	Hybrid	PET rope + Chain	1	1	[67]
Hexadecagonal frame	120 m	–	120 m	Taut	Spread	Hybrid	Fiber rope + Spring	4 × 1	4	[63]
Circular	18 m	–	20 m	Grid	Cluster-spread	Hybrid	Fiber rope + Chain	4 × 2	8	[71]
Square (3 × 3 array)	120 m	15 m	20 m	Catenary	Spread	Uniform	Chain	36 × 1	**36 – 8**	[72]
Circular (1 × 4 array)	53 m	28 m	80 m	Grid	Cluster-spread	Hybrid	Fiber rope + Chain	**10 × 2 – 6**	14	[61]
Dodecagonal frame	110 m	68 m	150 m	Catenary	Cluster-spread	Hybrid	Fiber rope + Chain	4 × 2	8	[68]
Circular	30 m	10 m	70 m	Taut	Cluster-spread	Uniform	UHMWPE rope	4 × 2	8	[66]
Circular	30 m	12.5 m	20 m	Grid	Cluster-spread	–	–	4 × 2	8	[73]
Circular	17 m	–	20 m	Grid	Cluster-spread	Uniform	Polypropylene rope	4 × 2	8	[74]
Vessel-shaped	40 m	16 m	40 m	Taut	Single-point	Hybrid	HDPE rope + Chain	1	1	[70]
Square (1 × 2 array)	40 m	15 m	28 m	Catenary	Spread	Uniform	Chain	**8 × 1 – 4**	4	[69]
Circular	30 m	12.5 m	50 m	Grid	Cluster-spread	–	–	4 × 2	8	[75]
Square (3 × 3 array)	40 m	16 m	20 m	Grid	Spread	Uniform	Chain	36 × 1	**36 – 8**	[62]
Circular (2 × 2 array)								**8 × 2 – 4**	12	
Circular (1 × 4 array)	50 m	25 m	52.5 m	Taut	Cluster-spread	Uniform	Chain	**10 × 2 – 6**	14	[65]
Circular (2 × 4 array)								**12 × 2 – 8**	16	
Circular (2 × 8 array)	25 m	30 m	50 m	Catenary	Cluster-spread	Hybrid	Fiber rope + Chain	**20 × 2 – 16**	24	[76]
Hexagonal frame	110 m	78 m	63 m	Catenary	Cluster-spread	Hybrid	Fiber rope + Chain	4 × 2	8	[77]

On the other hand, the massively interconnected grid-moored arrays of fish-cages involve a large number of mooring lines and thus failures are, in comparison to SPM, more frequent [74] and do not carry the same level of risk. Having said that, line failures need to be accounted for in the design stage to ensure sufficient redundancy in the system [74]. Hence, the R&D effort is focused on understanding the underlying causes of failure, studying the system response following a failure event as well as minimizing the number of failure events. In this context, the problem of fish escaping from grid-moored fish farms has been investigated by Cheng et al. [61] wherein human intervention during regular O&M activities was cited as a chief cause. They theorized that the presence of mullet boats could augment the anchor-line loads by 40 % and if said overloading causes a structural failure (mooring line breakage), it could overload the remaining lines by a factor of 1.75. Hou et al. [71] investigated the influence of wave groups on the fatigue life of mooring lines in a single aquaculture cage with grid-mooring. They observed that the line tension exhibited a strong dependence on the wave groupiness factor. In this context however, it was observed that the fatigue damage strongly correlated with the group factor of height (GFH: quantifies the group height) but not with the group length factor (GLF: length of the sequence of high waves in the group). In their subsequent study, Hou et al. [74] carried out a reliability assessment of a single grid-moored fish cage with a damaged mooring line. They stated that an intact mooring system is in an "ultimate limit state" (ULS) wherein the lines can be loaded to adequate capacity and risk assessment can be reasonably performed. Following a failure event, the damaged system enters an "accidental limit state" (ALS) wherein the lines can only be loaded to a certain capacity and it becomes difficult to quantify the probability of subsequent failures owing to the reallocation of line tension [74].

As mentioned previously, the traditional grid-moored fish-cages are gradually being replaced with rigid and modular floating platforms, especially in more energetic offshore locations. The total number of anchors/mooring lines in a modular platform is less than that in grid-moored cage arrays but greater than SPM or single-cage systems. As observable from Fig. 3, modular cage arrangements can have a single-column (series) or multi-column (parallel) layout. In this context, Ma et al. [62] recently studied the response of a 9-module floating aquaculture platform with shared anchors (cf. Fig. 5(a)) under irregular waves. They investigated the influence of the type of connector between the fish cages (flexible hawser and spherical joint; cf. Fig. 3) on the overall dynamic response. The influence of the angle between the mooring lines and the direction of wave-propagation on the mooring response was also investigated. It was observed that the spherical joint connector is more effective in restricting surge but in turn experiences ~35% higher mooring force. It was also observed that the central module, not directly connected to any mooring lines, experiences greater surge in comparison to the adjacent cages that are attached to the mooring system. Interestingly, the study also revealed that the mooring lines near the corners of the platform exhibit low frequency characteristics whilst those near the middle of the sides show characteristics close to the wave frequency [62].

The contributions from offshore aquaculture to FORE are primarily manifested in terms of shared mooring systems in which the anchors or mooring lines or both may be shared. The conventional concept of grid mooring may be adopted for deploying arrays of point-absorber type wave-energy converters (FWECs) to improve station-keeping as well as survivability of the devices in rough seas. The concept of bridle lines has already been adopted to moor spar-type FOWT platforms (cf. Fig. 8). Similarly, the concept of modular aquaculture platforms could be adopted for designing offshore solar farms (FPVs) since inshore FPV installations are also modular (cf. Section 1). The need for adopting shared moorings for FOWTs has been widely recognized by the industry [16,55,78]. The types of shared mooring systems suitable for FORE and their key aspects are discussed in detail in the next section.

3. Types of shared mooring systems

It is evident from Section 2.2 that there exist several ways in which mooring systems could be shared amongst adjacent floating bodies. In context of FORE, the industry recognizes the need for shared moorings; the technology has been adopted, to some extent, in the FWEC, FPV and FOWT sectors. The different types of shared moorings (either already deployed or in the planning stages) for FORE are discussed in the following subsections; the scope of adoption in individual sectors is presented in Section 4.

3.1. Sharing of anchors (all water depths)

According to a report by the Carbon Trust on the Floating Wind Joint Industry Project (FWJIP; [16]), the "simplest and most cost-effective implementation" of shared mooring systems is to share anchors between adjacent devices. The cost-effectiveness is due to a direct reduction in the number of anchors [79,80] whilst the simplicity is due to its viability in all water depths [16]. In the context of FOWTs, said viability encompasses relatively benign intermediate depths ($500\,\text{m} \le d \le 1000\,\text{m}$) as

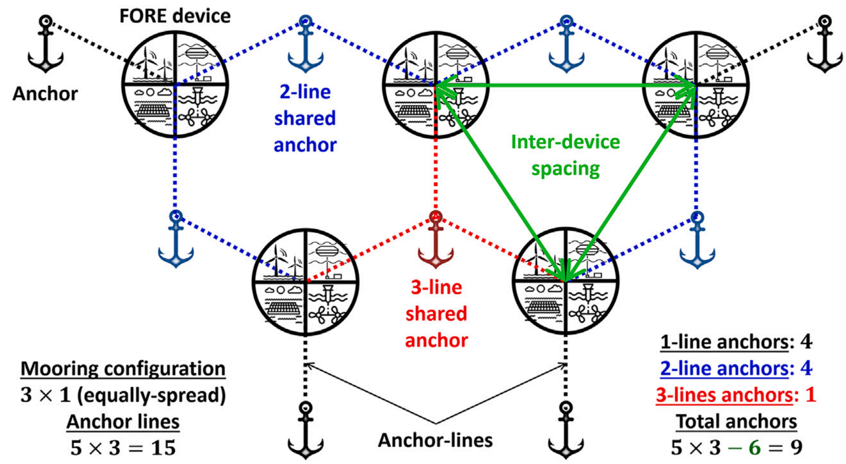

Fig. 6. Shared anchoring for an array of FORE devices (developed based on [80]).

well as more challenging conditions in shallow ($50\,\text{m} \leq d \leq 100\,\text{m}$) and ultra-deep ($d \geq 1000\,\text{m}$) waters [55]. A canonical shared anchor design in an array of FORE devices is illustrated in Fig. 6 where up to three devices share a common anchor. As seen previously in Fig. 5(a), the layout in Fig. 6 leads to an overall reduction in the total number of anchors but not necessarily in the number of mooring lines (anchor-lines). Further, the total mooring length ("mooring footprint") is expected to increase under shared-anchoring owing to a requirement to maintain inter-device spacing (cf. Fig. 6) which necessitates additional wire/rope length to reach a shared anchor [80]. The FORE industry (especially the FOWT sector) also acknowledges that shared anchoring necessitates different types of anchors within the same layout. With reference to Fig. 6, the "1-line" anchors could be drag embedment type but not the shared "2-line" and "3-line" anchors [16,80]; this is because of the inability of drag anchors to withstand sideways and vertical-loading (cf. Fig. 2). More suitable candidates for shared anchors would be suction piles and driven piles [80] which could withstand extreme multi-directional forces in shallow water as well as extreme vertical loads (also known as "peak anchor loads") in deep water [16].

Thus, the installation of shared anchors, albeit comparatively simple, necessitates optimization of the length of the mooring lines against the inter-device spacing (site-specific) to gain a net reduction in CAPEX; this is especially true for deployment of FOWTs in shallow water [80]. Nonetheless, projects necessitating large anchors clearly benefit from the (substantially) reduced number of anchors and consequently lower costs for AHTS (Anchor Handling Tug Supply) vessels. Some studies have also speculated that multi-directional loads could compensate at a shared anchor leading to an overall reduction in anchor size and potentially resulting in savings in CAPEX [78].

3.2. Sharing of mooring lines (deep water)

According to a recent FOWT anchor review report by ORE Catapult and ARUP [80], "the cost per mooring line is more expensive than the cost per anchor". Thus, one could potentially achieve greater savings in CAPEX by sharing mooring lines (also known as shared moorings) between adjacent devices. However, this solution is considerably more challenging to implement and is only viable in deep water ($d \gtrsim 1000\,\text{m}$) where the mooring line length is greater than the inter-device spacing. A canonical shared mooring design in an array of FORE devices is illustrated in Fig. 7 where up to three devices are linked by shared mooring lines. It is evident from the schematic that different implementations of shared moorings lead to different outcomes; this is despite the fact that both designs involve a 3×1 equally-spread

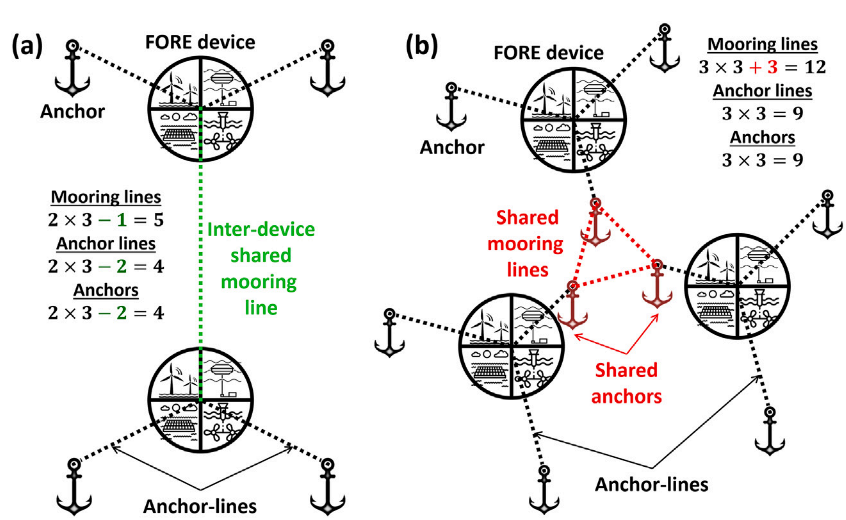

Fig. 7. Shared moorings for an array of FORE devices (developed based on [16,80]).

