CAN JACKETS AND TRIPODS COMPETE WITH MONOPILES?

Prof. Peter Schaumann[1], Cord Böker [1]

[1] Institute for Steel Construction, University of Hannover, Appelstraße 9A, 30167 Hannover Germany, www.stahlbau.uni-hannover.de

ABSTRACT

At the offshore wind parks already completed it got clear that the support structure holds great share at the investment costs in comparison with onshore units. The surprisingly strong rise in prices for steel has sharpened the situation. Of course the most economical solutions have to be developed. Nevertheless, these structures have to fulfil all necessary technical requirements including structural stability. The existing experiences mainly refer to Monopile structures until now. With regard to construction, production and assembly this simple shell structure has great advantages over filigree latticed structures. These advantages are paid for with a larger amount of material. On the other hand the unit price per tonne of steel weight is comparatively low.

This paper introduces some fundamental, qualitative considerations for the question to the optimal support structure. Applying particular design tools which have been developed in the frame of recent research projects a parameter study on a pre-design level for different power rates and a location in the North Sea is carried out. The results illustrate quantitatively the determinant parameters on the construction weight of Monopiles.

INTRODUCTION

In the course of the development of Offshore Wind Energy Conversion Systems (OWECS) with more and more rated power, the question arises up to which water depth and turbine size the comparatively simple foundation concept of the monopile could be technically and economically feasible. Up to now, it was common understanding in the industry that monopiles were the preferred solution up to water depths of not more than some 20m, referring to the larger diameters and masses that would be needed for deeper waters and the corresponding difficulties in the handling of these structures. In these cases, a Tripod or Jacket structure was deemed to be the concept of choice. Nevertheless, it is undoubted that the production of a monopile is the cheapest solution possible in terms of unit price per tonne of steel. It is then the question whether the additional costs needed for the handling of the large structures can be compensated by savings on the production cost of the units.

To give a proper answer to the question asked in the title of the paper a multitude of parameters and boundary constraints has to be considered. Therefore, this paper follows a two-step approach. Firstly, technical and economical aspects of the three concepts are compared on a qualitative basis. In the second step, a parameter study is performed to get a quantitatively realistic picture of the masses required for monopile foundations in growing water depths. To further narrow down the parameter range to be considered here, the paper concentrates on conditions that can be found at the upcoming German offshore projects.

Current Situation in Germany

Currently there are 10 projects in the so-called German Exclusive Economic Zone that have the approval of the authority in charge, the German Bundesamt für Seeschiffahrt und Hydrographie (BSH, Federal Maritime and Hydrographic Agency). Figure 1 shows some of the key facts of those approved projects in a summary. Looking at this figure, it becomes clear that the major challenge for companies and designers who participate in these projects is to come up with economically feasible solutions for water depths of not more than 20 to 40m. Also, the governing turbine size will be between 3 and 5 Megawatt (MW), whereas the majority of the projects tends to utilize the 5MW technology.

Project	Area	Water Depth [m]	Distance to Coast [km]	Number of Turbines	Max. Turbine Size [MW]
Butendiek	North Sea	16-20	34	80	3
Sandbank 24	North Sea	30-40	90	80	5
Nordsee-Ost	North Sea	19-24	30	80	5
Amrumbank West	North Sea	21-25	35	80	5
Borkum Riffgrund West	North Sea	30-35	40-50	80	3.5
Borkum Riffgrund	North Sea	23-29	34	77	3
Borkum West	North Sea	30	43-50	220	5
North Sea Windpower	North Sea	25-33	45	48	5
Dan Tysk	North Sea	21-33	70	80	5
Kriegers Flak I	Baltic Sea	20-40	30	80	5

Figure 1: Approved Windfarm projects in the German Exclusive Economic Zone (based on information to be found at www.bsh.de)

Additionally, most of the projects are located in the North Sea. This has a considerable impact on the design of the structures, since the environmental conditions that can be found in the North Sea are quite different to those in the Baltic Sea. This concerns for especially the soil and wave conditions, both of which often are more favourable in the North Sea.

At some of the projects in the list, the number of turbines represents only the number to be erected in a pilot phase of the project. But even with these careful figures, it becomes clear that with a total number of more than 900 single turbines to be erected under comparable environmental conditions as well as with comparable turbine sizes, there is a high potential of saving costs by developing designs and tools that can be used repeatedly at many of the projects. Obviously the first question to be answered is: What support structure concept is the most feasible one, both technically and economically, for the upcoming German projects?

