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Summary

The designs focus on three main aspects:

- Reduce the time spent transporting and installing offshore wind turbines
- Reduce cost for said phases
- Increase the likely hood for operation in rougher weather, effectively lengthening the weather window

This is achieved by reducing the time spent in all phases, while also allowing for transport and installation during rougher sea states. The invention covered in this document describes how this is to be done.

The calculations that has been undertaken and discussed in this document were:

- Initial Stability (GM)
- Heave, Pitch and Roll periods

From these results, weather windows for transport and installation have also been suggested.

Table of Contents

1. Introduction

Producing energy using wind turbines is a clean and renewable energy source. As the demands for energy gets higher, other methods of producing energy are needed than nuclear and the burning of fossil fuels.

A major issue for the development of wind farms offshore is the cost associated with transport, installation and maintenance. Therefore innovations and clever designs are needed to reduce these costs so that clean, and renewable, energy can be utilized more.

A design that does not only encompass regular designed offshore wind turbines, but also other designs (such as floating wind turbines), is in large demand to reduce costs of transport and installation of offshore wind turbines.

In this paper, new suggested designs are presented. The focus is on having the designs stable through each phase; assembly, transport and installation. In addition, the designs proposed reduce the environmental impact caused by other commonly used designs for transporting and installing offshore wind turbines, such as the legs of jack-ups when in contact with the sea bed.

By varying many parameters and, in so doing, providing insight in the designs presented will help in understanding how the design works and its relevant areas of use.

This document is a continuation of the idea presented by the author, André Myhre, to Prof. O. T. Gudmestad in early February 2011. The original description of the idea can be found in Appendix 2. It is possible that the idea should have been patented.

2. State of the Art for transport and installation of offshore wind turbines

The state of art is to use large vessels to transport and install wind turbines piece-by-piece. This is due to the large size of the wind turbine. The use of vessels such as jack-ups and heavy duty cranes makes for a costly, and time consuming, endeavor.

In case the wind turbine is assembled inshore and towed to the installation area, the largest constraining factor for the towing and installation is the weather. A window with calm weather is required for the towing, and the requirements are particularly restrictive during installation. If the weather is not sufficiently calm enough, the transport and installation cannot take place. Weather can therefore delay the transport and installation.

Furthermore, due to the weight of the generator house, blades and nacelle making the wind turbine ”top heavy” when assembled, the structures must have sufficient water plane area during the complete installation phase to be stable. This will restrict the geometry of the wind turbine and potentially make it large and costly.

Image 1: To the right; barge type installation of an offshore wind turbine. To the right; ship based installation of an offshore wind turbine [15].

Image 1 shows two examples of how an offshore wind turbine can be transported and installed. Largest constraining factor here is the calm weather window needed for installation. As is evident from Image 1, the barge/ship may become “top heavy” when lifting pieces into place and may capsize if the weather and sea state are too rough.

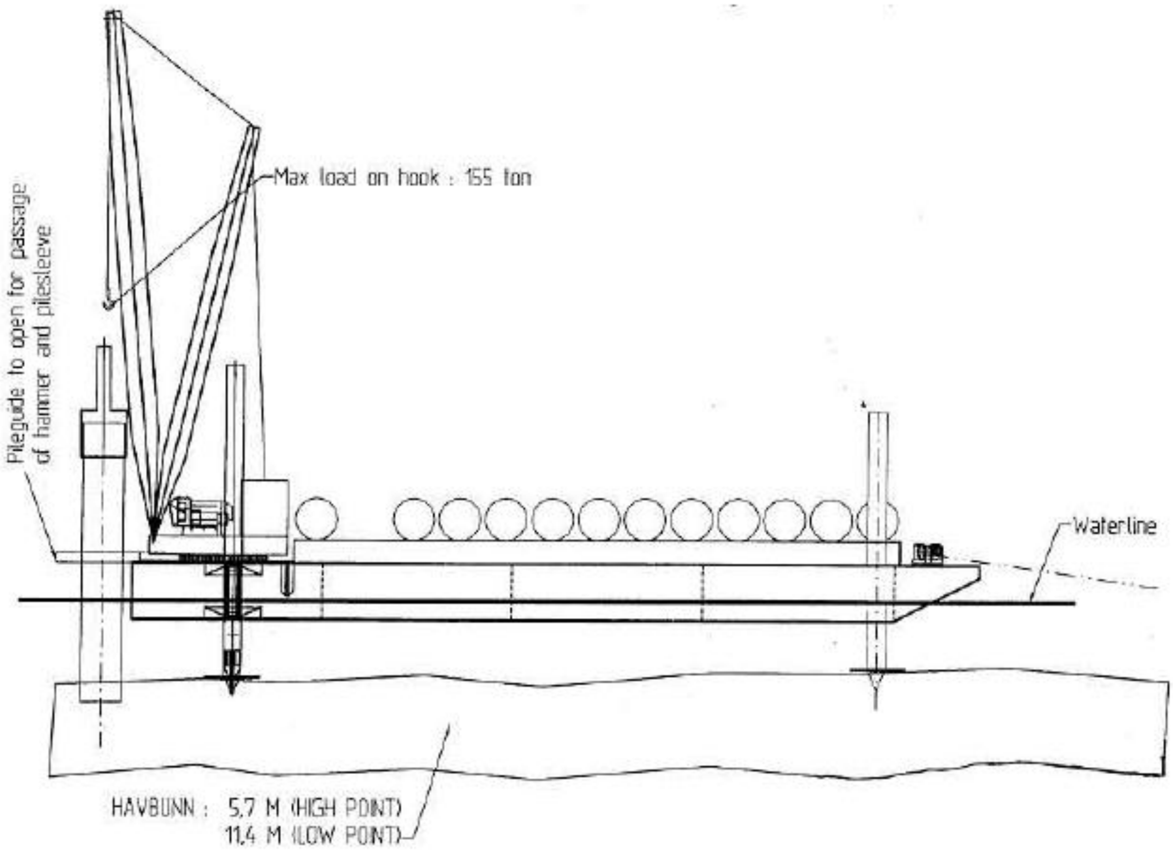


Image 2: Barge type vessel used in the installation of the Horns Rev wind farm offshore Denmark [15].

Image 2 shows a barge type vessel used for installation of the Horns Rev wind farm offshore Denmark [15]. As well as having complications mentioned earlier, barge type and jack ups can leave large footprints in softer soil [15], and given that the term “wind farm” entails more than one wind turbine to be installed, constantly needing to anchor and deanchor from the sea bed, the time spent actually installing is reduced.

2.1 Special adaptations/solutions

There are ways to reduce the center of gravity in the vertical axis and also to center it more in the cylinder (tower) to increase stability during different phases.

2.1.1 Retractable (telescopic) tower

To reduce the center of gravity in the vertical axis, a retractable tower can be utilized.

Image 3: Fully assembled wind turbine settled on a foundation offshore with pontoon connected, with a telescopic joint [15].

After being installed at its offshore site, the wind turbine proceeds to extend its telescopic joint, as shown in Image 4.

Image 4: Fully assembled wind turbine fully installed offshore [15].

2.1.2 Turning the generator house in combination with a telescopic joint, with blades attached

To further increase stability, the generator house can be turned as shown in Image 5 below:

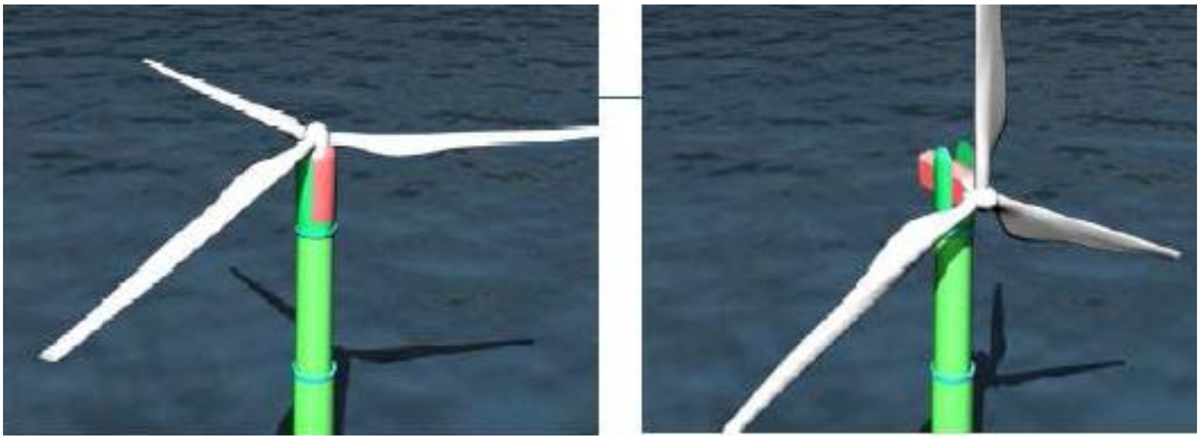


Image 5: A wind turbine with rotated generator house to further increase stability [15].