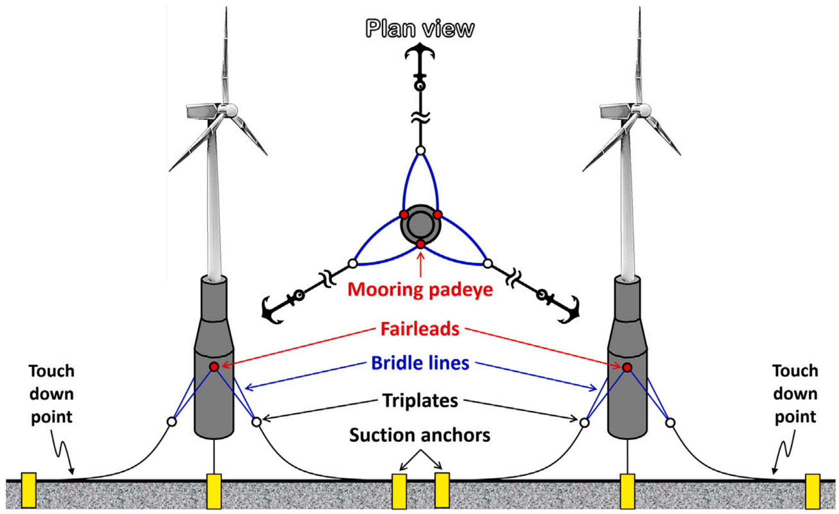

Fig. 8. Aquaculture-inspired bridle-lines-based system adapted to moored spar-type FOWTs in the Hywind Scotland wind farm (developed based on [82,83]).

mooring configuration. Referring to Fig. 7(a), two devices directly share a mooring line which leads to a reduction in the total number of mooring lines and anchors/anchor-lines by 16.67 % and 33.33 % respectively. On the other hand, Fig. 7(b) depicts a scenario where three devices connect to a central "virtual anchoring point" [16]. Interestingly, this arrangement leads to an increase in the total number of mooring lines by 33.33 % whilst the number of anchors/anchor-lines remains unchanged relative to a scenario in which the devices are deployed in a standalone manner. In this case, savings in CAPEX aren't achieved through a reduction in the number of moorings/anchors but rather through a reduction in the length of mooring lines required at the virtual anchoring point. One could appreciate why this would only be viable in deep water [16,78,80]; this aspect shall be explored in greater detail in context to FOWTs in Section 4.1.

Geographically speaking, shared mooring lines are "unlikely to have much applicability in the UK" [78] since the UK is surrounded by an extensive continental shelf ($\gtrsim$350 km). In contrast, the technology has considerable applicability off the US west coast where deep water is encountered only a few kilometers offshore owing to a short continental shelf ($\sim$ 25 km); the shelf off the Californian coast is one of the shortest in the world ($\lesssim$1 km)! Unlike shared anchors, shared mooring lines are yet to be deployed in a commercial-scale FORE project. This is primarily attributable to the increased complexity introduced into the system (cf. Fig. 7(b)), expensive installation and maintenance as well as a lack of adequate research into the wide range of possible mooring layouts and failure modes [16,79]. The R&D challenges associated with shared moorings will be discussed in greater detail in Section 5 and Section 6. The extent to which shared mooring systems could be adopted into the various individual sectors comprising FORE is discussed in the next section.

4. Scope for adoption of shared mooring systems in floating offshore renewables

The level of R&D carried out towards integrating shared mooring systems into FORE varies across different sectors because it is influenced by: (a) maturity level of the technology/device (or Technology Readiness Level, TRL), (b) feasibility of integration, (c) viability/complexity of integration and (d) perceived benefits to CAPEX and OPEX. Accordingly, the scope for adoption also differs across various FORE sectors; this is discussed in the following sub-sections.

4.1. Wind (FOWT)

The world's first full-scale floating wind farm is the 30 MW Hywind Scotland project from 2017. The concept of bridle lines has been adopted in the Hywind Scotland project to moor spar-type floating platforms using a 3×2 arrangement [78,81]; this is depicted by means of a schematic in Fig. 8. Hywind Scotland was succeeded by the 88 MW Hywind Tampen in 2022 which is the world's first FOWT farm to implement shared anchors [80]. Taking into account the rapid growth of the FOWT sector evidenced by the sheer scale of upcoming projects (cf. Table A1), there is, undoubtedly, scope for introducing shared mooring systems, which have been jointly acknowledged by the FORE industry [16,55,78,80] as well as academia [79,84–86]. Some of the key shared mooring concepts suitable for FOWT farms are illustrated in Figs. 9–11. It is seen from Figs. 9 and 10 that the honeycomb-type mooring layout with shared anchors has gained popularity especially following the successful commissioning of Hywind Tampen. In this arrangement, the FOWTs and anchors occupy alternate vertices of an imaginary hexagon. This simultaneously allows for sufficient staggering of the turbines as well as sharing of anchors. It is worth noting that Fig. 10 and Fig. 11 serve as three-dimensional perspective versions of Figs. 6 and 7(b) respectively. It is also worth mentioning that, for the same honeycomb mooring layout, two anchoring strategies have been depicted which principally differ in terms of whether the FOWT is directly moored to the suction anchor (cf. Fig. 10) or through an intermediate buoy (cf. Fig. 9). A considerably more complex mooring arrangement is depicted in Fig. 11 which is only viable in deep water and yet to be adopted by the industry in full-scale FOWT projects. The schematic depicts three semi-submersible platforms moored to a common "virtual anchoring point". Whilst the arrangement is conceptually similar to the general layout depicted in Fig. 7, the 3×2 cluster-spread configuration leads to a sharing of mooring lines *as well as* anchors.

First of all, two mooring lines from adjacent clusters merge into one below the buoys (highlighted in red in Fig. 11). Secondly, the profile below the buoys is no longer catenary but rather taut which, combined with the previous point, reduces the mooring length by more than 50 % below the buoy level. Thirdly, the anchors at the virtual anchoring point are shared which leads to an overall reduction of 16.67 % in the total number of anchors required. The aforementioned mooring arrangement could lead to considerable savings in CAPEX especially for cluster-spread configurations. Cluster-spread configurations are expected to increasingly become the norm in future FOWT installations wherein, by 2050, 60 % of the mooring clusters would need to be redundant [16,78].

4.2. Solar (FPV)

In contrast to inshore installations, offshore FPV is still an emerging technology (cf. Table A2). The total FPV installed capacity is $\lesssim$ 5 GW globally which is almost exclusively comprised of inshore projects [38]. It is conjectured by DNV that the emergence of nearshore and offshore

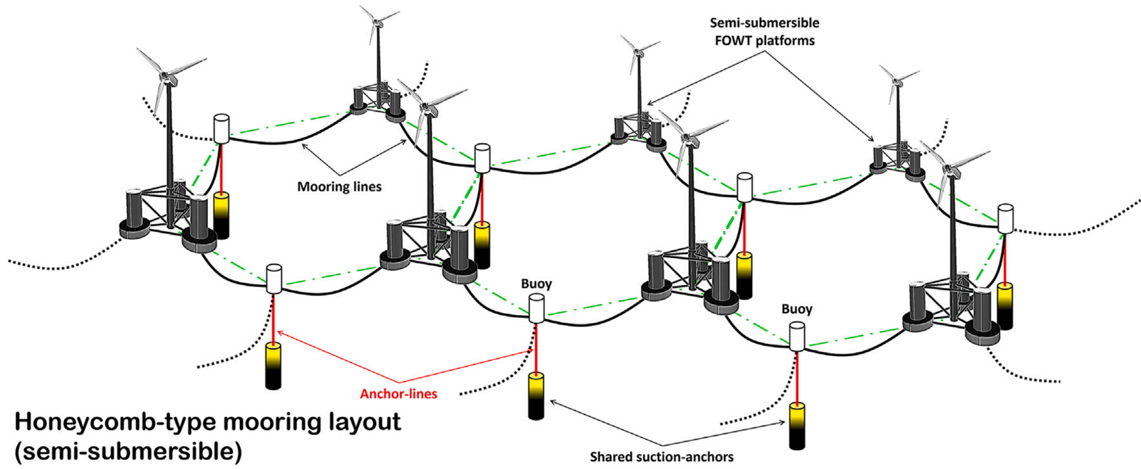

Fig. 9. Schematic illustrating a honeycomb arrangement for mooring semi-submersible type FOWT foundations to shared anchors. Note that the mooring lines do not directly attach to the suction anchor but rather to shared buoys which are in turn attached to the anchors through anchor-lines (developed based on [87]).

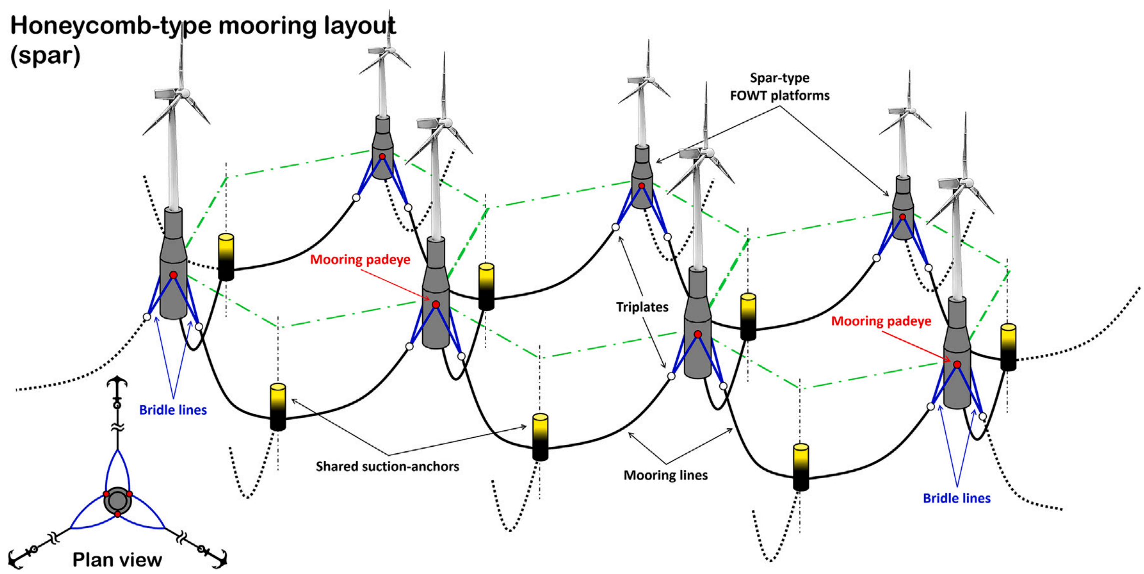

Fig. 10. Schematic illustrating a honeycomb arrangement for mooring spar type FOWT foundations to shared anchors as currently adopted at Hywind Tampen. Note the aquaculture-inspired bridle lines carried forward from Hywind Scotland (cf. Fig. 8) as well as the catenary mooring lines directly attaching to the suction anchors (developed based on [88]).