GENERAL CONSIDERATIONS

Comparison of the different concepts

The three concepts that are part of the title of this paper are shown schematically in Figure 2. These are the monopile, the tripod and the jacket. A monopile is effectively an extension of the steel tower and is driven or drilled into the seabed. Monopiles are used extensively in the off- and nearshore environment for supporting oil and gas platforms and other coastal structures. To some extent the monopile can be considered as the state of technical knowledge, as most of the wind farms realised in water depths more than 5m so far made use of this concept. The advantages are the comparatively easy design and production procedures and as a consequence the comparatively low unit price per tonne.

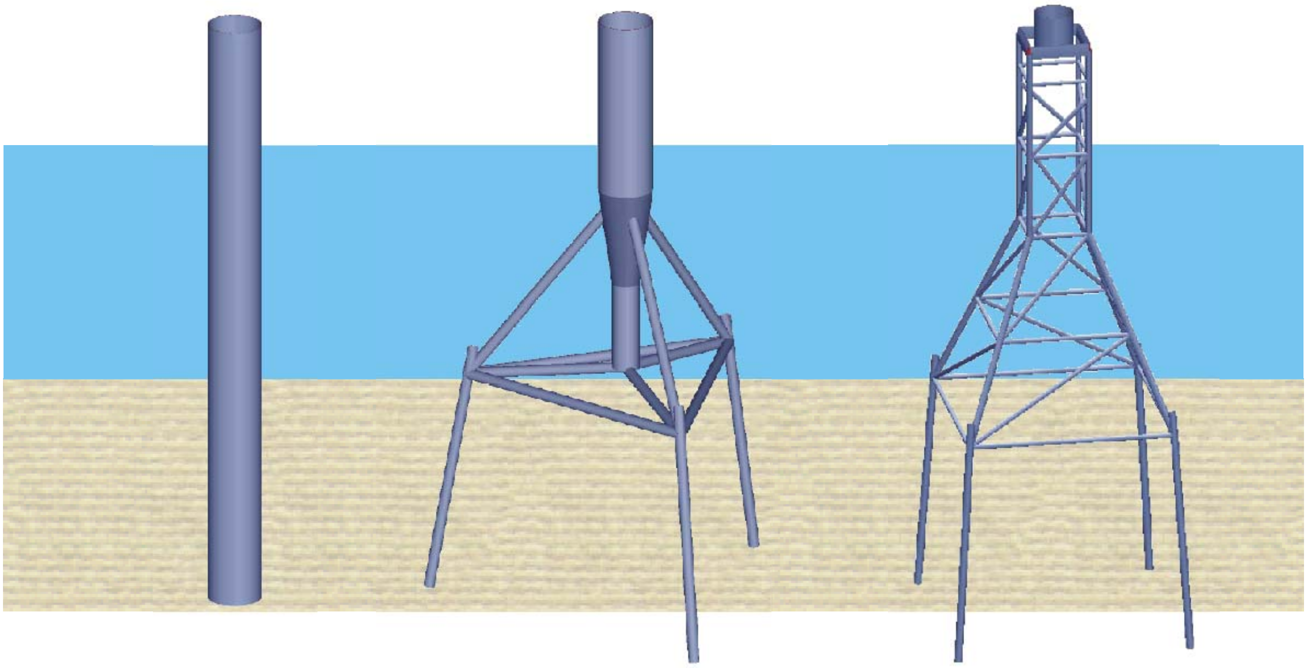

Figure 2: Schematic illustrations of the three concepts: monopile (left), tripod, jacket (right)

The tripod supports a central tube which extends into the tower, with each corner of the tripod support piled into the seabed. The jacket can be any of a variety of arrangements whereby a central tube is surrounded by numerous piled supports. Both share in principal the same idea of saving material, or economising material usage, by providing the required structural stiffness through extending the base of the support. Another difference that both have in common compared to the monopile is the global load transmission. While the monopile transfers the loads by bending to the soil, both the tripod and jacket dissolve the global moments to pairs of forces and transfer them as axial loads to the soil. This has advantages especially in weak soils.

In order to compare the three concepts regarding different criteria on a qualitative basis and at the same time produce a scale for this comparison a two-dimensional matrix is used, see Figure 3. In each row of this matrix it has to be decided which of the three concepts is the most preferable, the second-most preferable and which is not preferable regarding the respective criterion of that row. These three ranks are rated with 3, 1 and 0, respectively. Doing this, first places in the rankings are emphasized. In addition, the importance of the different criteria is considered by the multiplication of the ranks with an importance factor between 1 and 3.