The solutions proposed in chapters 2.1.1, 2.1.2 and other special solutions can be used in combination with the design proposed in this document to further the stability of the invention.

3. Models

Image 6 shows a cross-sectional area for a new assembly of wind turbines at the waterline as viewed from above, with associated annotations for calculations. The center circle is the middle structure with a pontoon as the outer circle. The outer circles are the wind-turbines with pontoons.

Image 7 shows a side view of one wind turbine of the invention, excluding the middle structure.

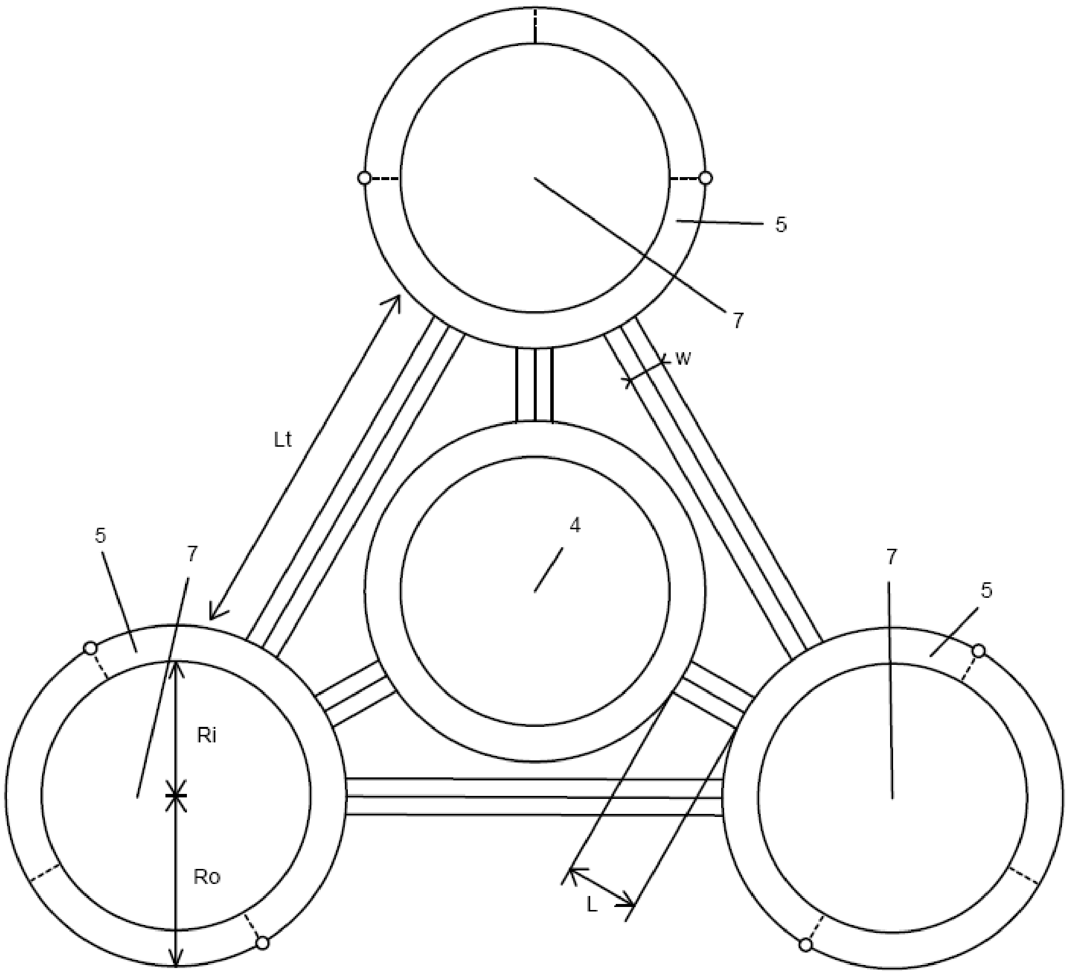


Image 6: Cross-section of the structure at sea level during tow to the offshore site.

Inner rings of the three corner structures are wind turbines (7), and outer rings are pontoons (5). The middle ring is the middle structure (4), which connects the wind turbines with each other and themselves.

Explanation of Image 6:

L: *Leg length (between a pontoon around a wind turbine and the middle structure)*

R_i: *Inner Radius of the Pontoon*

R_o: *Outer Radius of the Pontoon*

L_t: *Length of the span between each wind turbine*

w: *Width of the connecting truss or box system between the outer pontoons*

Furthermore:

$$Outer\ Diameter, OD = 2 \cdot R_o$$

$$Inner\ Diameter, ID = 2 \cdot R_i$$

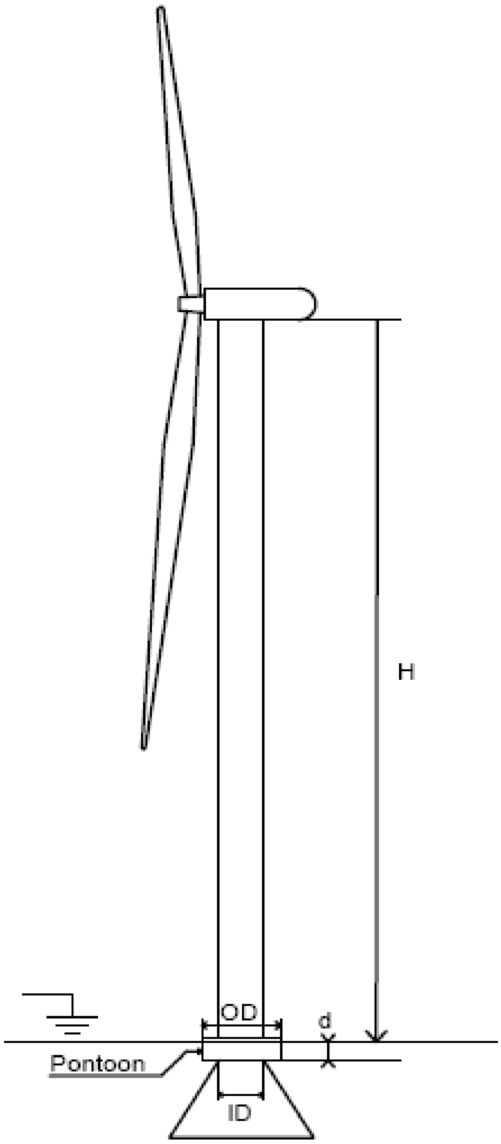


Image 7: Sideview of the invention with annotations. Wind turbine and pontoon only.

Explanation of Image 7:

$$H: Height\ from\ sea\ level\ to\ the\ nacelle$$

$$OD: Outer\ Diamater\ of\ the\ pontoon$$

$$ID: Inner\ Diameter\ of\ the\ pontoon$$

$$d: Draft\ of\ the\ pontoon$$

Image 8 below shows the whole structure with wind turbines connected. The drawing is in an approximate scale and displays a possible design for the invention. As is evident, space might be insufficient between each wind-turbine and the middle structure, even though the invention may be stable in the displayed design. For more breathing room, it is suggested to increase the leg length between the middle structure and the wind turbines to lower the chances of anything colliding with each other.

The rotor blades shall be placed such that they will not interact with rotor blades from another wind turbine connected, and locked during transport and installation. The leg length between a wind turbine and the middle structure may be influenced by the rotor diameter, as the blades of one wind turbine shall not interact with the blades of another wind turbine connected.

A close up of the area closer to sea level is shown in Image 9.