FPV would come at a time when it would already be in a “race for space” with other industries, particularly aquaculture and floating wind, which are poised to rapidly scale-up in contrast to FPV [38]. DNV also acknowledges the fact that future development of FPV, offshore in particular, is faced with several construction challenges that lie in the development of the station-keeping (mooring) system which has also been identified as the chief cause of failures [38]. A direct adoption of mooring solutions from the O&G industry, unlike FOWTs, is not recommended for FPVs owing to the following concerns [38]:

- lower load capacity of the FPV platforms necessitates load distribution,
- greater number of mooring lines and anchors required for load distribution,
- design challenges in estimating the loads and responses within a massively interconnected system,
- high water level variations leading to challenging mooring line design for the installation of FPVs in inland reservoirs and dams [41,42,44],
- lack of design and analysis standards specific to FPVs leads to ill-established QA/QC protocols which hampers consolidation of the technology into FORE.

Apart from the PV module itself, the greatest contributor to CAPEX in FPVs is the mooring system (floats, mooring lines and anchors) [38]. Studies anticipate the offshore mooring CAPEX to be as large as 20× that of its inshore counterparts [89] resulting in a 25 % increase in overall CAPEX [90]. The need for shared moorings in FPVs is yet to be explicitly recognized by the industry [18,38,55] probably due to the nascency of the technology. On the contrary, the lack of an explicit mention may also be due to the fact that the large number of mooring lines and anchors involved in an installation implicitly necessitates shared mooring systems in some form. This is evidenced from illustrations of FPV mooring systems reported in recent academic literature [27,40,91] which have been elucidated in Figs. 12 and 13. It can be seen that two broad strategies of mooring FPV modules emerge which are geared towards supporting massively interconnected arrays of floating devices and exhibit conceptual similarities to offshore aquaculture. In the first case (cf. Fig. 12),

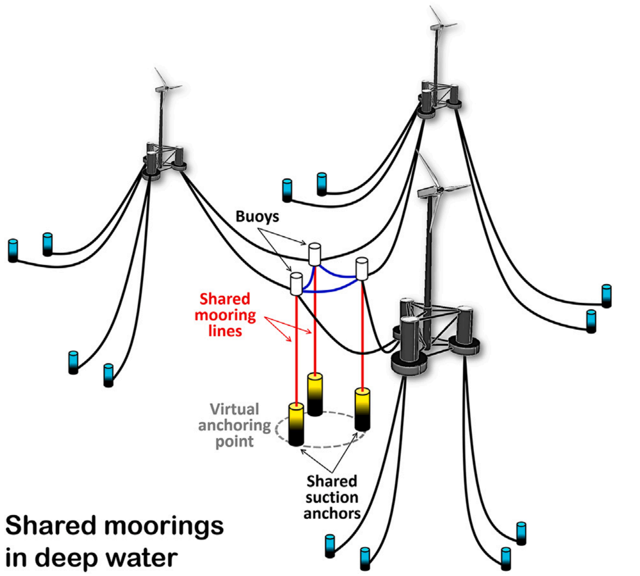

Fig. 11. Schematic illustrating sharing of mooring lines and anchors amongst three semi-submersible FOWT platforms employing a 3 × 2 cluster-spread catenary configuration with suction anchors (developed based on [16]); the installation is in deep water.

large floating platforms are developed by interconnecting individual pontoons using shared connectors. This strategy bears resemblance to the rigid multi-module platforms employed in offshore aquaculture (cf. Fig. 3) which also employ shared connectors [62]. In the second case (cf. Fig. 13), mooring components are directly shared. These include shared anchors as well as "aquaculture-inspired" grid-mooring of FPV panels with shared frame-lines. In fact, the grid-mooring concept has been recently proposed for the Banja FPV plant in Albania [91,92]. In context of the aforementioned proposed concepts, the hydrodynamics of an array of pontoons with shared rope connectors has been investigated in detail by Jiang et al. [40] (cf. Fig. 12(bottom)). They conclude that, although a 6-module array would be ideally characterized by 36 DOFs, the rope connections provide considerable rigidity such that the response amplitude operators (RAOs) of individual modules are comparable which in turn allows the system to be characterized by a single, mean RAO. However, barring the work of Jiang et al. [40], the authors couldn't find any dedicated investigations addressing the hydrodynamics of FPV arrays employing shared moorings.

The need for and scope of adoption of shared mooring systems in FPVs is substantiated by the preceding discussion. However, prior to commercial-scale deployment (particularly in nearshore/offshore locations), one must acknowledge the industry's concern that "mooring for floating solar is considered more immature than floating wind" [55] which primarily stems from a smaller overlap between the FPV and O&G sectors in terms of design standards, equipment and (even) manufacturing/installation companies [55]. Thus, commercial-scale integration

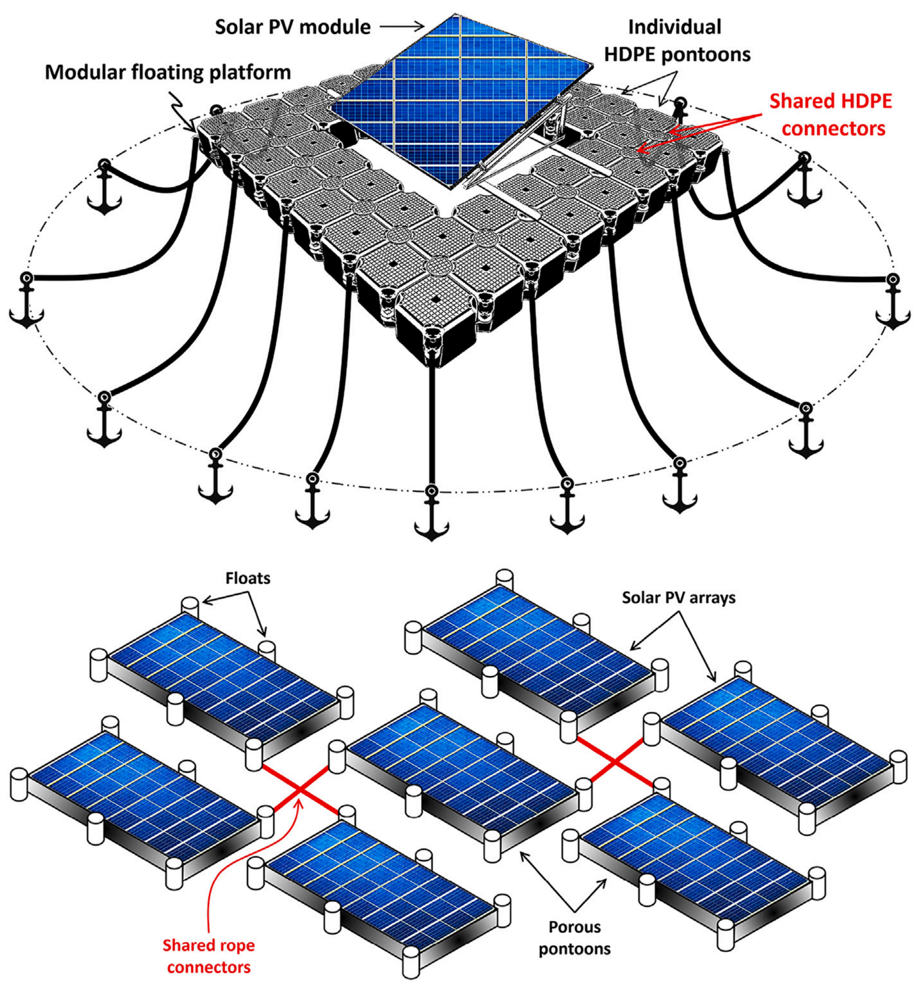

Fig. 12. Shared floats in inshore/offshore FPV: (top) modular platform employing shared HDPE connectors (developed based on [27]), (bottom) array of pontoons employing shared rope connectors (developed based on [40]).

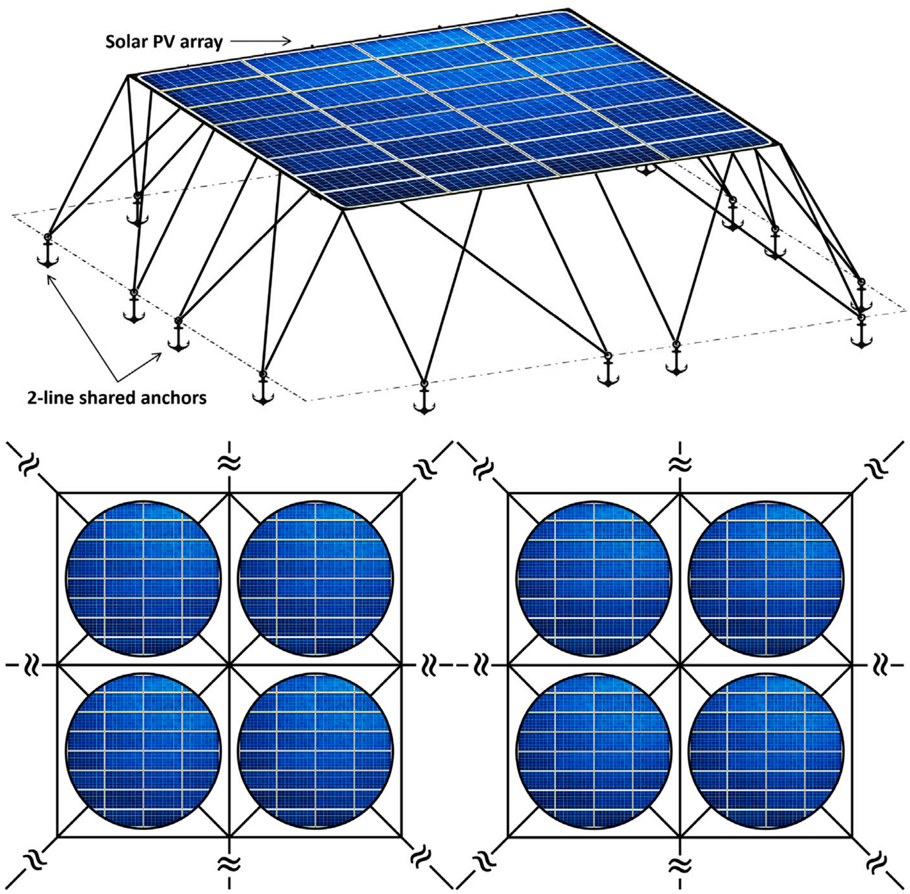

Fig. 13. Shared moorings in inshore/offshore FPV: (top) shared anchors (developed based on [40]), (bottom) grid-moored panels with shared frame-lines (developed based on [91]).

of shared moorings in offshore FPV should be preceded by addressing industrial concerns surrounding [55]: (a) lack of analysis tools, (b) challenging site conditions manifested by wave-current interaction, scour and ice-accretion (which alters platform draught), (c) CAPEX reduction through the usage of "not proven materials" (cf. the discussion on axial load reducing mechanisms later in Section 5.3) for thousands of mooring lines and qualification of equipment for long-term mooring (LTM), (d) standardization of installation and O&M procedures for a large number of mooring lines and (e) standardization of construction and installation procedures for the module to withstand large variations in water level (brought to light owing to the recent FPV failure at the Omkareshwar dam in India stemming from a climate-change-induced extreme-weather event [41]).

