Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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To cite this article: M Leimeister *et al* 2018 *J. Phys.: Conf. Ser.* **1104** 012007

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IOP Conf. Series: Journal of Physics: Conf. Series **1104** (2018) 012007 doi:10.1088/1742-6596/1104/1/012007

Critical review of floating support structures for offshore wind farm deployment

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Abstract. Floating structures enable offshore wind power deployment at numerous deep water sites with promising wind potential where bottom-fixed systems are no longer feasible. However, the large diversity in existing floater concepts slows down the development and maturing processes of floating offshore wind turbines. Thus, in this work, different floating support structures are assessed with respect to their suitability for offshore wind farm deployment. A survey is conducted to examine the capacities of selected floater types, grouped into ten categories, with respect to ten specified criteria focusing on wind farm deployment. By this means, a multi-criteria decision analysis (MCDA) is carried out, using the technique for order preference by similarity to ideal solution (TOPSIS). With the individual scores of the different systems, considering the weighting of each criterion, suitable concepts are identified and potential hybrid designs, combining advantages of different solutions, are suggested.

1. Introduction

Offshore wind energy is of high importance among renewable energies; however, most of the sites with good wind resources are at deep water (>60 m). This makes up around 80% of European seas [1], 60% of oceans in US [2], and 80% of Japanese oceans [1, 3, 4]. With floating offshore wind turbine (FOWT) systems, deep water sites with high potential for wind energy utilisation can be deployed, making offshore wind power no longer limited to water depths up to ∼50 m.

More than 30 FOWT concepts have been proposed [1, 2]. However, this broad range of floater types being up to now investigated - either as research designs, under development, in prototype stage, or already in demonstration projects - inhibits fast achievement of high technology readiness levels (TRLs). Furthermore, less diversity in floating support structures would allow more focused research, development of required infrastructure, specification and adaption of suppliers and manufacturers, as well as realisation of serial production [5]. Then, FOWTs could become soon cost-competitive with bottom-fixed offshore wind turbine systems. Thus, this work intends to examine different floaters, emphasising their suitability for deployment in offshore wind farms.

As fundamental basis for this study, a literature review on FOWT support structures, their characteristics, and the state-of-the-art is conducted. The main classification and the wide variety of existing floater concepts are presented in section 2. For the assessment of floating support structures (section 3), first, a SWOT (strengths, weaknesses, opportunities, and threats) analysis is carried out for the three main categories (subsection 3.1). This already indicates


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benefits and drawbacks of the technologies and, hence, supports the investigation of other concepts. On this basis, a set of criteria for assessing the potential of floating support structures for wind farm deployment is specified in subsection 3.2. The examined alternatives are defined in subsection 3.3. To obtain more meaningful results and to allow ranking of the different support structures, a MCDA (multi-criteria decision analysis) is carried out in subsection 3.4, based on survey results and using the TOPSIS (technique for order preference by similarity to ideal solution) method. A short summary with conclusions and outlook is given in section 4.

2. Review of FOWT support structures

In 2015, FOWTs counted already over 30 types [1, 2]. This broad range and huge diversity of are presented in subsection 2.2. Even if always new concepts and technologies are coming up, there are three main categories, which are introduced in the following subsection 2.1.

2.1. Main classification of floaters

Floating support structures can be categorised based on the primary mechanism adopted to fulfil the static stability requirements. There are three main stabilising mechanisms [5–7]:

- Ballast stabilised
  Having large ballast deep at the bottom of the floating structure moves the centre of gravity of the total system below the centre of buoyancy. This leads, when tilting the platform, to a stabilising righting moment which counteracts rotational displacements.
- Waterplane (or buoyancy) stabilised
  The waterplane area is the main contributor to the restoring moment of the floater. Having a large second moment of area with respect to the rotational axis, either due to a large waterplane area or due to smaller cross-sectional areas at some distance from the system central axis, creates a stabilising righting moment in case of rotational displacement.
- Mooring stabilised
  High tensioned mooring lines generate the restoring moment when the structure is inclined.