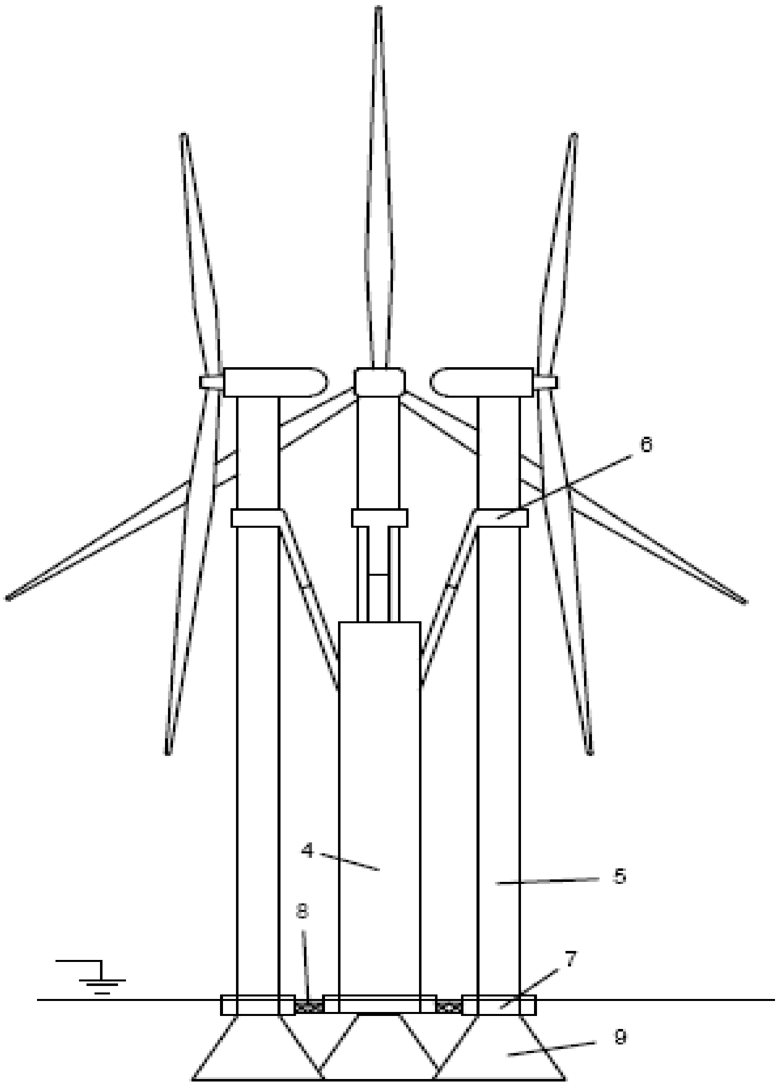


Image 8: Suggestion for a design of the invention in an approximate scale. The model is influenced by the wind turbines at the Thornton Bank in the Belgian part of the North-Sea [6].

Three wind turbines (5) are connected to the middle structure (4) by hydraulic arms (6) above sea level, and a truss/box system (8) below sea level. Foundations (9) are included in the tow out.

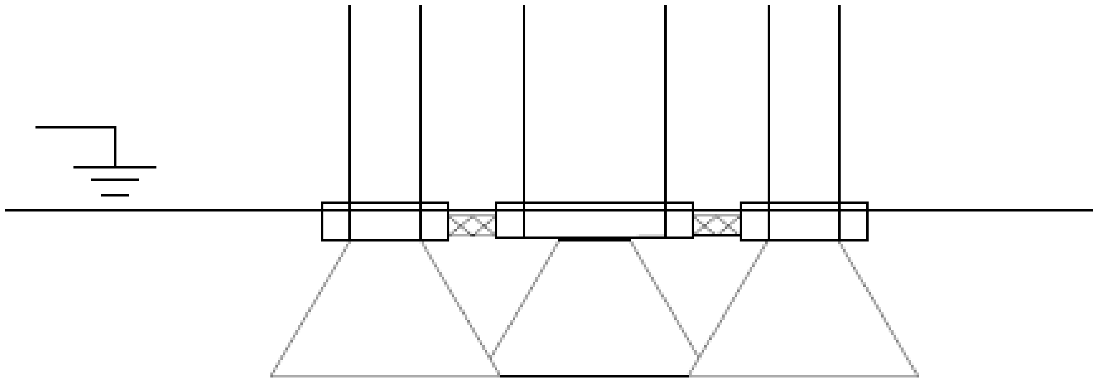


Image 9: Close up of the suggested design of the invention, at sea level.

4. Design Basis

The conditions in the North Sea will be the design basis for the invention. Typical and extreme situations during tow out and installation will be taken into consideration.

Typical installation and tow out conditions include the average weather and sea states which are common in the North Sea. Extreme conditions include storms, high and long waves and harsh wind conditions.

The data proposed in this document are an adaption from the data used for the wind turbines at the Horns Rev wind farm off shore from Denmark [16]. The data is presented in the table below:

Rotor Diameter	180m
Hub Height	160m
Weight, blade	10 tonnes
Weight, nacelle	90 tonnes
Weight, tower	180 tonnes
Weight, foundation	220 tonnes
Total weight per wind turbine	500 tonnes

Table 1: Weights of different parts of a wind turbine, including some dimensions, used in this document.

The Rotor Diameter and Hub Height displayed in Table 1 may be slightly exaggerated; however, the calculations of initial stability uses set values for the center of gravity vertically to show stability for different centers of gravity.

The center of gravity is taken as the middle of the wind turbine tower in the horizontal cross-section (see image 6).

Furthermore, the legs are not included in calculations pertaining to moments of inertia (with respect to area), weight or buoyancy. Only the distance is used in calculations.

5. Strength and Durability

Calculations must be undertaken to understand the impact of the weather on the structure.

A specific area of concern is the legs connecting the pontoons with each other. These shall be constructed to endure wave forces impacting the structure. To lessen the impact of waves on the spans between the pontoons, the spans will be submerged in the water during transport.

As each wind turbine gets disconnected during installation, there will not be much draft in the pontoon it is released from. This may cause large forces if the connection spans between the pontoons are rigid. Ballast water should be dynamically added during the installation process to ease these forces.

6. Stability

One of the major advantages of the aforementioned models is that the transport becomes a lot more stable than if the wind turbines were to be transported individually using current state of the art [15].

When assembled, the weight should be equally distributed for stability and strength purposes. However, this gives rise to the problem of installing, as the procedure is to install one wind turbine at a time. To remedy this, there are ballast tanks in the pontoons supporting the wind turbines. These can be adjusted dynamically to compensate for the weight loss of unlocking a wind turbine for installation.

6.1 Initial Stability

The biggest factor of initial stability is the parameter BM in the equation [9]

$$GM = BM + KB - KG,$$

which can be found by calculating [9]

$$BM = \frac{I}{V},$$

where

$$I: Moment\ of\ Inertia$$

$$V: Volume\ of\ displaced\ water$$

One benefit of the invention is the area it is spread over. With the length of the legs, L, adding to the distance between the structure in the middle and the outer pontoons, the moment of inertia is increase due to the added part in the equation for moment of inertia, as per Steiner's Theorem [11]

$$I = I_x + A \cdot d^2,$$

where the added part is the $A \cdot d^2$, where A is the area at a distance perpendicular to a given axis, d, to its epicenter.

Basis for calculations of initial stability is given in Images 6-13, with varying parameters as shown in figures 1-9, with reference to [2], [3], [4], [8], [9], [12] and data from Appendix 1.

6.1.1 Moment of Inertia of the invention in different phases

When all wind turbines are connected, the axis that is used to calculate the initial stability is shown in Image 10 below.

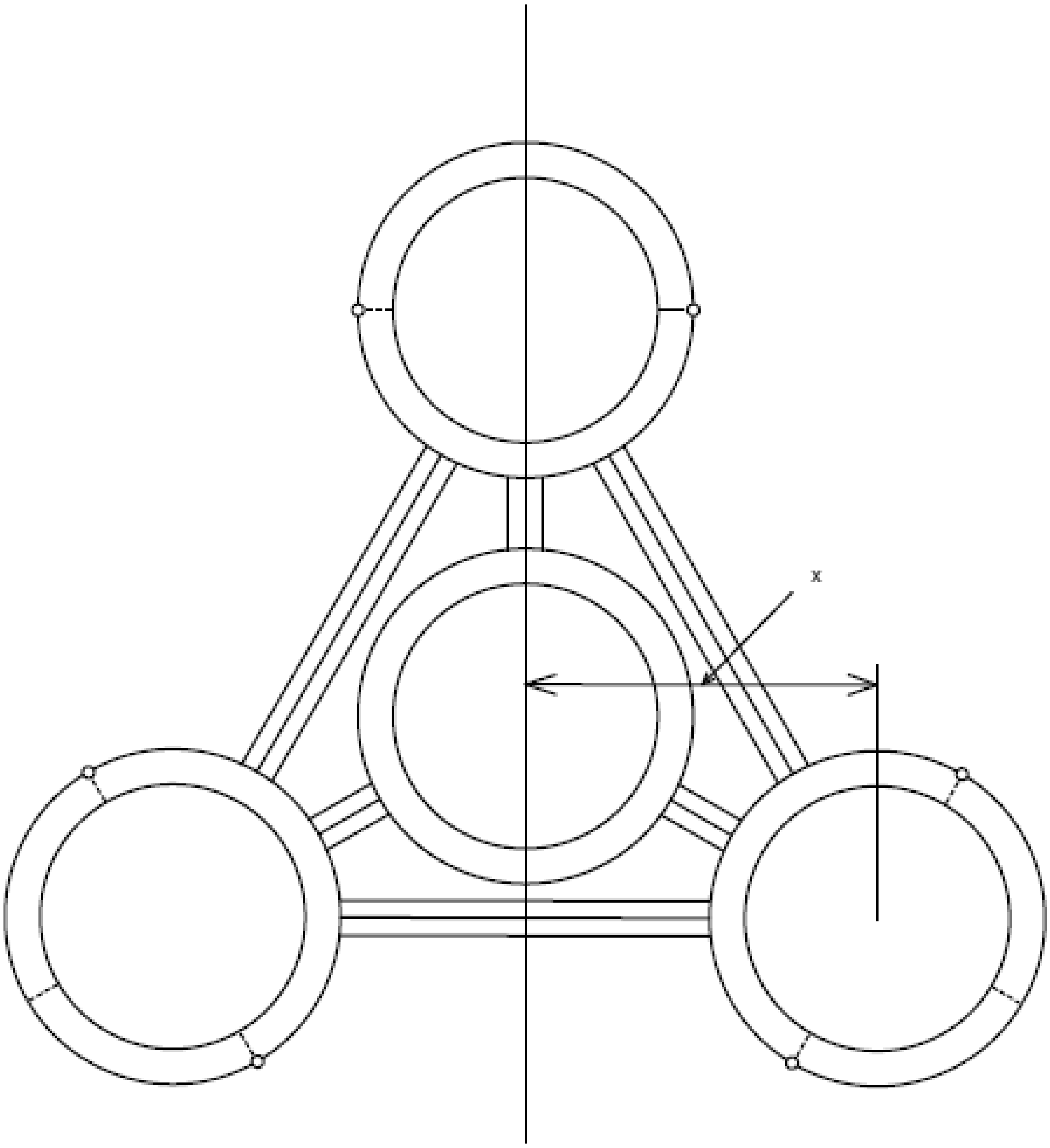


Image 10: Cross-sectional view of the invention at sea level, with axis and a distance x annotated. Basis for calculation of initial stability when 3 wind turbines are connected.