4.3. Wave (FWEC)

In their recent review on the cost of wind energy, the US National Renewable Energy Laboratory (NREL) estimated a Levelized Cost Of Electricity (LCOE) of \$78/MWh and \$133/MWh for bottom-fixed or floating offshore wind energy, respectively [93]. During the same period, an expert elicitation process was also conducted by NREL which yielded a mean LCOE of \$570/MWh for wave energy [94]. Thus, in order to become cost competitive with the more established technologies in FORE, there is a need to deploy FWECs in the form of large-scale arrays; this has been acknowledged by several studies [95–98]. In large-scale FWEC arrays, the LCOE would decrease not only because of the CAPEX savings derived from shared infrastructure (cables and moorings) but also, interestingly, due to improved power capture that results from intra-array device interactions [97,98]. Owing to the added improvement in performance (in addition to CAPEX), it could be argued that compared to FOWT and FPV, there is a stronger motivation to introduce shared moorings in FWEC arrays. In this context, Howey et al. [98] undertook an extensive experimental campaign to analyze the power capture characteristics of arrays of the Instituto Superior Técnico (IST) Spar-buoy OWC device [99] in which both standalone and shared-moored configurations were considered; the same have been illustrated in Fig. 14.

It is readily evident from Fig. 14 that the shared-mooring configurations bear resemblance to grid mooring, in particular, arrangements (c) and (d). Two different types of shared mooring lines (a.k.a. "inter-body" lines) are implemented: lines to the central OWC and lines to a neighboring OWC. Depending on the type of configuration, the number of mooring lines attached to a device may decrease (case b) or increase (cases c and d) relative to the standalone arrangement (case a). In fact, case d introduces some level of redundancy at the anchoring points (cluster-spread mooring) and thus leads to an increase in the overall number of mooring lines by +1 relative to case a. Having said that, there is a reduction in the number of anchors connecting to an FWEC as well as the overall number of anchors across all shared-moored configurations; what's interesting is that this reduction is achieved without any explicit sharing of anchors (unlike, for instance, the layout illustrated in Fig. 6).

In their experiments, Howey et al. [98] observed that all three shared-moored arrangements exhibited superior power capture characteristics when compared to the standalone case. This was attributed to a (beneficial) 180° phase difference between the heave of the OWCs and

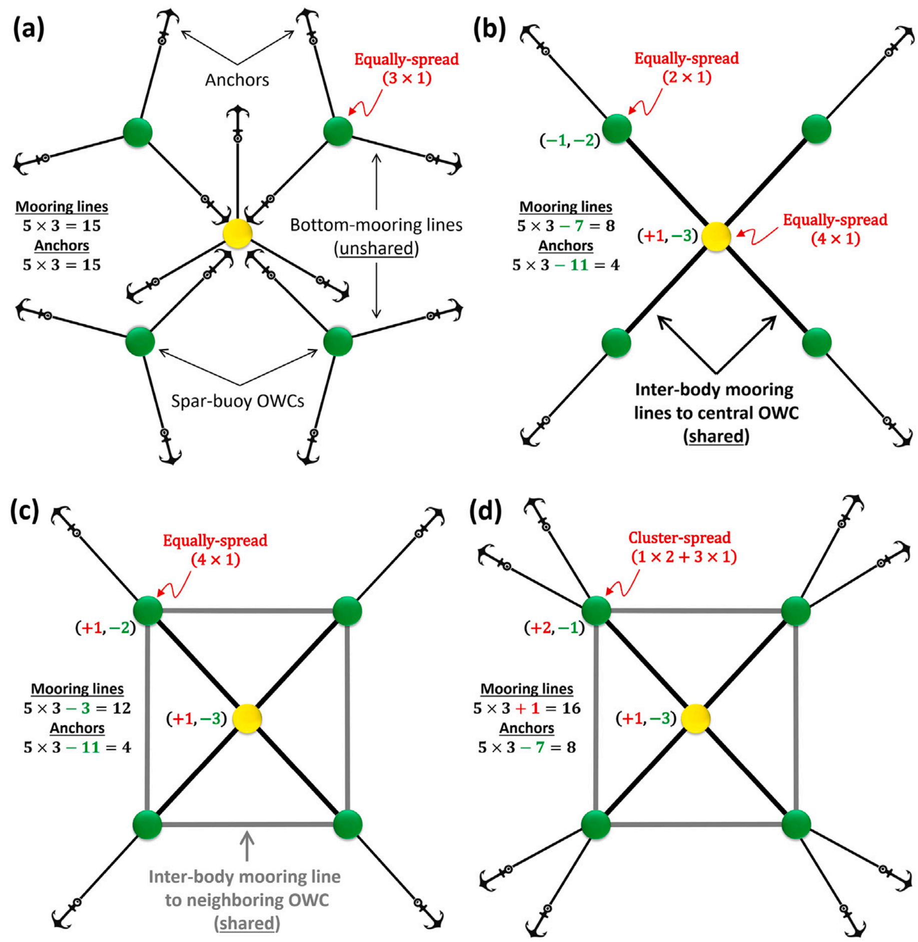

Fig. 14. Various arrangements to moor an array of five spar-buoy FWECs: (a) standalone devices and (b–d) shared-moored configurations with different levels of device interconnection and redundancy. The interconnection of devices is quantified by $(\mathcal{A}, \mathcal{B})$ where $\mathcal{A}$ and $\mathcal{B}$ respectively represent the change in the number of mooring lines and anchors directly connected to a device relative to the standalone case (developed based on [97,98]).

the motion of the water column when the devices were interconnected [98]. These findings might indicate that the sharing of mooring lines *would only reduce* the LCOE associated with FWEC arrays. However, an earlier investigation by the same group [97] discovered that, in energetic sea-states, (both categories of) inter-body lines (cf. Fig. 14) "frequently experienced" snap loads which did not occur when the devices were moored in a standalone arrangement [98]. Given the dramatic reduction in the number of mooring components (cf. Fig. 14), an increase in loads should, in fact, be expected in a system employing shared moorings.

The experiments on FWEC shared moorings by Gomes et al. [97] and Howey et al. [98] in conjunction with the comprehensive review on FWEC moorings by Xu et al. [5] highlight several design conflicts and technical bottlenecks:

- shared moorings reduce the overall DOFs of the FWEC system; however, restricting the motion response leads to a reduction in the power capture.
- FWECs are generally deployed in shallow water ($d < 100$ m) where the ideal site is typically characterized by strong tidal flows. A proposed shared mooring system must be designed to withstand peak loads induced by tidal currents, as well as loads induced by tidal variations.
- FWECs are susceptible to Stokes drift-induced misalignment which reduces power capture; the mooring system is expected to prevent misalignment by withstanding these second-order wave-loads.
- FWEC arrays must be densely deployed to maximize power capture; however, such deployment subjects shared anchors to multidirectional cyclic loading.
- large FWEC devices employ CALM (cf. Fig. 1) to facilitate weathervaning. A shared mooring system may hamper the ability of an FWEC to weathervane which needs to be restored through the use of compliant materials such as nylon ropes (cf. Section 5.3).
- the International Electrotechnical Commission (IEC) mandates that the Power Take-Off (PTO) attributes be considered during FWEC mooring design.

5. Thrust areas identified by the industry in shared moorings

As stated previously, the industry acknowledges the need to introduce shared mooring systems into FORE, as evidenced by several published technical reports on the subject [16,55,58,78,80,100]. However, shared mooring systems are characterized by a multitude of failure modes which stem both from the inherent variability in mooring components in general and the complexity introduced by sharing of mooring lines and/or anchors in particular. The various causes and modes of failure are summarized in Fig. 15. Stakeholders are prudent towards the adoption of this technology, which has prompted the industry to identify several key thrust areas in context to shared moorings; the same are depicted in the form of a mind-map in Fig. 16. DNV stated that "cost-effective mooring solutions" are not difficult to design for intermediate water depths ($100\,\text{m} \leq d \leq 500\,\text{m}$) but are faced with several design challenges in shallow ($50\,\text{m} \leq d \leq 100\,\text{m}$) and ultra-deep ($d \geq 1000\,\text{m}$) water

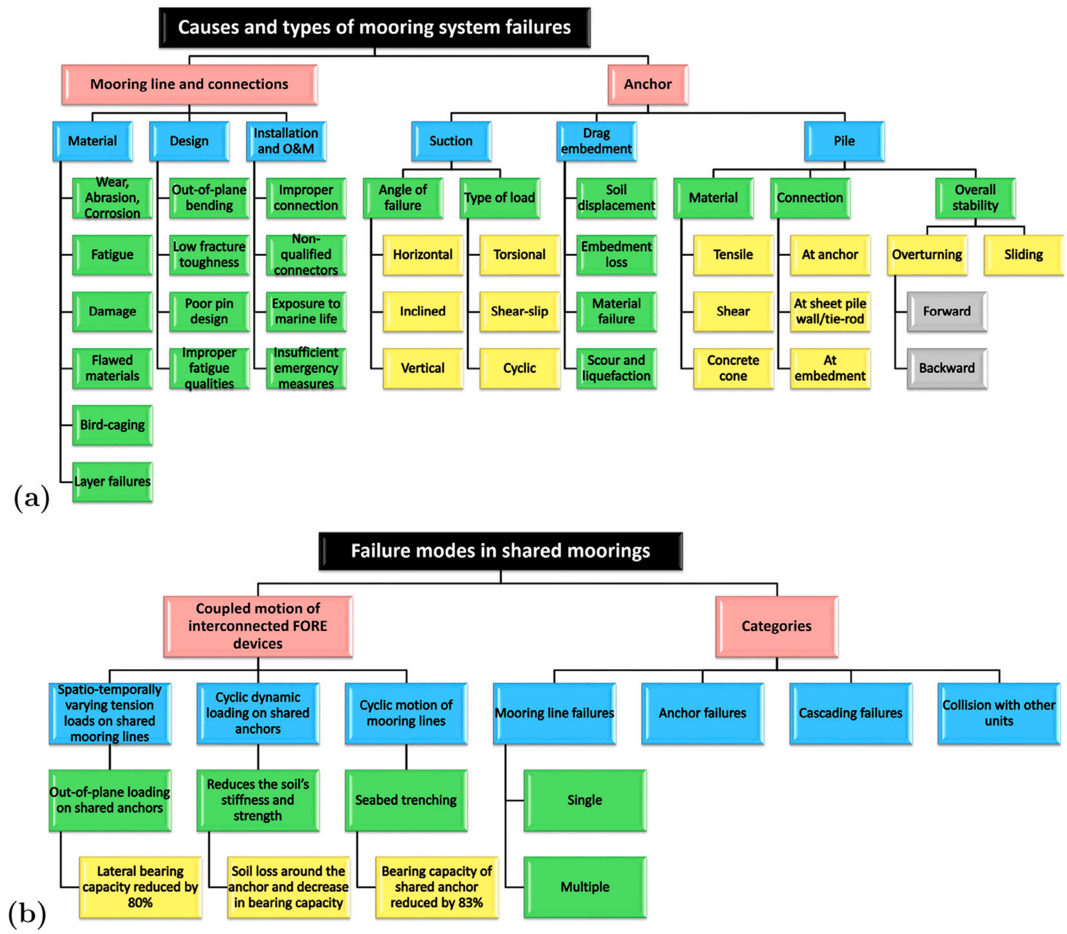

Fig. 15. Causes of failure and failure modes of: (a) mooring systems by virtue of the variability in mooring components and (b) shared moorings by virtue of their complexity. Developed based on [101–103].