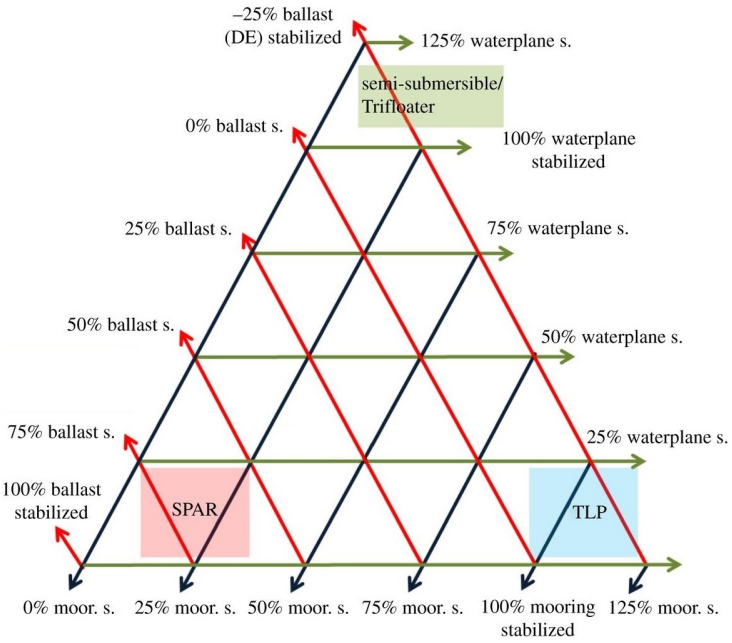


Figure 1. Stability triangle for floating structures, adapted from [7].

Spars, semi-submersibles or barges, and tension leg platforms (TLPs) rely, respectively, on the above mentioned stabilising mechanisms and thus make up the three cornerstones of floating support structures. This is visualised in figure 1 in form of a stability triangle.

Spars, the ballast stabilised floaters (figure 2a), usually consist of a long cylindrical structure which is filled with ballast at the bottom. For station keeping, the floater is commonly equipped with three catenary mooring lines. The same mooring system is used for semi-submersibles, shown in figure 2b. To obtain waterplane-based stability, this floater type is made out of three columns placed on the edges of a triangle. The wind

turbine is either mounted on one of these columns or supported by a fourth one in the centre of the triangle. Braces interconnect the columns. Unlike the multi-cylindrical semi-submersible, the waterplane-area stabilised barge is rather a plane structure. Finally, the mooring stabilised TLP (figure 2c) has a central column to support the turbine. At the floater base three arms reach out where the tendons are connected. The displaced volume should be high enough to provide excess buoyancy to ensure that the mooring lines are always under tension. Special vertical load anchors are required for the mooring lines going straight down to the seabed. [6, 8]

Due to the different mooring systems (catenary mooring for spar, semi-submersible, and barge; tendons for TLP), the floaters differ in their dynamics. For the catenary-moored floaters, the natural frequencies lie below the range of wave frequencies; however, for the TLP heave, roll, and pitch natural frequencies are above the first order wave load frequencies. Some typical numbers for the system natural frequencies are presented in table 1. [6]

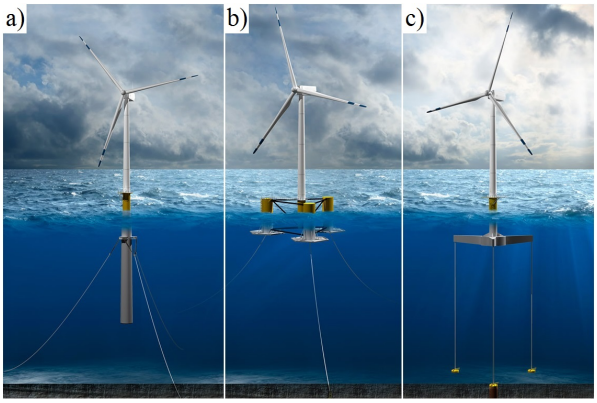


Figure 2. Three main floater categories [9]: a) spar, b) semi-submersible, c) TLP.

Table 1. Representative natural frequencies of the three main floater types [6].