In the case where 3 wind turbines are connected, the formula for moment of inertia becomes

$$I = 2 \cdot \frac{\pi \cdot OD^4}{64} + 2 \cdot \left(\frac{\pi \cdot OD^4}{64} + \pi \cdot R_o^2 \cdot x^2\right)$$

When one wind turbine is released and there are only two wind turbines connected, the formula will change. Image 11 below shows the new axis used for calculation of initial stability when only 2 wind turbines are connected.

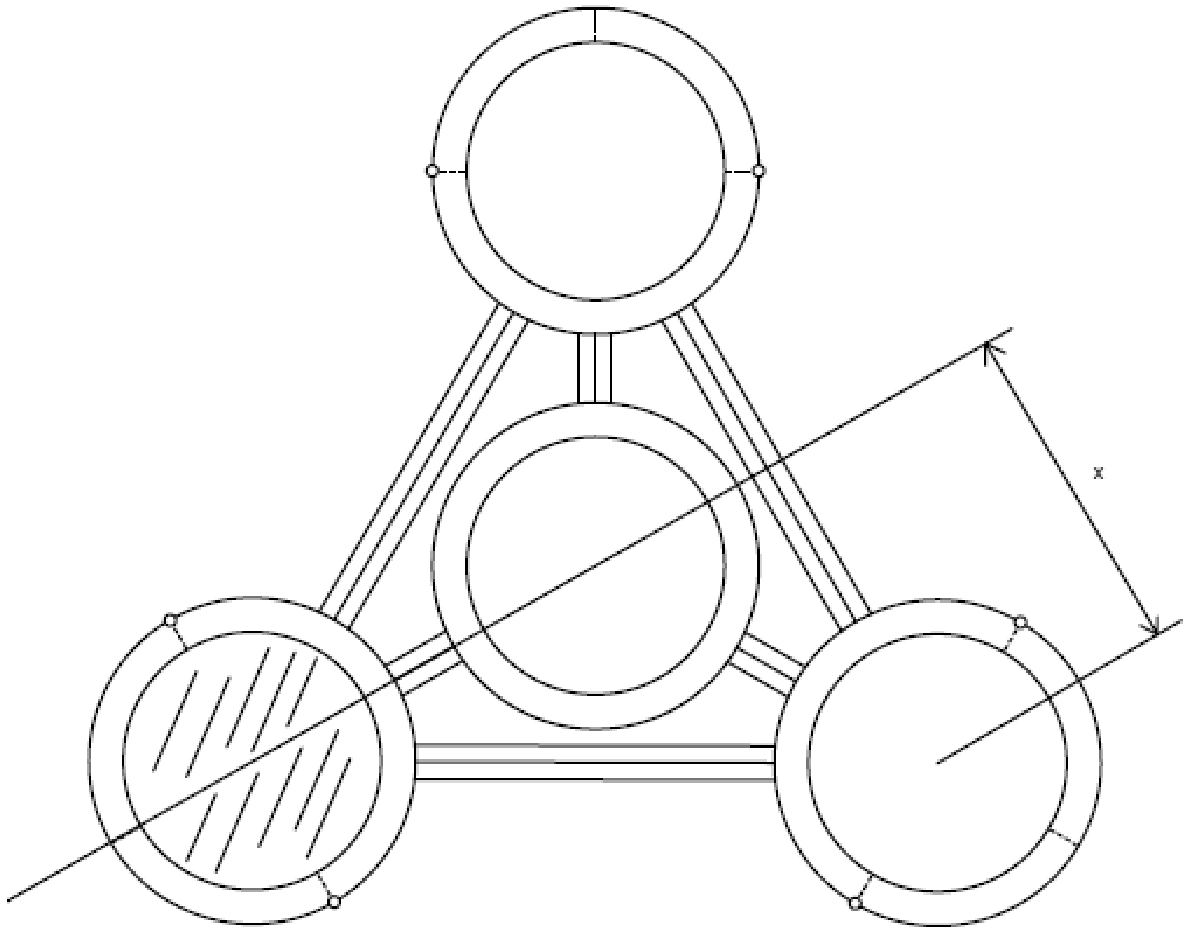


Image 11: Cross-sectional area of the invention at sea level, showing where one wind turbine has been disconnected (striped area), and the new axis used in calculation of initial stability. Distance x is drawn in as the distance between the central axis and to the epicenter of a connected wind turbine, including pontoon.

In the case displayed in Image 11, the formula for the moment of inertia becomes

$$I = \frac{\pi \cdot OD^4}{64} + \frac{\pi \cdot (OD^4 - ID^4)}{64} + 2 \cdot (\frac{\pi \cdot OD^4}{64} + \pi \cdot R_o^2 \cdot x^2)$$

When one more wind turbine is disconnected, there is only one wind turbine still connected. Image 12 below shows the new axis and the distance x used in calculation of initial stability when only one wind turbine is connected.

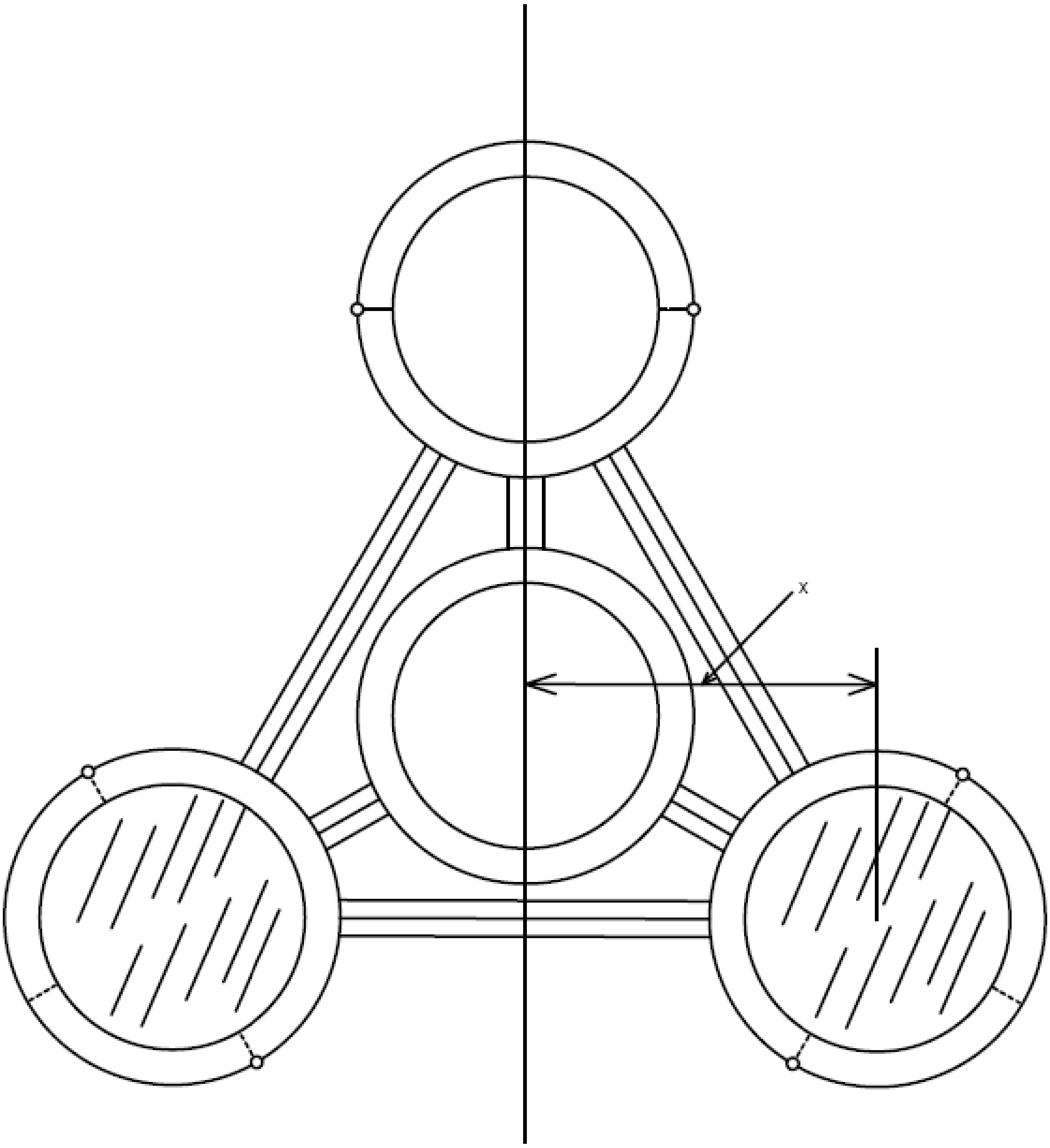


Image 12: Cross-sectional area of the invention at sea level, with only one wind turbine connected. The striped areas are empty spaces where a wind turbine has been disconnected. The axis for calculation of initial stability when one wind turbine is connected is shown, along with the distance x.