[55]. The aforementioned design challenges manifest differently in the two categories of water-depths [55] and are individually presented in the following sub-sections.

5.1. Challenges in shallow water shared moorings

In shallow water, the mooring lines are comparatively shorter. In context of FOWTs, reductions in line lengths stemming from sharing of mooring lines (Fig. 7) are largely inconsequential to the CAPEX and are thus not recommended for shallow water. Having said that, considerable cost reduction can be achieved through shared anchors [16,78]. Chain catenary moorings in shallow water are susceptible to snap loads.

Snap loads occur when there is a momentary slack in the mooring line (say) due to a strong downward heave of the platform and the line re-engages immediately afterward causing a spike in tension [57]. A snap-event is also interpreted as a shock load since it is accompanied by an elastic wave traveling through the material of the mooring line [104]. Snap loads pose a significant threat to shallow-water mooring systems due to their increased susceptibility to violent wave-current-structure interactions during extreme events and the propensity of individual loads to superimpose non-linearly with the structural response under wave-breaking conditions [105].

Another key challenge evidenced from Fig. 16 is the presence of multi-directional loading during storm events. Extreme sea-states lead to the inception of complex wave-induced kinematics which pose difficulties in sustaining the line-topology (mooring-layout) [55] as well as call for a redesign of the anchoring system [16]. The latter becomes necessary since shared anchoring would mandate that [78]: (a) suction anchors be deployed at a site where the seabed conditions may be more suitable for drag anchors and (b) the device layout be recalculated since the length of the mooring line would invariably change at a shared anchor. Finally, in scenarios where a single mooring line per device attaches to a shared anchor (cf. Fig. 6), there exist concerns surrounding redundancy [16] because the load redistribution stemming from a failure event would impact multiple devices.

Unlike FOWTs, shared mooring lines could indeed be deployed for FWEC and (in particular) FPV installations in shallow water through grid-mooring (cf. Fig. 13 (bottom) and Fig. 14(c,d)). Grid-mooring would bring forth its own set of challenges in terms of the massive interconnectedness introduced into the system as well as the susceptibility of inter-body mooring lines to snap loads [97]. It is also worth noting that the aforementioned challenges with grid mooring (or shared mooring lines in shallow water in general) are currently not being prioritized by the FORE industry probably due to the fact that the FWEC and FPV offshore sectors are less evolved in comparison to FOWTs.

5.2. Challenges in deep water shared moorings

In deep water, the length of mooring lines would exceed the inter-device spacing, especially in the case of FOWTs [78]. The key motivation behind deep-water shared moorings is to achieve CAPEX savings by sharing a portion of the mooring line between adjacent devices. In addition to reductions in mooring line lengths, shared moorings can also result in:

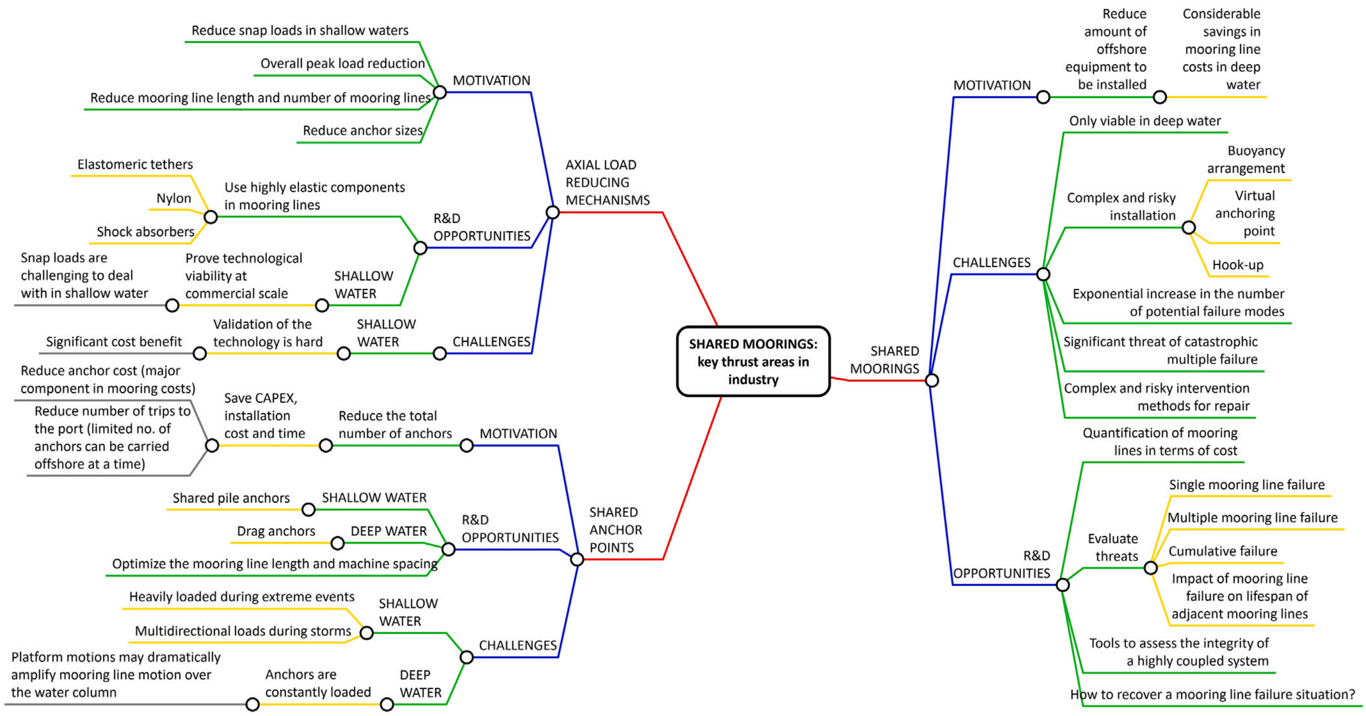

Fig. 16. A mind-map illustrating the key thrust areas in industry in context to shared mooring systems (developed based on [16,55,58,78,80,100]).

- reduction in the total number of anchors *without* anchor sharing – expected for inter-device moorings (cf. Fig. 7(a)) or,
- anchor sharing without reduction in the total number of anchors – expected for non-redundant configurations (cf. Fig. 7(b)) or,
- anchor sharing accompanied by an overall reduction in the number of anchors – expected for redundant configurations (cf. Fig. 11).

As evidenced from Fig. 16, in contrast to shallow-water installations, there appear to be a considerably greater number of challenges faced by deep-water shared moorings. Interestingly, these challenges manifest as a result of the constitution of the mooring system itself [16] which is in stark contrast to the shallow-water challenges that are largely environmental in nature [55]. The challenges in the former case are intrinsic to the system itself. Thus, prior to running integrity assessments for violent sea-states, there is a need to understand the behavior of the coupled system in benign albeit ultra-deep water first. Here, a primary cause for complexity is the extremely long mooring lines [55].

In case of FOWTs, the deep-water mooring system is susceptible to motions of the platform being amplified over the water column thus leading to large displacements in the mooring line [56]. This, combined with the fact that shared (suction) anchors would be constantly loaded (cf. Fig. 11) would result in “peak anchor loads” [106]. In addition, sharing a portion of the mooring lines in deep water results in a massively interconnected, strongly coupled hydrodynamic system with a multitude of failure modes [79]; such systems prove to be very risky and challenging to repair [16]. There exist considerable challenges pertaining to installation as well as O&M of deep-water shared mooring systems [16,78,79]:

- installation of and hook-up to the virtual anchoring point (cf. Fig. 11),
- exponential increase in the number of failure modes,
- shared systems are less redundant in comparison to standalone configurations which heightens the risk of cascade failures,
- large number of failure combinations necessitating the development of a multitude of emergency recovery procedures,
- difficult to separate a floater from a shared system for maintenance.

In addition to the above, the reader is referred to Gözcü et al. [79] for an in-depth discussion on the various installation challenges associated with shared mooring lines.

5.3. Axial load reduction mechanisms

Conventional chain-based mooring configurations such as catenary, taut or semi-taut configurations, respectively, are designed to withstand tensile but not compressive loads [107]. In violent sea-states, the FORE platform may undergo coupled heave and pitching motions which can cause the connection point to move “backwards and down fast” towards the anchor point [16]. Whilst these motions are accommodated in deep water due to the long mooring lines, the same is not true in shallow water where coupled platform motions would compress the middle section of the mooring chain and the subsequent re-engagement would cause a snap load. The alternating slack-taut cycles could substantially increase the dynamic tension and may lead to line failure [107]. Rather than redesigning the mooring layout to accommodate snap loads, the industry has instead opted to develop axial load reducing mechanisms to mitigate this issue in shallow water; this is depicted in Figs. 16 and 17.

The aim is to replace a portion of the mooring chain with [16,55]: (a) elastomeric products (such as the “Exeter Tether”), (b) nylon/polyester ropes and (c) shock absorbers or load-reduction devices “LRDs” (such as the TFI polymer mooring spring; also known as “SeaSpring”). Through this development, the industry intends to not only reduce snap loads but also to reduce overall loads, peak anchor loads, mooring line lengths as well as anchor size [16]. Thus, the development of load reduction mechanisms is aimed at achieving similar objectives as shared moorings but at a lower cost. It is worth reiterating that the cost impact of such technologies would only be substantial in shallow waters where snap loads are considerably more pervasive than in deep waters [16].

In addition to axial load reducing mechanisms, several other tools aimed at improving performance as well as facilitating O&M procedures in challenging environments are also currently under development (cf. Fig. 17). These include [16,55]:

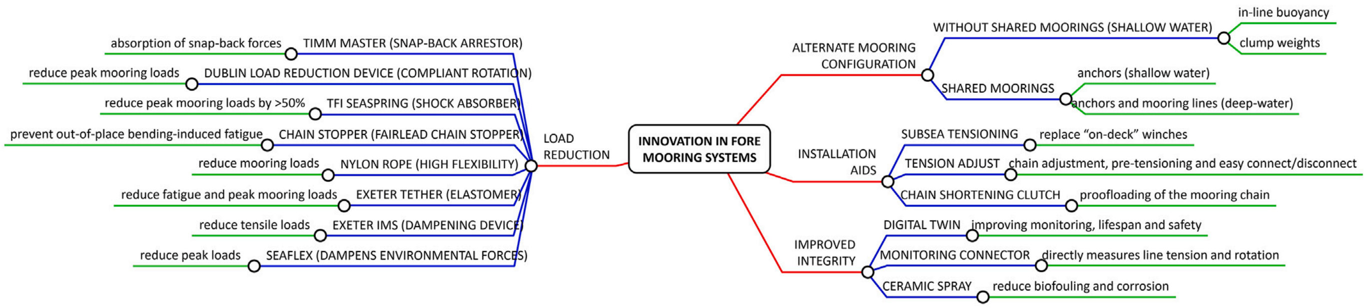

Fig. 17. A mind-map illustrating industrial innovations in FORE mooring systems (developed based on [55]).