Degree of freedom	Spar	Semi-submersible/ Barge	TLP
surge	0.02 Hz	0.02 Hz	0.04 Hz
sway	0.02 Hz	0.02 Hz	0.04 Hz
heave	0.07 Hz	0.07 Hz	0.44 Hz
roll	0.05 Hz	0.05 Hz	0.43 Hz
pitch	0.05 Hz	0.05 Hz	0.43 Hz
yaw	0.02 Hz	0.02 Hz	0.04 Hz

2.2. Broad range of existing floater concepts
Most of the existing floating offshore wind turbine support structures can be assigned to the main categories presented in subsection 2.1. Some other designs are found to be a combination of different floater types, termed hybrid concepts in the following. Finally, multi-purpose floaters exist: a structure that carries more than just one wind turbine, so-called multi-turbine concepts, or a mixed-energy design, with which not only wind energy but also another energy source is captured. In the following, examples of existing FOWT concepts are shortly presented. References with more details about each design are mentioned for further reading. Market study reports about existing concepts and projects are presented as well in [1, 2, 4, 10].

2.2.1. Spar concepts The general principle of spar floaters is introduced in subsection 2.1: a long cylindrical structure, ballasted at the bottom to obtain stability, and moored with three catenary lines. Some modifications for improving performance and floater characteristics could be a delta-connection of the mooring lines to the floater, vacillation fins, or a reduced draft.

Already in the 1970s a spar-type floater was proposed - Heronemus - which, however, was not technologically developed [11]. Nowadays, the most well-known spar FOWT is the Norwegian project Hywind by Statoil, which - after a single prototype - is already used in a prototype floating wind farm off the Scottish coast [1, 12–15]. Further optimisation is still needed, as this structure is currently very over-designed [12]. Research is also conducted on the use of concrete: FLOAT by GH-Tecnomare is a concrete buoy [12, 16], the Hybrid spar by Toda

Construction uses steel at the upper and concrete at the lower section [1], the Universitat Politècnica de Catalunya designed an one-piece concrete structure for tower and floater [1], and within the Kabashima Island Project in Japan a hybrid (concrete/steel) spar floater is developed [2, 3]. Even some advanced spars, modified for improved performance, exist already. The delta-connection, also called crowfoot connection, of the mooring lines to the structure is often used, as well as redundant mooring lines, as for example for the double taut leg buoy by MIT [5]. More advanced improvements, such as reduced draft or stabilising fins for improving sway and heave response, are integrated in the advanced spar floater within the Fukushima-FORWARD Floating Project in Japan by Japan Marine United [1, 3, 17]. Finally, some quite different spar floaters are developed to support a vertical axis wind turbine (VAWT). In these designs, such as the SeaTwirl by SeaTwirl Engineering in Sweden [1] or the DeepWind Spar by the DeepWind Consortium [1], the support structure is rotating together with the turbine.

2.2.2. Semi-submersible concepts The semi-submersible floater is explained in subsection 2.1. In addition to the catenary-moored three- or four-cylindrical structure, heave plates are often attached to the bottom of the columns to reduce heave motion. Further improvements with respect to stability can be achieved by designing the geometry for wave-cancellation or by using an active ballast system [18]. A braceless design would simplify manufacturing and inspection.

The floating structure developed within the Fukushima-FORWARD Floating Project in Japan by Mitsui Engineering & Shipbuilding [1, 3, 17, 18], as well as WINFLO in France [12, 18], VolturnUS by the DeepCwind Consortium [1], Drijfwind or FloatWind from the Netherlands [12, 18, 19], and VERTIWIND in France by Technip and Nenuphar for a VAWT [1], represent the basic semi-submersible type with three or four columns, braces, and catenary moorings. Some simplified floaters without braces are the Dutch Tri-Floater by GustoMSC [1, 5, 20], SeaReed by DCNS [1], OO-Star Wind Floater in Norway by Olav Olsen [21], SPINFLOAT by EOLFI for a VAWT [1], and TetraFloat by TetraFloat - a special light-weight design of the entire FOWT system [1]. As well braceless, but more innovative are the V-shape semi-submersible of the Japanese Fukushima-FORWARD Floating Project by Mitsubishi Heavy Industries [1, 3, 17, 18] and Nezzy SCD by Aerodyn Engineering, which is a turret-moored Y-shaped structure but uses plastic-composite buoys instead of cylindrical columns [1]. Active ballast system is additionally used in the NAUTILUS concept by NAUTILUS Floating Solutions [1, 22] and the WindFloat by Principle Power in Portugal [1, 12, 15, 18, 23, 24].