In the case when only one wind turbine is connected, as shown in Image 12, the formula for the moment of inertia becomes

$$I = 2 \cdot \frac{\pi \cdot OD^4}{64} + 2 \cdot (\frac{\pi \cdot (OD^4 - ID^4)}{64} + \pi \cdot (R_o^2 - R_i^2) \cdot x^2)$$

For the case of no wind turbines connected, the axis used for calculation of initial stability is the same as the ones in Image 10 and Image 12, aswell as the distance x. The formula for the moment of inertia then becomes

$$I = \frac{\pi \cdot OD^4}{64} + \frac{\pi \cdot (OD^4 - ID^4)}{64} + 2 \cdot (\frac{\pi \cdot (OD^4 - ID^4)}{64} + \pi \cdot (R_o^2 - R_i^2) \cdot x^2)$$

There are two more cases where the two axes, as shown in Image 13, can be initially less stable than the others from Images 11 and 12.

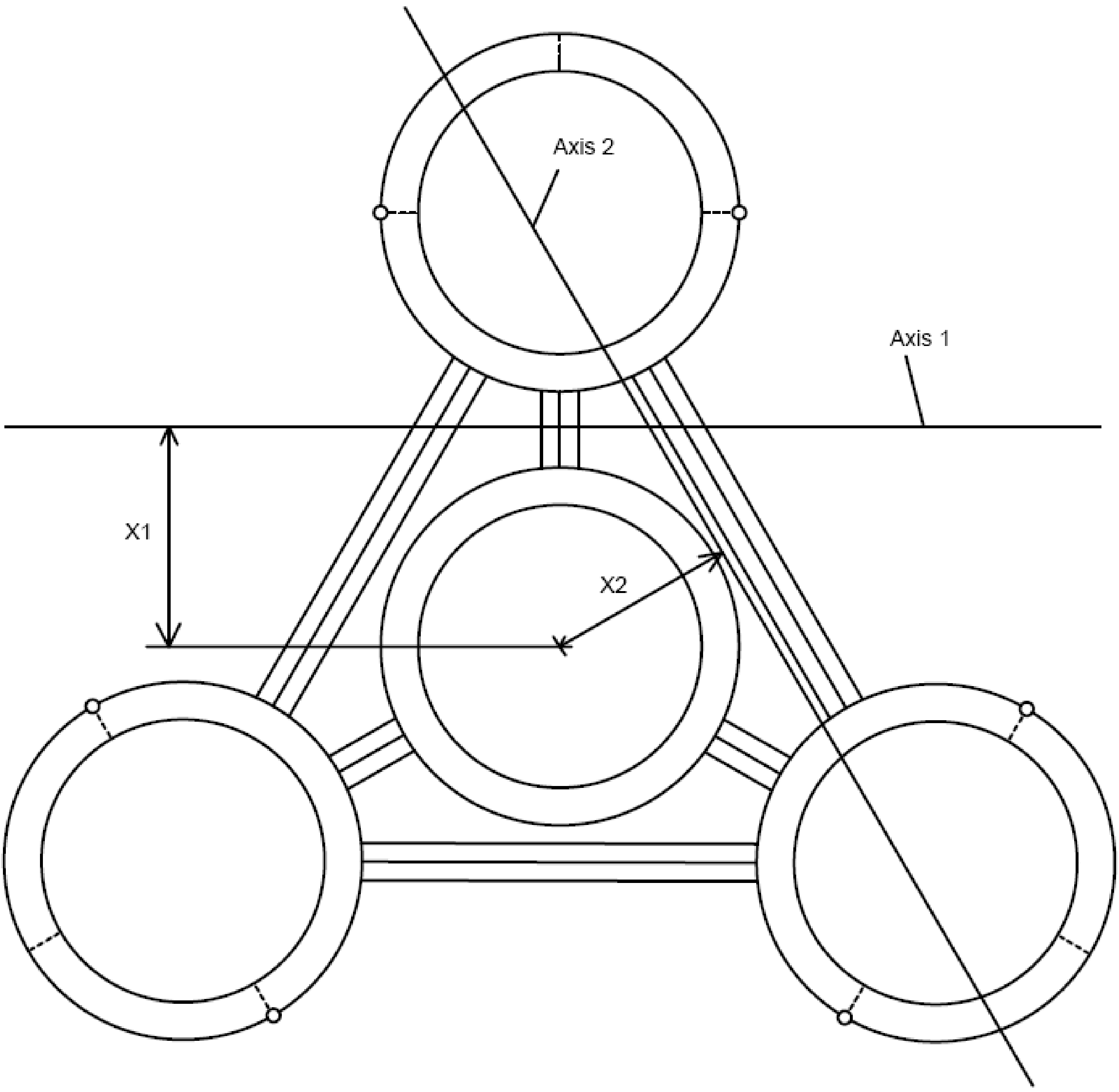


Image 13: Cross-sectional area of the invention at sea level. Two axis for calculation of initial stability is drawn in. Axis 1 is perpendicular to the axis shown in Image 12 while Axis 2 is perpendicular to the axis shown in Image 11.

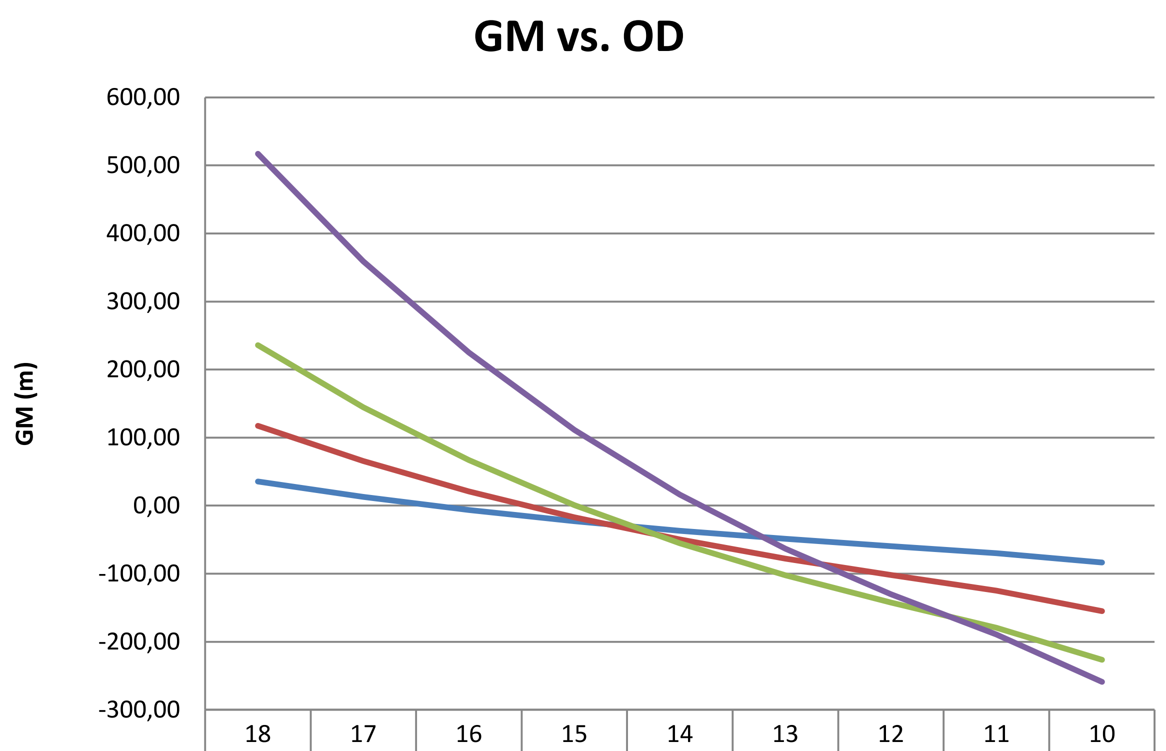
The distances X1 and X2 can be found by the formulas shown in chapter 13.1 (Appendix 1). All values are given in chapter 13 (Appendix 1) for every situation displayed in chapter 6.1.1.