Which concept is preferable in terms of…	**Importance**	**MP**	**Tripod**	**Jacket**
Transportability	1	3	1	0
Corrosion protection / corrosion allowance	2	3	1	0
Scour	3	0	1	3
Ship collision	2	3	0	1
Availability of installation equipment for large water depth	1	0	3	3
Design experience with regard to OWECS	2	3	1	0
Complexity of joints, esp. for fatigue design	1	3	0	1
Serial production	2	3	1	0
Installation procedure (soil preparations, levelling)	2	3	1	0
Deconstruction after lifetime	2	3	1	0
Deflection at tower top	2	0	1	3
Dependancy on soil conditions	3	0	3	3
Unit price per tonne of steel	2	3	1	0
Overall weight to be expected	2	0	1	3
Sum of Importance factors * Comparative factors		**48**	**32**	**36**

Figure 3: Comparison matrix for the different concepts

The result of this comparison is that in the sum of all criteria the monopile is the preferable concept. It has to be kept in mind though that the weighting with importance factors and also the ranking between the three concepts has been done only qualitative. Also, the study does not include any monetary evaluation of the different aspects. The latter point, the monetary evaluation, is one of the big issues throughout the industry.

From the experience of the authors the cost for a monopile consists of three approximately balanced shares:

- material costs, i.e. the amount of steel required
- manufacturing costs, including welding, painting etc.
- transportation and installation costs

The cost for structural steel is constant for all concepts. As to the manufacturing costs, it can be assumed that this will be cheapest for the monopile, while the jacket solution will be the most expensive one in this regard. Transportation and installation costs are hard to determine since no project utilizing either tripods or jackets has been built so far, but it can be expected that here also the monopile offers the cheapest solution. All this leads to higher unit prices per tonne of steel for tripods and jackets. Hence, if tripod or jacket shall be economically competitive they have to provide savings in material consumption by a factor that at least compensates the higher unit prices.

General mechanical considerations for a monopile

How does increasing the water depth influence the material needed? Obviously, lengthening the structure means to invest more material at least for the additional length. Ideally, the weight per unit length can be kept constant so that the additional cost for a deeper location is only this weight per unit length (as known from shallower sites) times the additional depth. Is that possible for a monopile?

To be technically feasible, each concept has to provide the following:

- the dynamic behaviour of the overall system has to be such that the first fundamental natural frequency is in a relatively small band, typically between 0.25 Hz and 0.35 Hz, in order to avoid excessive dynamic excitation of the global system
- The structure has to provide sufficient bearing capacity to survive the design lifetime. This includes the ultimate limit state (ULS) situations, i.e. extreme loads caused by wind and wave occurring during the lifetime, as well as the fatigue limit state (FLS)

There are some basic section properties that control the behaviour of the system regarding the above-mentioned requirements. These are the moment of inertia I of the cross-sections for the dynamics and the section modulus W for the load bearing capacity.

To understand how going to deeper waters influences these requirements, simplifying the wind turbine with a monopile foundation is modelled as a single degree of freedom system (SDOF), see Figure 4. I.e., the rotor and nacelle are represented by a single mass and the distributed bending stiffness is idealized as a single spring.

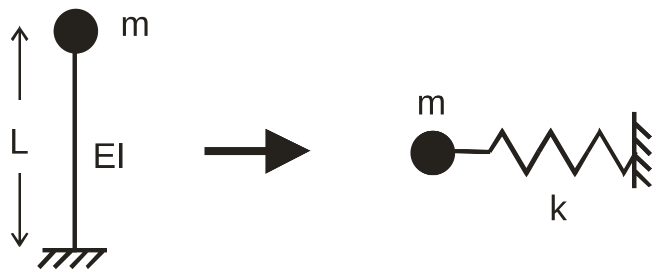

Figure 4: Simplified statical system of a wind turbine and equivalent SDOF

The fundamental frequency of the system is then

$$\omega = \sqrt{\frac{k}{m}}$$

with m being the top mass and k the spring stiffness, which is equivalently represented here by the bending stiffness of the system, hence

$$k = \frac{3EI}{L^3}$$

where L is the length of the system or the height of the tower down to a thought fixed support. Going to deeper waters means increasing this length. In order to keep the eigenfrequency constant at the same time, the moment of inertia has to be increased:

$$I_{req} = \frac{m \cdot \omega^2}{3E} L^3$$

This shows that the required moment of inertia is proportional to the length of the system to the power of three. On the other hand, the loads, both wind and wave loads, increase the maximum bending moment depending on the increased lever arm, i.e. the load effects are proportional to the increased water depth. Since this simplifying approach neglects the mass of the beam as well as the support stiffness it is a quite approximate approach, but it shows that the most important thing for a sub-structure to provide when going to deeper water depths is stiffness.