2.2.3. Barge concepts Just as a semi-submersible, a barge floater is a waterplane-area stabilised structure. The main difference between these floaters, however, is that a semi-submersible has distributed buoyancy and consists of columns, while a barge is typically flat without interspaces.

Only a few barge-type FOWT systems exist. ITI Energy Barge [13] is very standard. Floatgen by the French Ideol, however, is quite special with its concrete ring-shaped support structure utilising a moonpool, also called damping pool, system for motion reduction [1, 18, 25].

2.2.4. TLP concepts The TLP system is explained in subsection 2.1. As a TLP is most reliant on the tendons and highly dependent on the soil conditions, improvements can be achieved through redundant mooring lines and different, more soil-insensitive, anchors.

An early design is the Eolomar ring-shaped TLP [12]. More contemporary and very basic is the TLP by MIT and NREL [12, 13, 20]. GICON in Germany with GICON-SOF [1, 26], the American Glosten Associates with PelaStar [1, 15], Iberdrola with TLPWind [1, 27], and I.D.E.A.S with the TLWT [23] have addressed the high risk problem by equipping the floater

with additional mooring lines, either via an increased number of arms or a supporting redundant mooring system. The strong soil dependence is solved by DBD Systems (Eco TLP) [1], Arcadis in Germany [12], and the Dutch Blue H Group (BlueH) [1, 12, 28] with (concrete) gravity anchors.

2.2.5. Hybrid concepts Combination of any of the three stability mechanisms, represented by spar, semi-submersible or barge, and TLP in figure 1, leads to so-called hybrid floating concepts. In this way, advantages of different systems can be combined in one floating structure.

Quite common is the tension leg buoy (TLB), which is a spar floater moored with tendons, such as the Floating Haliade by Alstom in France [10], the Ocean Breeze by Xanthus Energy in UK [10], the TLB series by the Norwegian University of Life Science [23], and the SWAY or Karmoy in Norway [1, 12, 23]. Nautica Windpower in the US combined in the single-point moored AFT (advanced floating turbine) a TLP with a semi-submersible to support a two-bladed wind turbine [1], while Concept Marine Associates added to a TLP a barge-shaped structure, which is ballasted offshore and, thus, functions as gravity-based anchor [5].

2.2.6. Multi-turbine concepts Placing more than one wind turbine on top of one floater reduces the structural mass [1], as well as the mooring and anchoring costs per turbine, and increases the stability [20]. On the other hand, the loads on the structure might increase, the overall size is enlarged, which complicates manufacturing and handling, and the turbines are likely to operate sometimes in the wake of the other turbine(s) [1, 20]. This needs to be considered when designing a support structure for multi-turbine utilisation.

Two turbines are deployed on Hakata Bay Scale Pilot Wind Lens by the Japanese Kyushu University [3], while the semi-submersibles MUFOW (multiple unit floating offshore windfarm) [12, 16] and the design by Lagerwey and Herema [12] support several turbines. Hexicon by Hexicon in Sweden carries three turbines in a row [1] and WindSea by FORCE Technology in Norway is a tri-floater with two upwind and one downwind turbine [1, 12].

2.2.7. Mixed-energy concepts Another option of higher utilisation of one floating support structure is to capture not only wind but also another energy source, such as wave, current, tidal, or solar energy. This way, the power density can be increased and the fluctuations in the power production can be balanced to some extent. However, as for the multi-turbine floater, the complexity and overall dimension of the system, as well as the loads on the system are increased [1].

Such multi-energy floaters are examined in the TROPOS, MERMAID, H2OCEAN, and MARINA projects [10, 29]. A quite common combination is wind and wave energy, as realised by W2power in Norway with the Pelagic Power floater [1] and by Floating Power Plant in Denmark with the Poseidon P80 semi-submersible [1]. Wind and ocean current turbines are combined in the SKWID (Savonius keel & wind turbine Darrieus) by MODEC in Japan [1, 3]. Finally, the multi-turbine floater Hakata Bay Scale Pilot Wind Lens accommodates also solar panels [1, 3].