6.1.2 Varying the outer diameter (OD)

By varying the outer diameter, OD (see Image 7), of the pontoons supporting the structures, different results emerge.

Figure 1 below shows how the GM varies with the change in outer diameter, OD, of the pontoons.

With a leg length, L (see Image 6), of 6 meters, weight of one complete wind turbine at 500 tonnes and the center of gravity for a complete wind turbine at 110 meters above sea level, the results are as shown in figure1 below



	18	17	16	15	14	13	12	11	10
0 Turbines	281,19	214,46	157,95	110,57	71,27	38,98	12,53	-9,72	-32,59
1 Turbine	118,44	79,21	45,96	18,02	-5,24	-24,50	-40,56	-54,71	-71,45
2 Turbines	82,06	52,51	27,10	5,38	-13,11	-28,86	-42,48	-55,13	-71,15
3 Turbines	35,37	13,01	-6,23	-22,72	-36,80	-48,87	-59,48	-69,68	-83,74

Figure 1: GM in meters versus outer diameter (OD) of the pontoons, in meters. Leg length, L (see Image 6), of 6 meters, weight of one wind turbine at 500 tonnes, middle structure (see Image 6 and Image 8) at 400 tonnes, and a center of gravity at 110 meters above sea level.

This figure shows that

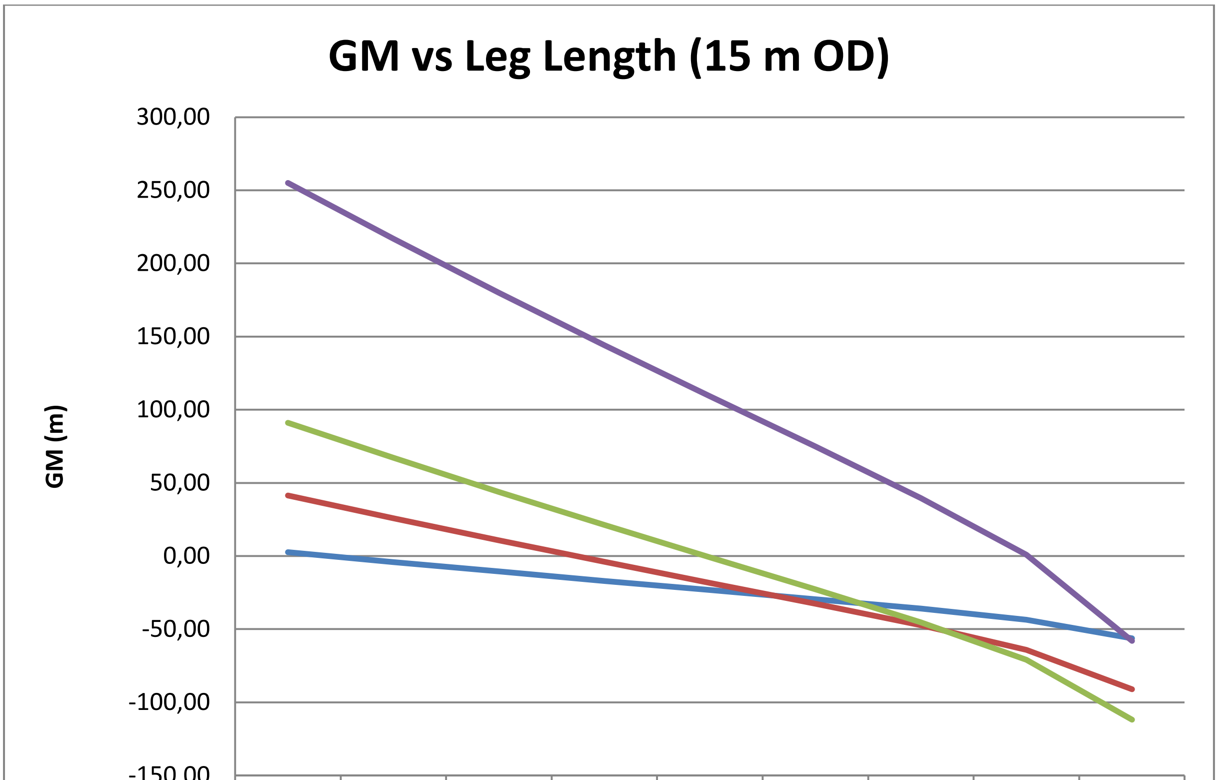
- The tow with 3 wind turbines connected is the most critical
- The OD must be larger than 16.5 meters in case of a leg length of 6 meters
- For and OD e. g. 16 meters, the leg length must be increased

6.1.3 Varying the leg length, L

By varying the leg length, L (see image 6), connecting the pontoons, the result will be different.

Figure 2 below shows how the GM varies with the change in leg length, L.

Selecting an OD (see Image 7) of a pontoon at 15 meters and all other parameters as previous, we get:

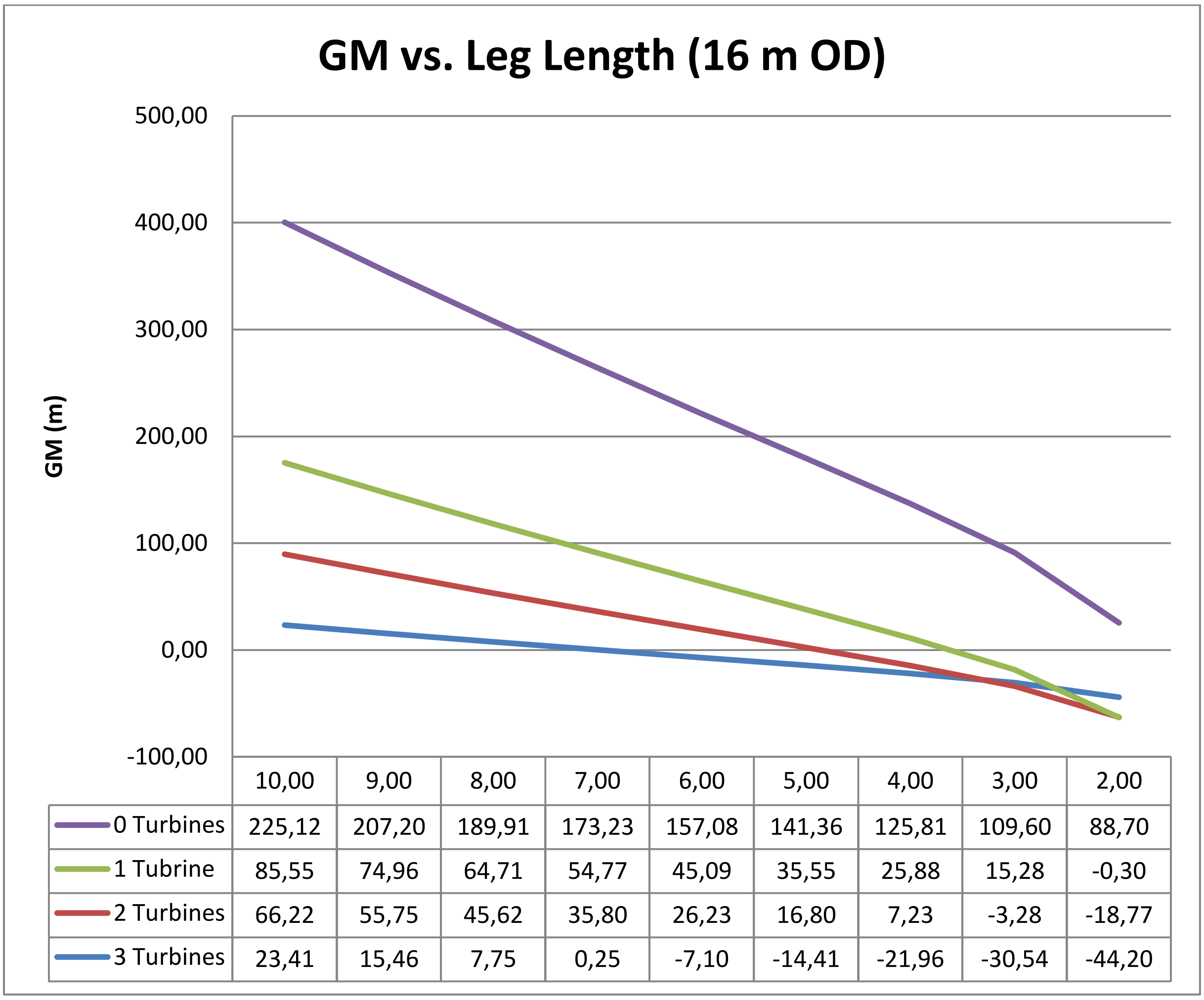


	10,00	9,00	8,00	7,00	6,00	5,00	4,00	3,00	2,00
0 Turbines	164,00	149,79	136,09	122,87	110,06	97,57	85,10	71,87	53,82
1 Turbine	49,70	41,28	33,14	25,23	17,51	9,86	2,01	-6,85	-20,76
2 Turbines	38,76	29,89	21,31	12,98	4,87	-3,16	-11,38	-20,58	-34,82
3 Turbines	2,68	-4,06	-10,60	-16,97	-23,23	-29,48	-36,00	-43,60	-56,32

Figure 2: GM in meters versus leg length, L, in meters. Outer diameter, OD, set at 15 meters, weight of wind turbines at 500 tonnes and center of gravity at 110 meters above sea level.