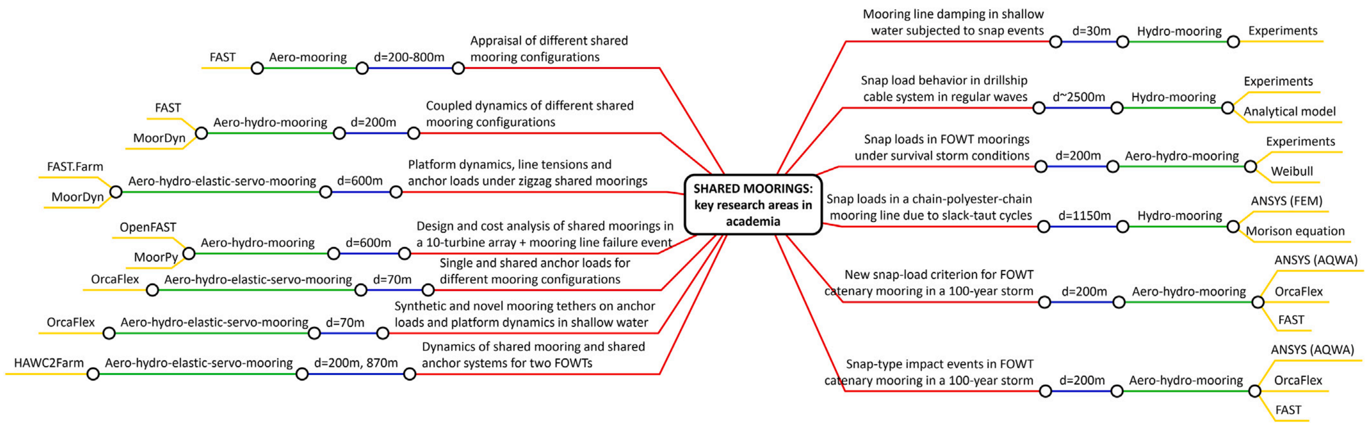

Fig. 18. Key areas of academic research in context to shared mooring systems as well as snap loads.

- clump weights, synthetic ropes and buoyancy – mooring load reduction,
- hook-up and tensioning tools – connecting the FORE platform to a pre-laid mooring line followed by pre-tensioning,
- quick disconnect tools for recovery of the platform – for tow to port O&M activities especially in deep water.

As noted in the Phase III summary report of the Floating Wind Joint Industry Project [16], the aforementioned tools as well as axial load reducing mechanisms are in various stages of development. With standardization still pending for these designs, the innovations are yet to be implemented on a commercial scale and present a tremendous scope for research and development.

6. The academic research effort

The key thrust areas identified by the industry in context of the development of shared mooring systems as well as mitigation of snap loads have been described in Section 5. The corresponding academic research effort is presented in this section by means of a mind-map reported in Fig. 18 wherein studies dealing with shared moorings are listed on the left whilst those dealing with snap loads are listed on the right.

6.1. Shared moorings

Different shared mooring configurations (predominantly for FOWTs) have been appraised in terms of the strong coupling between platform responses, mooring line tensions and anchor loads in [84–86,108,109]. These investigations revealed that sharing mooring lines is effective in maintaining platform spacing as well as in reducing the number of anchors required [84]. The studies also revealed that increasing the mooring footprint leads to a reduction in platform excursions as well as peak anchor loads [86]. Other recent studies have explored the transient responses following mooring line failure [110] as well as the use of synthetic components (such as the Exeter Tether or polyester ropes) to achieve as much as ~80 % reduction in peak anchor loads [106]. It is worth noting that the aforementioned investigations analysed peak anchor loads in "relatively shallow" depths ($70\,\text{m} \leq d \leq 600\,\text{m}$) compared to the (more challenging) $800\,\text{m} \leq d \leq 1000\,\text{m}$ range propounded by the industry [16,55].

Snap loads in mooring systems have also received considerable attention in the literature. As evidenced from Fig. 18, some of the studies consider a single mooring line in isolation [104,107,111] rather than it being connected to a platform/FORE device. In this context, recent studies have also focused on the development of finite volume method (FVM)-based numerical tools that are capable of modeling the dynamics of a single mooring line and more accurately accounting for the propagation of tensile shocks during snap events [112]. Studies in which the mooring line is connected to a platform or FORE device are largely statistical and/or experimental in nature. For instance, Xu et al. [113] carried out a combined experimental and probabilistic analysis into the extreme mooring tensions occurring in a taut-moored semi-submersible platform (3×4 cluster-spread in deep-water) as well as in a slack-moored point absorber FWEC (3×1 equally-spread in shallow-water). When simulated for a 100-year JONSWAP spectrum corresponding to the South China Sea, it was observed that the line tensions are temporally stable for the semi-submersible but exhibit dramatic variations over time for the FWEC indicating the prevalence of snap loads. Studies dealing with snap loading in FOWT moorings have mostly been restricted to intermediate depths ($d \sim 200\,\text{m}$; cf. Fig. 18). In these studies, a probabilistic approach was adopted to evaluate the peak line tensions in survival storm conditions (100-year storm) and to identify snap-type events [114–116]. In context of FWECs, various shared mooring configurations were investigated in terms of mooring loads [97] as well as device performance [98] through physical experiments at model scale. Said studies have already been discussed in detail in Section 4.3 with the mooring configurations illustrated in Fig. 14. The key takeaway from [97,98] is that grid-moored arrays of FWECs improve the power capture characteristics but at the same time induce snap loads in inter-device moorings which is a direct consequence of lessened redundancy in the shared configuration compared to the standalone case.

6.2. Development of synthetic ropes for load reduction

Over the past two decades, the O&G industry has moved into waters that are ≳3 km deep which has led to conventional mooring chains being replaced with synthetic ropes. This move has been motivated not only by the synthetic ropes' ability to absorb tensile loads but also due to their lower cost and lower weight per unit length [117]. In FORE, the same move is motivated by the need to reduce snap loads in shallow water ($d < 100$ m); this is reflected in the academic research efforts on development of synthetic rope-based mooring systems.

Recent academic investigations have been primarily focused on the performance of synthetic ropes made of nylon (also known as polyamide), polyester, HMPE (High Modulus Polyethylene; also known as UHMWPE (Ultra-High-Molecular-Weight Polyethylene)), aramid and CFRP (Carbon Fiber Reinforced Polymer). Some of the key performance indicators include [118]: (1) breaking load, (2) elastic modulus, (3) damping[1], (4) constraining capacity, (5) tension characteristics, (6) corrosion resistance, (7) creep properties[2], (8) durability, (9) weight, (10) range of application and (11) market price. In experiments, the performance of mooring materials is evaluated through fatigue testing in which a rope specimen is subjected to cyclic loading. The long-term fatigue life is quantified by means of $S-N$ curves [119] which establish the relationship between the stress amplitude (S) applied to a material and the number of cycles (N) it can withstand before failure.

Weller et al. [117] tested Nylon-6 ropes using the University of Exeter's South West Mooring Test Facility (SWMTF) in Falmouth Bay, UK. New as well as aged rope specimens were subjected to tension-tension fatigue cycling for 18 months. Owing to their excessive compliance, a need for re-tensioning the nylon ropes to reinstate their station-keeping properties was identified. It was also observed that the increase in compliance and reduction in strength were accelerated due to ingress of debris and growth of mussels. Lian et al. [120] investigated the long-term fatigue behavior of UHMWPE ropes (in the O&G industry, UHMWPE (or HMPE) is preferred over polyester due to the former's lower weight and higher stiffness). In the experiments, 12-strand UHMWPE ropes having a diameter of 0.006 m were subjected to cyclic loads of various amplitudes and periods. This in turn yielded a wide range of failure cycles (∼5000 to ∼0.36 million) and failure times (∼ 8 hours to ∼ 8 days). It was observed that the period of cyclic loading had a negligible impact on the failure time. Thus, an empirical expression for the fatigue life was proposed which takes into account both the mean load and the loading amplitude. Xu et al. [121] conceptualized seven mooring designs for the 5 MW OC4 semi-submersible FOWT in shallow-water ($d = 50$ m). The designs differed in terms of the line material (chain and synthetic fiber rope), mooring components (clump weight and buoy) and anchors (drag embedment (DEA) and suction anchor). The designs were simulated under turbulent wind and irregular wave loads using SINTEF's SIMA workbench [122]. A subsequent cost analysis revealed that the cost of the mooring chain was offset by the DEA whilst savings gained from the synthetic fiber rope were nullified by the cost of the suction anchor. It was concluded that a chain-clump-buoy-DEA hybrid mooring and a fiber-suction anchor mooring were (equally) cost-competitive concepts in shallow water. Very recently, Li et al. [118] carried out small-scale (1 : 100) experiments in a wave-current flume to understand the dynamic behavior of a submerged floating tunnel (SFT) when moored with cables of different materials. In their experiments, Li et al. [118] considered a range of testing environments which included: (a) only regular waves, (b) only irregular waves, (c) only current and (d) combined regular waves and current. Some of the key findings from this comparative assessment of five mooring materials (steel, chain, nylon, aramid and CFRP) include [118]:

- the breaking load was highest for steel (6 kN) and lowest for nylon/CFRP (2.5 kN).
- the damping was highest for chain and about an order of magnitude lower for the three synthetic materials.
- CFRP exhibited the highest corrosion resistance whilst the same was lowest for steel/chain.
- a very high propensity for creep was observed, but only for nylon.
- steel and chain were deemed applicable in shallow water whilst the three synthetic materials were recommended for deep water.
- nylon exhibited the worst constraining capacity. Steel, chain and CFRP were observed to have a good constraining capacity. However, the chain was deemed to perform the worst under resonance; this is interesting given the fact that the chain also provided the highest damping.

Whilst the relationship between an SFT and FORE may not be immediately apparent, a submerged floating tunnel is geometrically similar to the submerged cylindrical WEC concept proposed by Crowley et al. [123]. Hence, the above findings are strongly applicable to FWECs and possibly to other FORE devices.

6.3. Research gaps

The appraisal of the state-of-the-art indicates that the current academic research is advancing in concert with the thrust areas identified by the industry. However, there remain gaps in the research effort, particularly in terms of the fidelity of numerical tools currently being implemented to analyze shared mooring configurations.