3. Assessment of floating support structures

The assessment of different floating support structures is carried out in two steps: first (subsection 3.1), a basic SWOT analysis is performed for the three main floater categories mentioned in subsection 2.1, and secondly (subsection 3.4), a MCDA is carried out. The criteria, focussing on the potential for offshore wind farm deployment, as well as the selected floater concepts used in the MCDA, are defined and specified beforehand in subsections 3.2 and 3.3, respectively. Based on the results of the MCDA, the TRLs and potentials to scale up to serial production for multi-MW wind farm deployment are estimated at the end (subsection 3.5).

3.1. SWOT analysis

Based on the initially performed literature study the benefits and drawbacks of spars, semi-submersibles, and TLPs are presented in form of a SWOT analysis (tables 2 and 3).

Table 2. SWOT analysis of floater concepts - strengths and weaknesses.

Type	Strengths	Weaknesses
spar	• inherent stability [1–3, 5, 6, 8, 18, 30, 31] • suitable for even higher sea states [5] • soil condition insensitivity [5, 8] • cheap & simple mooring & anchoring system [6, 18, 20] • low operational risk [3] • little susceptible to corrosion [5] • simple structure, easy manufacturing & maintenance [1, 2, 5, 6, 8]	• relative large motions [12] • unsuitable for shallow water [1–6, 8, 12, 30, 31] • large seabed footprint [2] • long mooring lines (costs) [5] • assembly in sheltered deep water [2, 3, 8, 18] • challenging, time-consuming & costly float-out & installation [1–3, 5, 8, 18] • long & heavy structure (costs) [5, 6] • high fatigue loads in tower base [2]
semi-submersible	• heave plates for reducing heave response [2, 18] • broad weather window for float-out & installation [5] • depth independence [1, 2, 5, 6, 8, 12, 30, 31] • soil condition insensitivity [2, 5, 8] • cheap & simple mooring & anchoring system [5, 6, 18, 20] • low overall risk [8, 32] • onshore or dry dock assembly [5, 6, 8, 18] • simple installation & decommissioning [1, 2, 5, 8, 12, 30]	• lower stability, higher motions [2, 3, 5, 8, 30, 31] • wave sensitivity • large seabed footprint [2] • long mooring lines (costs) [5] • subject to corrosion & ice-loads [2, 5, 6, 8, 20] • large & complex structure, more challenging manufacturing & maintenance [1, 2, 6, 8] • large & heavy structure (costs) [1, 5, 6, 8, 12] • larger impact on turbine due to motions [2, 5, 8, 30, 31]
TLP	• high stability, low motions [1–3, 6, 8, 12, 18, 20] • little wave sensitivity (in case of submerged platform) [30, 31] • suitable for even high sea states (in case of submerged platform) [5] • suitable for intermediate depths [2, 12] • small seabed footprint [2, 5, 6, 8, 20] • short mooring lines [5, 8] • little susceptible to corrosion (in case of submerged platform) [5] • simple, small & light structure, easy maintenance [1, 2, 6] • onshore or dry dock assembly [1, 2]	• unsuitable for strong tidal currents or storm surges [2–6, 8] • unsuitable for shallow water • unsuitable for challenging soil conditions [2–6, 8] • complex & costly mooring & anchoring system [1, 5, 8, 18, 20] • high risk if tendon or anchor fails [1, 3, 6, 12, 18] • complex & risky installation & disconnection for onshore maintenance [1, 2, 5, 6, 8, 12, 18, 20, 30, 31] • large stresses in structure [1, 5]

Table 3. SWOT analysis of floater concepts - opportunities and threats.