Is it possible to increase the stiffness of a monopile without increasing the weight per unit length at the same time? The weight per unit length only depends on the area

$$A = \frac{\pi}{4}\left(D^2 - d^2\right)$$

with D the outer diameter and d the inner diameter of the pile. Increasing stiffness means to increase the outer diameter. To keep A, i.e. weight per unit length, constant, while increasing D, the wall thickness t has to be decreased:

$$t = \frac{D}{2} - \sqrt{\left(\frac{D}{2}\right)^2 - \frac{A_{ref}}{\pi}}$$

where A_{ref} is the area of the references structure that shall be kept constant.

Figure 5 shows the developing of the moment of inertia I vs. the diameter while keeping the weight per unit length constant as described above. The values are related to a reference tube of ∅5000x50mm, which is equivalent to a weight of about 6 tonnes per meter length. In addition, the moment of resistance W^* is shown, which has been reduced by a factor to account for the influence of shell buckling acc. to [2] and [1].

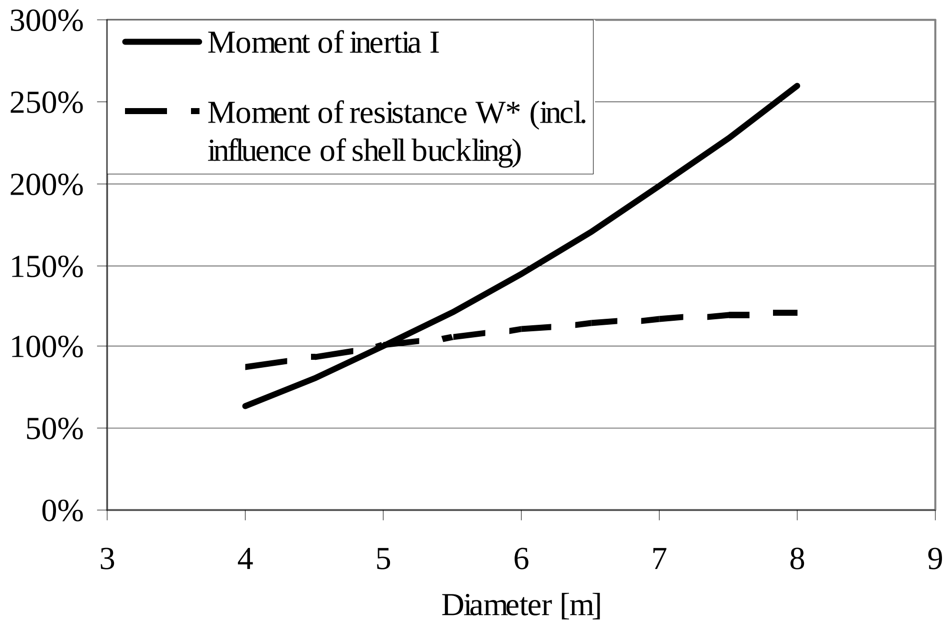

Figure 5: Moment of inertia I and the moment of resistance W^* (related) vs. the diameter of a steel tube; weight per unit length kept constant

As can be seen it is possible to increase the moment of inertia without having to increase weight per unit length significantly. On the other hand, the moment of resistance stays at almost the same level. This is mainly due to the consideration of shell buckling effects. Effectively this is not a problem, because the wall thickness has to be increased anyway, if only to fulfil the minimum wall thickness requirements as prescribed in [1], [2] and [4] to avoid hard driving. Unfortunately, this increases the weight per unit length, too. With tripod and jacket it is possible to come around this problem, since these provide the required stiffness by a sufficient height of construction without increasing the required weight per unit length significantly. This allows for a more economical usage of the material.

Another factor to be considered is the quantity distribution of the support structure, see [5]. While most of the tonnage required for a monopile is needed below mudline, a tripod or other lattice type structure buries only about 20% of its overall weight. Increased water depth often means also increased penetration depth due to the increased loads. While a monopile has to be extended with its heavy cross section to activate the required soil resistance, for the lattice structures it is possible to use much more filigree foundation piles.