It is evidenced from Fig. 18 that most of the studies on FOWTs use either FAST (by NREL) or OrcaFlex (by Orcina Ltd.) which in turn use either the empirical Morison equation (ANSYS®Aqwa), frequency-domain methods (WAMIT) or linear potential theory (OpenFAST) to compute the hydrodynamics. Potential theory cannot account for the vorticity layers formed adjacent to the moving platform, the large-scale coherent vortices shed in water due to platform motions, their impact on the mooring system and the overall turbulence damping introduced into the system as a result. It is widely accepted in the O&G industry that mooring line damping may account for ≳80 % of the total damping in the system [56]. Major contributors to the mooring line damping are the hydrodynamic drag and vortex induced vibrations [56] which cannot be resolved using potential theory. Potential theory-based solvers also cannot account for the impulsive and highly oscillatory loads that result from breaking-wave-induced aerated impacts [105].

As recognized by DNV [18], high-fidelity hydrodynamic simulations using CFD are the next frontier in floating renewables research since they are more detailed than existing design tools yet cheaper than large-scale experimentation. This would lead to more reliable design tools and guidelines thus reducing the extent of over-design as well as the risk of failures. In this context, only very recently have attempts been made to simulate the hydrodynamics of moored spar-type [13] and semisubmersible [77] FOWT platforms using hybrid potential theory-CFD models albeit for a single device, not for arrays.

In light of the preceding discussion, the following research gaps have been identified in context to shared moorings in FORE:

- **Shallow water:** many potential sites for future FORE installations have wide continental shelves thus demanding nearshore deployment of devices in shallow waters ($d \leq 100$ m). There is a need to investigate snap events in shared moorings, both numerically and through physical modelling, in such challenging environments [55].

[1] damping is important for the mooring material as it helps dissipate energy and reduce the amplitude of oscillations which in turn reduces the likelihood of resonance and fatigue failure.

[2] creep is a gradual, time-dependent elongation of the mooring material under constant load which leads to a reduction in strength.

The complexity is manifested in terms of multi-directional kinematics, slamming, aeration and turbulence stemming from wave-breaking in storm conditions. The scope of investigation is augmented by the fact that different FORE devices would necessitate different types of shared mooring systems. Whilst FOWTs would exclusively implement shared anchors in shallow water, both shared anchoring as well as mooring lines (grid-mooring) would be feasible for FPVs and FWECs.

- **Ultra-deep water:** on the other end of the spectrum are sites that are virtually devoid of a continental shelf where ultra-deep water ($d \gtrsim 1000\,\mathrm{m}$) is encountered just a few kilometers offshore. No commercial-scale FORE installation employing shared moorings exists in ultra-deep water [16] and there is a need to investigate the dynamics of such systems through dedicated experimental and numerical paradigms. Here, the challenge is manifested in terms of the sheer complexity of the resulting mooring layout, amplification of platform motions over very long mooring lines (leading to peak anchor loads) as well as the unknown impact of turbulence and VIV-induced line damping on the overall dynamics of the system.
- **Hybrid numerical modeling for large-scale farms:** the current state-of-the-art in simulating (for instance) FOWT farms employing shared moorings is based on mid-fidelity tools such as FAST.Farm which implement linear hydrodynamics through the Morison's equation and neglect hydrodynamic coupling between adjacent platforms [108]. Whilst CFD is deemed too expensive to be directly implemented at the scale of a farm, hybrid models employing: (a) fully nonlinear-potential theory (FNPT) [124], (b) Reynolds-Averaged Navier-Stokes (RANS) [125] and (c) Large-Eddy Simulation (LES) [126] could indeed be implemented through a zonal domain-decomposition strategy. The wave hydrodynamics in the far-field of the array would be handled by FNPT, the subgrid-scale flow features in the vicinity of the floating platform would be resolved by RANS whilst the inertial-scale flow structures formed within the spacing between adjacent platforms would be resolved by LES. Such a modeling strategy would result in a high-fidelity multi-scale solver for wave-current-structure interaction with viscous and aeration effects being fully accounted for in violent sea-states.
- **High-fidelity analysis tools for mooring lines:** the capabilities of conventional mooring line dynamics solvers such as MoorDyn aren't well-established in terms of capturing snap loads turbulence-induced line damping or analyzing floating systems that are comprised of a very large number of mooring lines (say FPV farms). In this context, there is a need to develop finite-element-based full structural solvers to account for the multi-DOF coupled dynamics of several mooring lines [55] as well as to facilitate the modelling of elastic materials and other load-reducing devices (LRDs).
- **Analysis tools for very large floating structures:** in case of offshore FPV, the floating platforms are extremely large and highly modular with tens of thousands of PV modules being supported by millions of individual pontoons [127]. As pointed out by DNV [55], conventional rigid-body dynamics solvers would fail to accurately predict the loads and responses of such large-scale floating platforms (whose area may approach $\sim 0.1\,\mathrm{km}^2$) owing to the inherent flexibility of the overall structure. Only recently, monolithic finite element methods are being developed to model the complex hydroelastic and viscoelastic behavior of such very large floating structures [128,129]. Such futuristic methods could be employed to more realistically model the dynamics of shared moorings attached to thin membrane-like floating structures; this is yet to be attempted in the literature.
- **Shared moorings for FTCECs:** the concept of shared moorings has never been explored for tidal energy devices (FTCECs). Unlike FOWTs, the working fluid for FTCECs is water and hence the thrust loads involved are much greater. A shared anchor couldn't possibly withstand the extreme thrust loads transmitted by multiple large-scale FTCECs. Nonetheless, the feasibility of shared moorings is worth exploring for smaller-scale FTCECs particularly if the shared layout could lead to an improvement in the overall energy capture performance.
- **Standardization of design practices for shared mooring systems:** owing to the nascency of the technology, there is a lack of and (as a consequence) need for standardization to facilitate consolidation of shared moorings into the FORE industry. Said need encompasses key areas of [16,18,55,78,80]:

  1. design and analysis of system components such as new anchor types, mid-water buoys, mooring layouts and load reducing mechanisms;
  2. installation and O&M procedures in ultra-deep water as well as for offshore FPV projects;
  3. mandating a certain level of redundancy – this is especially critical for shared mooring systems for FOWTs in deep-water;
  4. predicting the consequences of a mooring line failure in a shared system as well as recovery of a failure scenario;
  5. accounting for the variability in geographical location as well as soil types.

- **Synthetic mooring materials:** it is seen from Section 6.2 that considerable progress has been made towards understanding the characteristics and applicability of various synthetic mooring line materials. However, to the best of the authors' knowledge, there have not been any (experimental or numerical) studies where the long-term performance of synthetic ropes has been investigated for FORE shared mooring configurations in particular. There have also not been any studies in which the performance of different mooring materials (say chain/steel vs. nylon/UMHWPE/CFRP) is analyzed for shared mooring configurations.
- **Co-located arrays:** very recently, there have been several studies exploring the feasibility of co-locating various floating technologies such as: (a) FOWTs and FPV [130–132], (b) FWECs and FPV [133], (c) FOWTs and FWECs [134], (d) FWECs and offshore aquaculture [135] and (e) FOWTs and offshore aquaculture [136]. Arrays of FWECs are usually co-located upstream of FOWTs/FPVs/offshore-aquaculture to exploit their wave-sheltering properties [133–135]. In addition, FPV/offshore-aquaculture can also be co-located with FOWTs to maximize the utilization of marine space but also in scenarios where the water is too deep for fixed OWT foundations to be economically feasible [130]. Linearized FEM-BEM simulations of the hydroelastic response of a large FPV platform sheltered by a floating breakwater integrated with FWECs [133] have indicated that the FPV platform only undergoes large deformations at the edges. A similar behavior was observed in a previous study [131] which concluded that, even in energetic sea-states, the overall tilt (and thus the energy capture performance) of the PV panels is not significantly altered far from the edges of the FPV platform. Whilst these studies establish the co-location feasibility from an energy perspective, the hydrodynamics remains largely unexplored which is understandable given the technical complexity involved. One of the greatest challenges with co-located systems is the collision risk, which is especially high with offshore aquaculture [136]. Hence, there is a need to explicitly consider the mooring lines (not done in any of the aforementioned studies) to better establish the hydrodynamic feasibility of co-located farms. Subsequent studies could then explore the feasibility of introducing shared moorings for co-located technologies. Studies could also be focused towards understanding mooring design challenges stemming from conflicting stability requirements between rigid (FOWT) and compliant (FPV) floating platforms.

7. Conclusion

In the present paper, the concept of shared mooring systems in context of the floating offshore renewable energy (FORE) sector has been comprehensively reviewed in terms of: (a) tracing the roots of the technology to conventional offshore industries, (b) exploring the ways in which mooring systems could be shared within an array of canonical FORE devices, (c) the nature and scope for adoption into individual FORE sectors (namely floating wind, solar and wave), (d) key thrust areas of R&D identified by the industry, (e) the commensurate academic research effort and (f) existing knowledge gaps.

Through an appraisal of the historical wisdom gained from conventional offshore industries, it is seen that the O&G industry has contributed in terms of the development of floating infrastructure and mooring system components (anchors in particular) whilst the concept of shared moorings (more) directly stems from offshore aquaculture which is characterized by grid-moored arrays of fish cages involving a large number of mooring lines.

Shared mooring systems can be broadly classified based on whether only anchors, only mooring lines or both are shared within an array. Provided the design has sufficient vertical and directional loading capacity, shared anchors can be deployed in any water-depth and are relatively straightforward to deploy. In contrast, for a given FORE technology, shared mooring lines may only be suitable for a particular category of water-depths. In case of FOWTs for instance, the CAPEX savings stemming from shared mooring lines are only justifiable in ultra-deep water. It is also observed that, depending on the layout, shared mooring lines may or may not result in: (a) shared anchors or (b) a reduction in the total number of anchors. In case of FPVs and FWECs, mooring lines may be shared through grid-mooring which closely resembles aquaculture layouts rather than O&G moorings.

The key challenge facing shared moorings is the existence of snap loads and peak anchor loads in shallow and deep-water respectively. Whilst the current academic research effort progresses in concert with the thrust areas identified by the industry, the tools currently being implemented are of limited fidelity. The industry has recognized a need for developing higher fidelity analysis tools to simulate and more accurately predict the hydrodynamics of arrays in violent sea-states (in particular viscous and aeration effects), the propagation of tensile shocks through the mooring line material as well as hydro- and viscoelastic responses of very large moored floating structures. There is also a need for standardization to facilitate consolidation of shared moorings into the FORE industry.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

A multitude of floating renewable energy projects have been commissioned or are currently in the deployment/planning stages globally. An exhaustive listing is provided in Tables A1–A4 for floating offshore wind turbine (FOWT), floating solar PV (FPV), floating wave energy converter (FWEC) and floating tidal current energy converter (FTCEC) concepts, respectively.

Table A1
Commissioned and upcoming floating offshore wind (FOWT) projects as well as floater concepts [18,58].