Type	Opportunities	Threats
spar	• serial fabrication, synergies with tower manufacturing [1, 2, 5, 6, 8] • delta-connection for yaw stabilisation • stabilising fins for sway & heave stabilisation [1, 4] • horizontal transportation [5] • high TRL [8]	• special purpose vessels required [8] • no global market [8]
semi-submersible	• cost reduction through mass production [8] & braceless design • geometry for wave-cancellation [6, 18] • stabilising active ballast system [1] • high TRL [8] • large global market [8] • may carry more than one turbine [6]	• large internal forces if geometry designed for wave-cancellation [6] • costly active ballast system [1] • high competition [8]
TLP	• low mass production cost [8] • redundant moorings reduce risk • less soil dependent gravity anchors • low competition [8]	• special purpose installation ships required [8] • low TRL [8] • no global market [8]

3.2. Set of criteria

FOWT support structures can be assessed based on different criteria, as done in [6, 30, 31, 33–35]. This study, however, focuses on offshore wind farm deployment. Thus, the following ten criteria are specified (table 4), with a (+)/(-) indicating a positive/negative criterion, meaning that a higher score corresponds, respectively, to a more positive/negative aspect for the floater.

Table 4. Set of criteria.

Criterion		Included aspects	Type
1.	LCOE	levelised cost of energy (LCOE), rate of return, power density, outer dimension, mooring footprint, turbine spacing	(-)
2.	volume production	ease of manufacturing, modular structure, fabrication time, onshore fabrication	(+)
3.	ease of handling	outer dimension, total weight, assembly, transport, installation, decommissioning, required equipment and vessels	(+)
4.	durability	corrosion resistance, fatigue resistance, redundancy, aging	(+)
5.	flexibility	offshore site, water depth, soil condition, environmental loading	(+)
6.	certification	time to achieve, ease to achieve, TRL	(+)
7.	performance	deflections, displacements, nacelle acceleration, dynamic response, overturning resistance, torsion resistance	(+)
8.	maintenance	frequency, redundant components, costs, downtime	(-)
9.	time-efficiency	assembly, transport, installation, maintenance, decommissioning	(+)
10.	mooring requirements	number of mooring lines, motions wrt need of flexible cables, length of lines, anchoring system costs	(-)

3.3. Set of alternatives
The assessed floaters are specified in table 5 according to the categorisation in subsection 2.2.

Table 5. Set of alternatives.

Alternative		Description
I.	spar - standard	common spar floater type
II.	spar - advanced	improved spar (reduced draft, vacillation fins, crowfoot/delta mooring connection, horizontal transportation methodology)
III.	semi-submersible - standard	common semi-submersible floater type
IV.	semi-submersible - advanced	improved semi-submersible (braceless, wave-cancelling geometry, inclined/shape-optimised columns, active ballast system)
V.	barge floater	common barge floater type
VI.	TLP - standard	common TLP floater type
VII.	TLP - advanced	improved TLP (redundant mooring lines, gravity anchors)
VIII.	hybrid floater	mixed spar, semi-submersible, TLP floater types
IX.	multi-turbine floater	floater supporting more than one wind turbine
X.	mixed-energy floater	floater for wind & wave/tidal/current/photovoltaic utilisation

3.4. MCDA via TOPSIS
Several approaches, such as weighted sum or product methods (WSM/WPM), TOPSIS, analytical hierarchy process (AHP), ELECTRE (elimination et choix traduisant la realité), and PROMETHEE (preference ranking organization method for enrichment evaluation) can be used to rank alternatives, taking account of multiple criteria. Based on studies applying and comparing MCDA methods for the assessment of offshore wind turbine support structures [30, 31, 34, 35], TOPSIS is selected in this work, as it is based on easy, robust calculation methods, deals with criteria of quantitative or qualitative nature, and incorporates expert opinions [31, 35]. The basis of TOPSIS is a set of alternatives and criteria, as specified in subsections 3.2 and 3.3. By means of a survey, scores for each criterion are assigned to each alternative, in this study from 1 (least applicable) to 5 (most applicable), and weights are set to represent the importance of each criterion with respect to offshore wind farm deployment, here again values between 1 (not important) and 5 (important). The scores yield a decision matrix, which is - after normalisation - multiplied with the weight vector. The final ranking of the alternatives is obtained based on their closeness to the positive ideal solution and distance to the negative ideal solution. [30, 31]

The survey was sent to knowledgeable academic, as well as industrial experts in the field of floating offshore wind and was answered completely by seven individuals. These seven participants had on average more than five and a half years of experience in floating offshore wind energy, ranging individually from one and a half year to even ten years.