However, keeping in mind the above-mentioned unit prices per tonne of steel it is the overall tonnage required that determines the overall production cost. To quantify the key numbers, i.e. required masses and diameters, for monopiles in larger water depths a parameter study has been performed.

PARAMETER STUDY

The above-mentioned considerations refer to general mechanical interrelationships. In order to take into account effects like soil conditions and the offshore environment a more precise parameter study has been performed. The purpose of that is to get some realistic answers on the following questions:

- Which overall masses can be expected for a monopile depending on the water depth?
- What will be the lengths of such monopiles?
- What diameters will be needed?

With realistic answers to these questions it will be possible to evaluate the feasibility of monopiles for larger water depths.

Basic assumptions

Turbines: The current 3MW and 5MW class machines represent the state-of-the-art. Developments to turbines sizes beyond 6MW are currently not being planned. The actual challenge is rather to optimize and evaluate the existing multi-megawatt-technology. Thus a representative 3MW machine with a head mass of 280 t and a 5MW machine with a head mass of 400 t have been chosen for the study. A representative set of loads, both extreme and fatigue loads, has been used to evaluate the structural durability of the foundation systems. Extreme loads are used as tower top loads, fatigue loads are considered using damage equivalent loads. The loads have been derived based on the experience of the authors with other projects. For each turbine, the tower section, starting at an elevation of 16m above still water level, has been kept constant, only the lower sections might have been changed slightly to allow for the connection with a bigger diameter monopile.

Soil conditions: Since the German offshore projects are mainly located in the North Sea (see Figure 1) a typical north sea location has been chosen for the study with respect to the soil conditions and general offshore environment. The soil that has been assumed corresponds to the situation that can be found at the location of the FINO-platform. The results of the soil survey together with soil parameters are published at [6].

Wave conditions: Extreme wave conditions always depend on the exact site, the predominant wind direction and fetch lengths etc. However, in order to have a basis for a comparison, an extreme wave height of H_{max}=20m with a related wave period of T_{rel}=16s has been chosen. Obviously, this value had to be corrected for the 10m sites due to wave breaking criteria. Here, the maximum wave height chosen was $H_{max,10m}$=12.8m.

For the evaluation of the fatigue limit state, fatigue wave loads have been considered based on a scatter diagram for the north sea that has been derived from measurement data at the FINO-platform, see [7]. For details on the fatigue assessment of support structures for offshore wind turbines please refer to [8] and [9].

Methodology

In the scope of this study a predesign of monopile support structures for the above-mentioned turbine types and conditions is required. In the course of the predesign of the different locations it is preferred to keep the tower section constant. Therefore, starting with the upper tower flange, only minor changes have been made, e.g. in order to connect the tower with a larger diameter foundation pile.

The first step in the predesign is always to meet the dynamic requirements, i.e. to design a structure with a fundamental frequency between 0.25 Hz and 0.35 Hz. For this parameter study, a target frequency of 0.28 Hz has been chosen.

In the second step, checks in the following limit states are performed:

- resistance against local buckling
- resistance against fatigue
- soil capacity using the "no-toe-kick"-criterion

The latter point, the fulfilment of the "no-toe-kick"-criterion, is the governing criterion for the penetration depth of the piles in most of the cases. The diameters and wall thicknesses have been adjusted to fit the assessments. A minimum D/t ratio of 100 has been considered, which often was the driver for the wall thickness.

Results

Figure 6 shows a summary of the results of the parameter study. As a first result, for all configurations it was possible to design a support structure with the required stiffness, i.e. with a fundamental frequency of about 0.28 Hz. Furthermore, it was also possible to find an equilibrium for the extreme load cases. In this context it has to be noted again that the bearing behaviour of laterally loaded piles in soil is almost unknown in the parameter ranges investigated here. In this regard, the results have to be used carefully. Also it has to be noted that up to now there is no equipment available to drive an 8m-pile with 100m length and a weight of almost 1800 tonnes into the soil. Nonetheless, these are important data points for a comparison of the different concepts.

The masses given in the table relate to the definition given in [1], Fig. 4.A.1. This means that the monopile covers both sub-structure and foundation.