Project	Capacity	Depth	Foundation	Partners	Country	Commission	Ref.
Hywind Scotland	5 × 6 MW	95–120 m	Spar	Equinor, Masdar	Scotland	2017	[82]
FloatGen	1 × 2 MW	33 m	Moonpool	BW Ideol, École Centrale de Nantes, Bouygues Travaux Publics, University of Stuttgart, RSK Group, Zabala, Fraunhofer-IWES	France	2018	[137]
Hibiki	1 × 3 MW	55 m	Moonpool	BW Ideol, Hitachi Zosen, Marubeni	Japan	2018	[138]
WindFloat Atlantic	3 × 8.4 MW	100 m	Semi-submersible	Principle Power	Portugal	2020	[139]
Kincardine	5 × 9.5 MW	60–80 m	Semi-submersible	Principle Power	Scotland	2021	[140]
TetraSpar Demonstrator	1 × 3.6 MW	200 m	TetraSpar	Shell, TEPCO RP, RWE, Stiesdal	Norway	2021	[141]
Hywind Tampen	11 × 8.6 MW	260–300 m	Spar	Equinor, Petoro, OMV, Vår Energi, Wintershall Dea, INPEX Idemitsu Norge AS	Norway	2022	[142]
EOLMED	3 × 10 MW	55 m	Moonpool	BW Ideol, Qair, TotalEnergies, MHI Vestas	France	2024	[143]
New England Aqua Ventus	1 × 11 MW	–	Semi-submersible	Diamond Offshore Wind, RWE	US-ME	>2025	[144]
MunmuBaram	84 × 15 MW	120–160 m	Semi-submersible	Shell Overseas Investments, CoensHexicon	South Korea	2027	[145]
Korea Floating Wind	75 × 16 MW	175–275 m	Semi-submersible	Ocean Winds, Mainstream Renewable Power, Kumyang Electric Co.	South Korea	2028	[146]
South Brittany (FOW tender: A05)	240–270 MW	60–100 m	–	BW Ideol, EDF Renewables, Maple Power	France	2030	[147]
Mediterranean (FOW tender: AO6)	500 MW	60–130 m	–	BW Ideol, EDF Renewables, Maple Power	France	–	[148]
North Channel Wind	1.42 GW	120 m	TLP	SBM Offshore, NMK Renewables	Ireland	2030	[149]
Olympic Wind	2 GW	–	–	Trident Winds	US-WA	2030	[150]
Morro Bay (OCS-P 0563)	2 GW	–	–	Equinor	US-CA	2030	[151]
ScotWind	960 MW	75–110 m	Moonpool	BW Ideol, BayWa r.e., elicio, Ardersier Port Authority	Scotland	2035	[152]
OO-Star Wind Floater	–	> 50 m	Concrete Semi-sub.	Dr.techn. Olav Olsen, FWS, Bouygues Travaux Publics	–	–	[153]

Table A2
Commissioned and upcoming floating solar PV (FPV) projects.

Project	Capacity	Area	Waterbody	Partners	Country	Commission	Ref.
Three Gorges	150 MW	791 acres	Inland lake	China Three Gorges Corp (CTG), Xihe Power, LONGi Solar	China	2018	[154,155]
Xinji Huainan	40 MW	198 acres	Inland reservoir	Sungrow	China	2018	[156]
CECEP	70 MW	345 acres	–	China Energy Conservation and Environmental Protection Group, Ciel & Terre, LONGi Solar	China	2019	[154,157]
Sirindhorn Dam	45 MW	178 acres	River dam	Electricity Generating Authority of Thailand, B.Grimm Power Plc, China Energy Group Shanxi Electric Power Engineering Co Ltd	Thailand	2019	[154,158]
Yuanjiang Yiyang	100 MW	–	Inland River	Datang Huayin Electric Power CO. LTD., State Grid Hunan Comprehensive Energy Service CO. LTD.	China	2019	[159]
Dezhou Dingzhuang	320 MW	–	Inland reservoir	Huaneng Power International	China	2020	[154,160]
Hapcheon Dam	40 MW	–	River dam	Korea Water Resources Corp., Hanwha Q CELLS Korea	South Korea	2021	[161]
King Eider	0.065 MW	–	Inland River	SolarDuck B.V	The Netherlands	2021	[162]
NTPC-Simhadri	25 MW	75 acres	Inland reservoir	Bharat Heavy Electricals Limited	India	2021	[163]
Sembcorp Tengeh	60 MW	111 acres	Inland reservoir	Sembcorp Industries Ltd.	Singapore	2021	[154,164]
Canoe Brook	8.9 MW	–	Inland reservoir	NJR Clean Energy Ventures	US-NJ	2022	[165]
Changbing	88 MW	213 acres	Nearshore	Ciel & Terre, Principia	Taiwan	2022	[166]
NTPC-Kayamkulam	102 MW	350 acres	Kerala backwaters	Tata Power Solar Systems Limited	India	2022	[167]
NTPC-Ramagundam	100 MW	–	Inland reservoir	Bharat Heavy Electricals Limited	India	2022	[168]
304 Industrial Park	60 MW	–	Inland reservoir	China Energy Engineering, National Power Supply Public Co.	Thailand	2023	[169]
Grafenwörth	25 MW	35 acres	Former sand pit	BayWa r.e., ECOwind, EVN	Austria	2023	[170]
SeaVolt	–	–	Offshore	Tractebel, DEME, Jan De Nul	Belgium	2023	[171]
Omkareshwar Dam	600 MW	3000 acres	River dam	Rewa Ultra Mega Solar Limited, AMP Energy, National Hydroelectric Power Corporation, Satluj Jal Vidyut Nigam	India	2024	[43,172]
Merganser	0.5 MW	–	Offshore	SolarDuck B.V, TU Delft, TNO, MARIN, Deltares	The Netherlands	2024	[173]
Hollandse Kust West	5 MW	–	Offshore	SolarDuck B.V, Oranje Wind Power II (RWE)	The Netherlands	2026	[174]
Tokyo Bay ESG	–	–	Offshore	SolarDuck B.V, Tokyu Land Corporation, Everblue Technologies	Japan	–	[175]

Table A3
Commissioned and upcoming floating wave energy converter (FWEC) projects; ones marked with "⋆" are decommissioned.

Project	Capacity	Depth	Device type	Partners	Country	Commission	Ref.
Wave Carpet⋆	–	–	Attenuator	Knowledge Based Systems, Inc.	US-TX	2002	[176]
Wave Dragon⋆	20 kW	6 m	Overtopping	Wave Dragon ApS	Denmark	2003	[177]
AquaBuoy⋆	250 kW	60 m	Single point absorber	Finavera Renewables Ocean Energy (Europe) Ltd	Portugal	2007	[178]
Pelamis⋆	3×0.75 MW	>50m	Attenuator	Pelamis Wave Power	Portugal	2008	[179]
Anaconda⋆	–	–	Distensible tube	Checkmate Seaenergy Limited	UK	2009	[180]
Parasitic Power Pack (P3)	4 mW	–	Energy storage	Knowledge Based Systems, Inc.	US-TX	2010	[181]
Wave Star 1:2⋆	110 kW	5-8 m	Multi point absorber	Wave Star A/S	Denmark	2010	[182,183]
Crestwing⋆	1–10 MW	–	Hinged raft	Crestwing, Aalborg, DTU, Aarhus, Harvard, Stanford	Denmark	2011	[184]
Azura-Oregon⋆	18 kW	–	Single point absorber	Northwest Energy Innovations (NWEI), EHL Group	US-OR	2012	[185]
Penguin⋆	≤ 1 MW	50–70 m	Rotating mass	Wello Oy	Finland	2012	[186]
Oceanlinx blueWAVE⋆	≥ 3 MW	40–80 m	Floating OWC	Oceanlinx	Australia	2013	[187]
WAVE PIONEER⋆	–	–	Single point absorber	Flanders Electricity from the Sea	Belgium	2013	[188]
Albatern WaveNET⋆	6×7.5 kW	–	Multi point absorber	Albatern	Scotland	2014	[189]
Azura-Hawaii⋆	18 kW	30 m	Single point absorber	Northwest Energy Innovations (NWEI), EHL Group	US-HI	2016	[190]
Oceanus 2⋆	162 kW	51–57 m	Single point absorber	Seatricity, Keynvor MorLift (KML), Seawide Services	UK	2016	[191]
PB3 PowerBuoy	3–7.5 kW	> 20 m	Single point absorber	Ocean Power Technologies, Inc.	US-NJ	2018	[192]
AMOG WEC	75 kW	20–50 m	Single point absorber	ERDF, University of Exeter, University of Tasmania, University of Plymouth	UK	2019	[193]
Wavepiston	12 kW	–	Floating OWSC	Wavepiston ApS, Vryhof, Fiellberg, Technical University of Denmark	Denmark	2019	[194]
Blue X	5–30 kW	21–25 m	Hinged raft	Mocean Energy, Wave Energy Scotland, EMEC, Blackfish, Leask Marine, University of Edinburgh, Supply Design	Scotland	2021	[195]
CorPack	300 kW	>40 m	Single point absorber	CorPower Ocean	Sweden	2022	[196]
HiWave-5	300 kW	45 m	Single point absorber	CorPower Ocean, EDP, Simply Blue Group, ENEL Green Power	Portugal	2024	[197]
Saoirse	5 MW	–	Single point absorber	CorPower Ocean, Simply Blue Group	Ireland	2026	[198]

Table A4
Commissioned and upcoming floating tidal current energy converter (FTCEC) projects; ones with "⋆" have been dropped.

Project	Capacity	Depth	Peak current	Partners	Country	Commission	Ref.
O2	2 MW	12–50 m	3 m/s	Orbital Marine Power, European Marine Energy Centre (EMEC), SKF, University College Cork, University of Edinburgh, ENGIE Laborelec	Scotland	2021	[199–201]
PLAT-1	0.42 MW	45–60 m	5 m/s	Sustainable Marine, Fundy Ocean Research Centre for Energy (FORCE)	Canada	2022	[202,203]
Dragon 4	2 × 100 kW	–	–	Minesto AB (publ)., SEV (Streymoy, Eysturoy and Vágar)	Faroe Islands	2022	[204,205]
Pempa'q⋆	9 MW	45–60 m	5 m/s	Sustainable Marine, Fundy Ocean Research Centre for Energy (FORCE)	Canada	2022	[203,206,207]
Dragon 12	1.2 MW	–	–	Minesto AB (publ)., SEV (Streymoy, Eysturoy and Vágar)	Faroe Islands	2023	[208]
Tidal Power Tug	160 kW	21–25 m	1.1 m/s	Aquantis Inc., Mitsubishi Heavy Industries, Ltd. (MHI)	Scotland	2023	[209,210]
PTEC	30 MW	–	3.2 m/s	European Marine Energy Centre, Orbital Marine Power, Isle of Wight Council	Scotland	>2023	[199,211,212]
FORWARD2030	2.03 GW	12–50 m	3 m/s	Orbital Marine Power, European Marine Energy Centre (EMEC), SKF, University College Cork, University of Edinburgh, ENGIE Laborelec	Scotland	<2030	[213,214]
Morlais	240 MW	40 m	3.7 m/s	Menter Môn, Aquantis Inc., Big Moon Power LLC, Instream, Inyanga Maritime Ltd., Magallanes Renovables SL, Nova Innovation Ltd., Orbital Marine Power Ltd., QED Naval Limited, SABELLA SA, Verdant Isles Ltd.	UK	–	[199,215,216]
Holyhead Deep	60 × 1.2 MW	80–100 m	1.5–2 m/s	Minesto UK	Wales	–	[217]
Hestfjord	24 × 1.2 MW	–	–	Minesto AB (publ)., SEV (Streymoy, Eysturoy and Vágar), University of Faroe Islands	Faroe Islands	–	[205,218]

Data availability

No data were used for the research described in the article.

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