The survey results are presented in table 6 in form of the mean values of scores (decision matrix) and weights (weight vector), as well as the final TOPSIS score and rank. This shows that cost is the most important factor, while flexibility is judged to be least important. From the considered concepts, the advanced spar ranks first, directly followed by standard spar and advanced semi-submersible, whereas the TLPs make up the tail. Thus, advanced spars and semi-submersibles are assessed to be most suitable for deployment in offshore wind farms, which is especially due to the high opportunity for volume production and certification, as well as the

low LCOE and mooring requirements in case of the advanced or standard spar, and due to the easy handling, high flexibility and low mooring requirements for the advanced semi-submersible. On the other hand, handling, certification, mooring requirements, and also maintenance are the criteria that let TLPs fail in the comparison.

Table 6. Decision matrix, weight vector, TOPSIS scores and ranks, based on survey results.

	1	2	3	4	5	6	7	8	9	10	score	rank
I	3.20	4.00	3.00	3.00	3.20	3.40	3.00	3.40	3.20	3.40	0.651	2
II	3.17	4.33	3.17	3.33	3.33	3.17	3.17	3.50	3.17	2.83	**0.763**	**1**
III	3.50	2.83	3.50	3.33	3.50	3.17	2.83	3.50	2.83	3.00	0.532	5
IV	3.50	3.17	3.67	3.50	3.50	2.83	3.17	3.33	2.83	2.83	0.600	3
V	3.67	3.67	3.17	3.00	2.67	3.20	2.67	3.00	2.67	3.00	0.549	4
VI	3.43	3.00	2.57	3.14	2.43	2.83	3.33	3.50	3.33	4.33	0.319	10
VII	3.33	3.00	2.17	3.50	3.00	2.50	3.33	3.50	3.33	4.00	0.335	9
VIII	3.67	3.17	3.17	3.17	2.83	2.83	3.17	3.33	3.17	3.83	0.425	7
IX	3.33	3.00	2.83	3.33	3.00	2.50	3.33	3.17	3.00	3.33	0.436	6
X	3.67	2.83	2.67	3.17	3.50	2.67	2.67	3.17	2.83	3.17	0.390	8
weight	**4.26**	3.43	2.91	3.24	2.33	3.40	3.38	3.59	3.02	3.06		

Apart from the mean values of the survey results, the standard deviations among the answers from the survey participants are at least as important. These are presented for the decision matrix and weight vector in table 7, including also averaged values for the standard deviations of each concept alternative and each criterion. This shows that all survey respondents agree on the performance of standard spars, while on average they are most confident with the advanced semi-submersible. This good agreement underlines the meaningfulness of the TOPSIS result for the most potential floater concepts. The largest discrepancy in the survey responses is found in the durability of barge floaters; however, the survey participants seem to be most uncertain about mixed-energy floaters in general. Looking at the criteria, the difference in the answers is the largest for the LCOE, both in decision matrix and weight vector. This large deviation is striking, but still does not affect the clear outcome that cost is the most important criterion. The best agreement in weighting the criteria concerns the mooring requirements, while on average the smallest deviation in the decision matrix has the performance of floating concepts.

Table 7. Standard deviations among survey participants for decision matrix and weight vector.