	Water depth	[m]	3 MW			5 MW		
			10	**30**	**50**	**10**	**30**	**50**
1. natural frequency	w/ soil springs	[Hz]	0.30	0.28	0.28	0.28	0.28	0.27
	stiff	[Hz]	0.37	0.34	0.32	0.34	0.31	0.32
Masses	Support Structure *)	[t]	580	843	1362	665	1105	2026
	Sub-structure + foundation *)	[t]	382	640	1159	442	878	1792
Monopile Geometry	Penetration Depth	[m]	30	33	40	35	40	50
	Diameter	[m]	5	6	7	6	7.5	8
	Overall length	[m]	40	63	90	45	70	100

*) denomination acc. to [1], Fig. 4.A.1

Figure 6: Summary of the results of the parameter study

Design is mainly driven by dynamic requirements. This leads to an uneconomical use of the material, since the ultimate load bearing capacities are not utilized. It can be seen that the heavier top mass of the 5MW machine has a great negative impact on the material consumption for the support structure.

In order to be able to evaluate the results that have been determined in the parameter study these masses have to be compared to the alternatives. In [10] the results of a similar parameter study as has been done in this paper are presented. There, the masses for a tripod foundation for a 3MW and a 5MW turbine have been shown depending on the water depth. Figure 7 shows both the results of the previous section as well as the masses presented in [10].

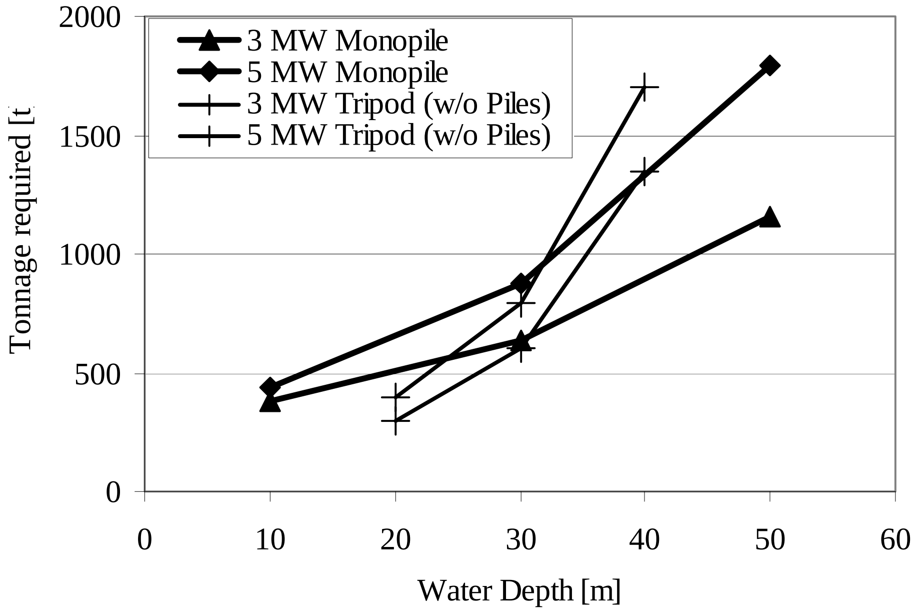

Figure 7: Monopile and Tripod masses for a 3 and 5 MW turbine in different water depths. Monopile masses from parameter study, tripod masses from [10]

The pile weights required for fixing the tripod structure on the sea floor are not included. In this sense, the diagram shows only the masses of the sub-structure of the tripod as defined in Fig 4.A.1 of

[1]. The monopile masses in Figure 7 include both the sub-structure and the foundation acc. to this definition. The required masses for the foundation piles of the tripods are typically in the range of 100 to 300 tonnes. Taking this into account, it can be seen that monopile and tripod designs yield comparable overall weights for sub- structure and foundation.

CONCLUSIONS AND OUTLOOK

The evaluation of different foundation concepts for OWECs is a complex, interdisciplinary task. In this paper some technical aspects regarding the comparison of tripods and jackets with the more or less well-known monopile concept have been investigated. For this purpose the investigation focused on boundary according to German sites in the North Sea. In a first step, the concepts have been compared qualitatively. The result was that given the soil conditions are acceptable and the required tools to install the rather heavy structures will be available on the market, the monopile is a competitive concept. To understand the technical difference between monopile and the lattice structures, some general mechanical considerations have been presented. In the following, a parameter study has been performed in order to get some realistic data regarding the required amount of steel for monopiles depending on the water depth. This yielded an opportunity to compare the results to a similar study on tripods in the literature.

To sum up, the answer to the initial question whether tripods or jackets can compete with monopiles depends on the individual case. The governing parameters in a site specific assessment are turbine size, water depths and soil conditions. However, in case both monopile and tripod or jacket are technically possible, the alternatives have to offer significant savings in weight in order to be competitive.

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