	1	2	3	4	5	6	7	8	9	10	average
I	1.48	1.41	1.22	0.71	1.30	0.89	**0.00**	0.55	1.30	1.34	1.02
II	1.33	1.03	1.17	0.82	1.21	0.98	0.75	0.55	1.17	1.17	1.02
III	1.05	1.17	1.05	0.82	0.84	0.98	0.75	0.84	0.75	1.10	0.93
IV	1.05	0.98	1.03	0.55	1.22	0.75	0.75	0.82	0.75	0.98	**0.89**
V	1.03	0.82	0.41	**1.67**	0.52	0.45	1.21	1.10	0.82	1.10	0.91
VI	1.27	1.10	1.51	0.69	0.79	1.17	1.03	1.05	1.37	1.21	1.12
VII	1.37	1.10	1.17	0.55	0.63	1.05	1.03	0.55	1.37	1.10	0.99
VIII	0.82	1.17	1.17	0.75	0.75	1.33	0.75	1.03	0.75	0.75	0.93
IX	1.03	1.10	1.33	1.03	0.89	1.38	1.21	1.33	1.10	1.21	1.16
X	1.51	0.98	1.37	1.17	1.38	1.51	1.21	1.60	1.33	1.47	**1.35**
average	**1.19**	1.09	1.14	0.88	0.95	1.05	**0.87**	0.94	1.07	1.14	
weight	**1.83**	1.47	1.45	1.44	1.50	1.55	1.60	1.46	1.61	**1.40**	

3.5. TRLs of floater concepts

The TRL gives a measure of the development status of a technology, as defined in table 8. TRL estimates for different FOWT concepts are given in [1, 15] and also obtained through the survey. Based on this, the different floater categories are ranked with respect to their TRLs, as well as their potential to scale up to mass production for multi-MW wind farm deployment (TOPSIS score), visualised in figure 3 with the size of the bubbles representing the standard deviation.

Table 8. TRLs according to Horizon 2020 definition [36].

TRL	Description
1	basic principles observed
2	technology concept formulated
3	experimental proof of concept
4	technology validated in lab
5	technology validated in relevant environment
6	technology demonstrated in relevant environment
7	system prototype demonstration in operational environment
8	system complete and qualified
9	actual system proven in operational environment

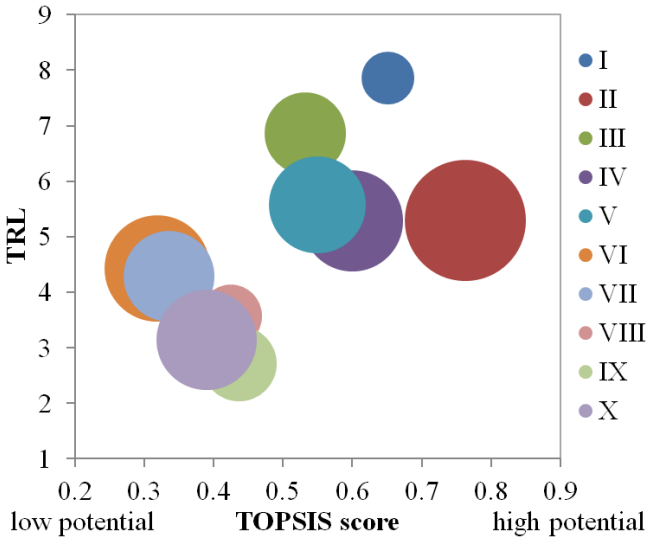


Figure 3. TRLs versus potential for wind farm deployment.

4. Conclusion

In this paper, ten FOWT support structures are assessed with respect to ten criteria focusing on wind farm deployment. The MCDA is based on survey results and uses TOPSIS method. Even if the results depend on the specified categorisation and general assumptions, e.g. use of the same wind turbine, costs proved to be still most important, as Habib Dagher stated [37]: "Each solution has its pros and cons. There's lots of solutions out there. The bottom line is what is most cost-effective at the end of the day." The survey reveals that the advanced spar, directly followed by the most developed standard spar, has the highest potential for multi-MW wind farm deployment. In general a correlation trend between TRLs and TOPSIS scores emerges.

Acknowledgments

This work was supported by grant EP/L016303/1 for Cranfield University and the University of Oxford, Centre for Doctoral Training in Renewable Energy Marine Structures - REMS (http://www.rems-cdt.ac.uk/) from the UK Engineering and Physical Sciences Research Council (EPSRC) and the German Fraunhofer Institute for Wind Energy Systems IWES. The authors also want to thank the knowledgeable people that have participated in the survey.

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2018-10-31

http://doi.org/10.1088/1742-6596/1104/1/012007

M Leimeister, A Kolios and M Collu. Critical review of floating support structures for offshore wind farm deployment. Journal of Physics: Conference Series, Volume 1104, 2018, Article number 012007

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