This figure shows that for an OD of 15 meters, the leg length must be 10 meters or more to be stable.

Figure 3 below shows how GM varies with leg length, however with an outer diameter, OD, of 16 meters.



	10,00	9,00	8,00	7,00	6,00	5,00	4,00	3,00	2,00
0 Turbines	225,12	207,20	189,91	173,23	157,08	141,36	125,81	109,60	88,70
1 Tubrine	85,55	74,96	64,71	54,77	45,09	35,55	25,88	15,28	-0,30
2 Turbines	66,22	55,75	45,62	35,80	26,23	16,80	7,23	-3,28	-18,77
3 Turbines	23,41	15,46	7,75	0,25	-7,10	-14,41	-21,96	-30,54	-44,20

Figure 3: GM in meters versus leg length, L, with 16 meter OD compared to an OD of 15 meters. Wind turbine weight of at 500 tonnes and center of gravity at 110 meters above sea level.

This figure shows that stability is obtained with and OD of 16 meters in the case of leg length of more than 7 meters.

6.1.4 Varying the weight of the wind-turbines

Figure 4 below shows how GM varies with the change in turbine weight.

Leg length, L, of 6 meters, OD of 16 meters and no change in center of gravity for any structure, we get:

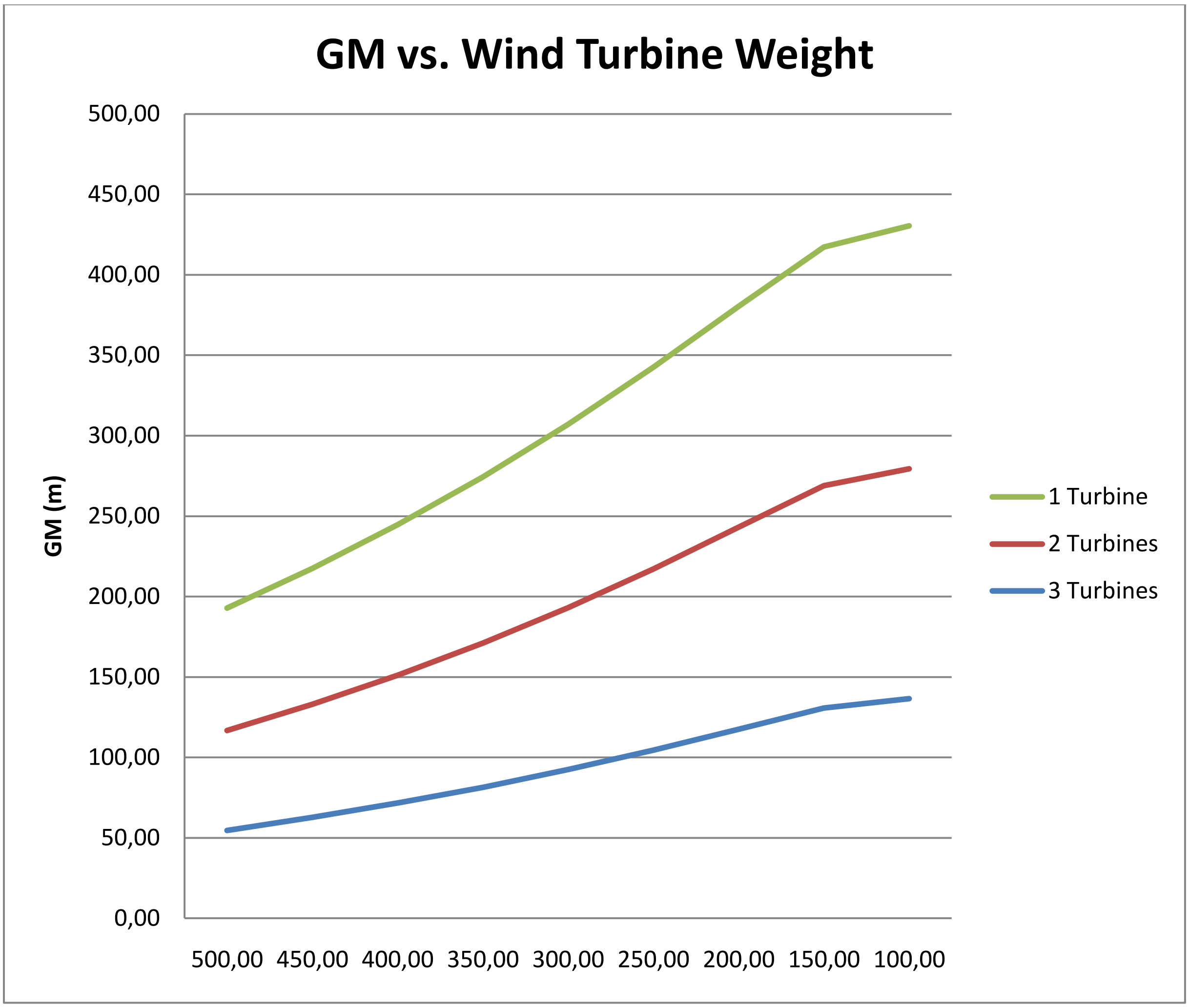


Figure 4: GM in meters versus wind turbine weight in tonnes. Leg length of 6 meters, outer diameter of the pontoons at 16 meters and a center of gravity at 110 meters above sea level.

This figure shows that the invention is stable for weights up to 500 tonnes of a complete turbine.

6.1.5 Varying the center of gravity of the wind turbines

In Figure 5 below, the center of gravity for the connected wind turbines vary. This shows where the structure becomes unstable and also where it is stable.

With a leg length, L, of 6 meters, weight of one wind turbine at 500 tonnes, middle structure weight at 400 tonnes and an OD at 16 for the pontoons, we get:

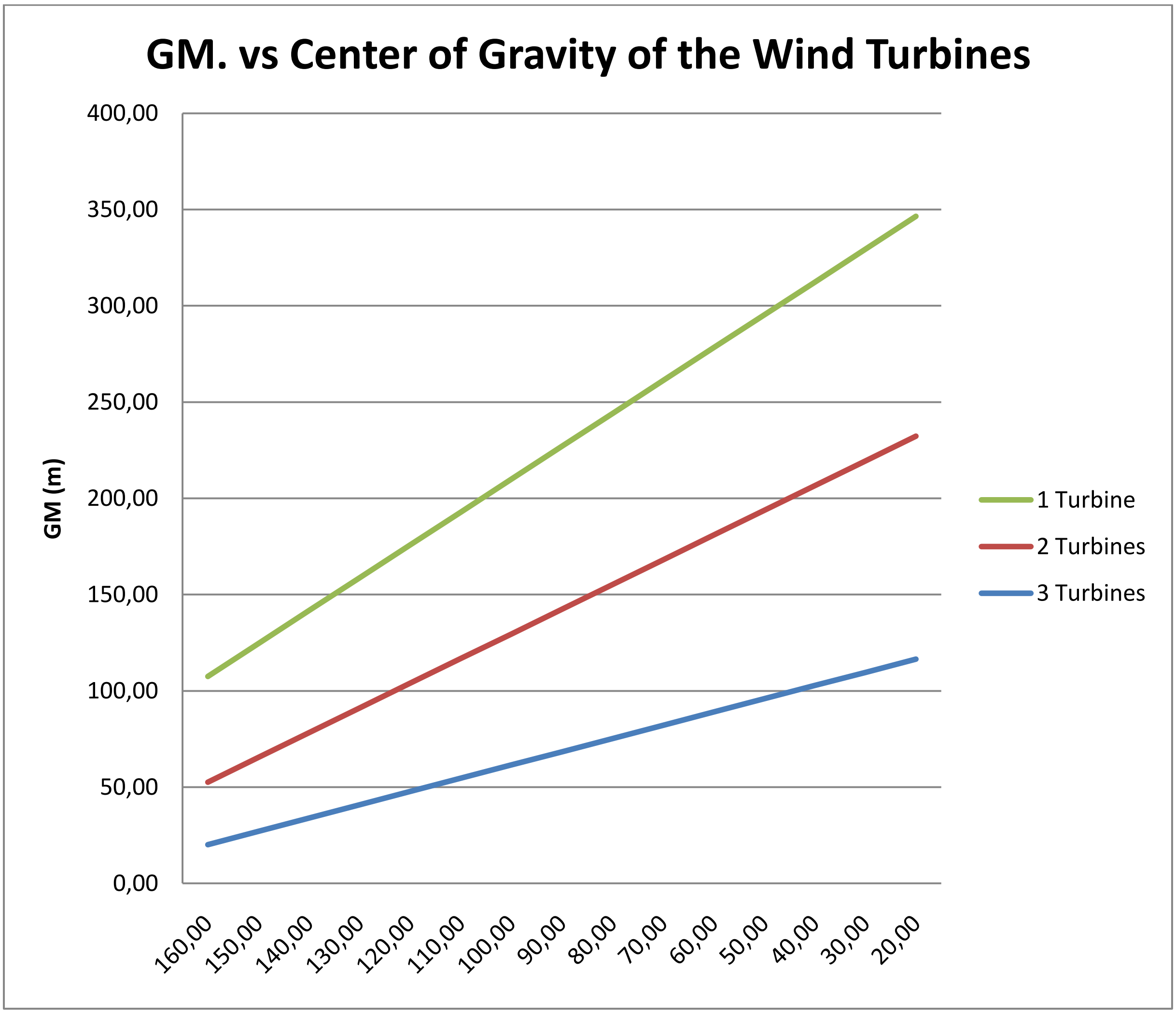
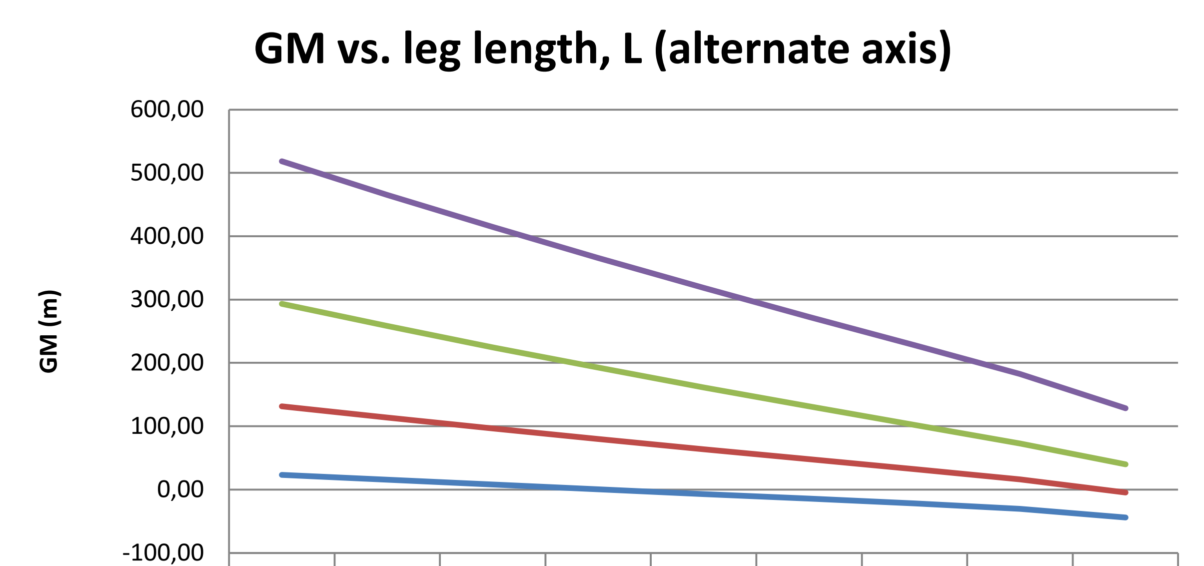


Figure 5: The change in GM in meters, as the center of gravity for the wind turbines vary (horizontal axis). Leg length, L, at 6 meters, wind turbine weight at 500 tonnes, middle structure weight at 400 tonnes and an OD of the pontoons at 16 meters.

This figure shows that the invention is stable for high elevations of the center of gravity; however, the scenario where the center of gravity is at the maximum height of the wind turbines is not realistic i.e. here 160 meters.

6.1.6 Calculation of GM with respect to the axis shown in image 12, varying leg length, L



	10,00	9,00	8,00	7,00	6,00	5,00	4,00	3,00	2,00
0 Turbines	225,12	207,20	189,91	173,23	157,08	141,36	125,81	109,60	88,70
1 Turbine	161,64	144,63	128,29	112,61	97,60	83,26	69,59	56,58	44,24
2 Turbines	108,15	98,22	88,68	79,53	70,77	62,40	54,42	46,83	39,63
3 Turbines	23,41	15,46	7,75	0,25	-7,10	-14,41	-21,96	-30,54	-44,20

Figure 6: Value of GM when varying the leg length, L. Here, the axis for 1 and 2 wind turbines connected are the ones shown in image 13 – Axis 1 is for 2 wind turbines connected, while Axis 2 is for 1 wind turbine connected.

Figure 6 shows results of calculations of GM while varying the leg length, L. However, for the curves annotated “1 Turbine” and “2 Turbines”, the axis taken into account are Axis 1 and Axis 2 (image 13) respectively.

6.1.7 Comparison: What if a wind turbine was to be supported entirely by itself?

Figure 7 below shows how GM changes when the outer diameter varies, however, for a single wind turbine alone.

Figure 8 below shows the same as Figure 7, however, the center of gravity is instead reduced to 10 meters above sea level.

Figure 9 below shows the same as Figure 7, however, with large changes in outer diameter.

With no change in center of gravity or weight, we get:

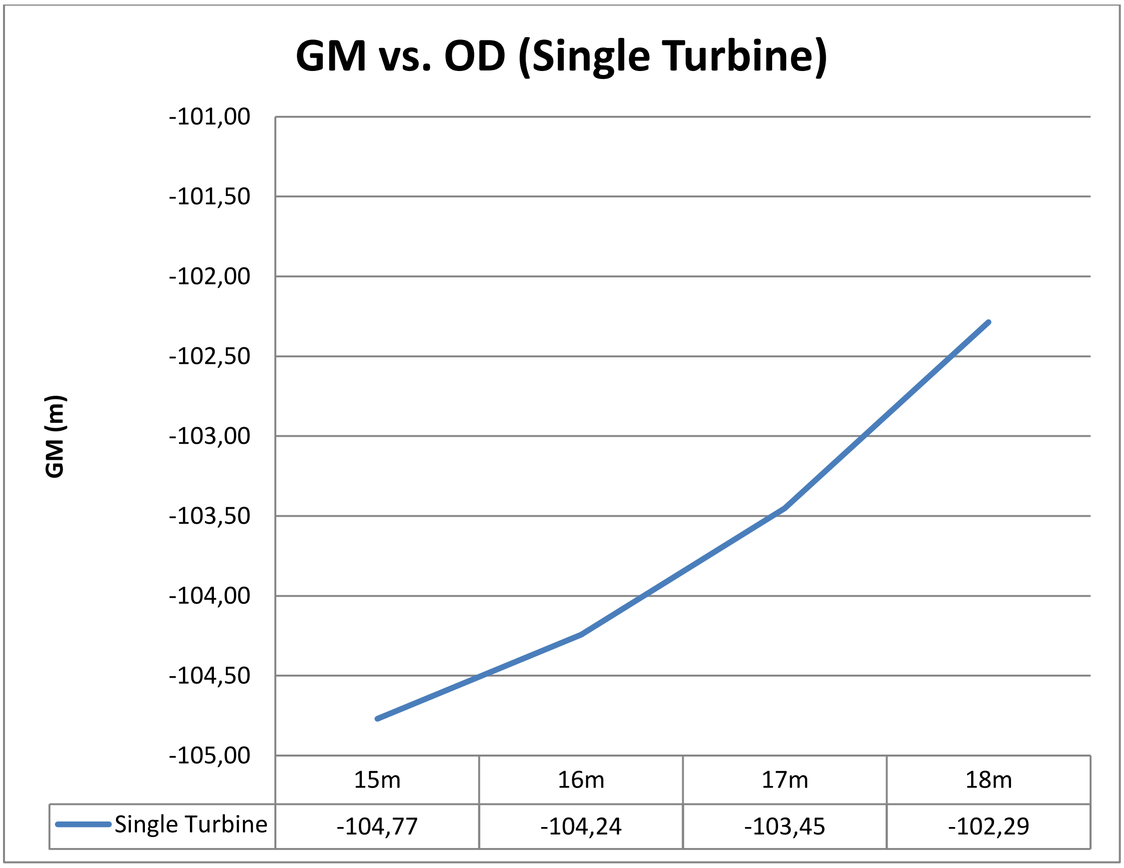


Figure 7: GM in meters versus outer diameter, in meters. With a center of gravity at 110 meters above sea level and a weight of 500 tonnes.

By comparison, if the center of gravity is reduced to only 10 meters, compared to 110 meters, the GM is given in Figure 8:

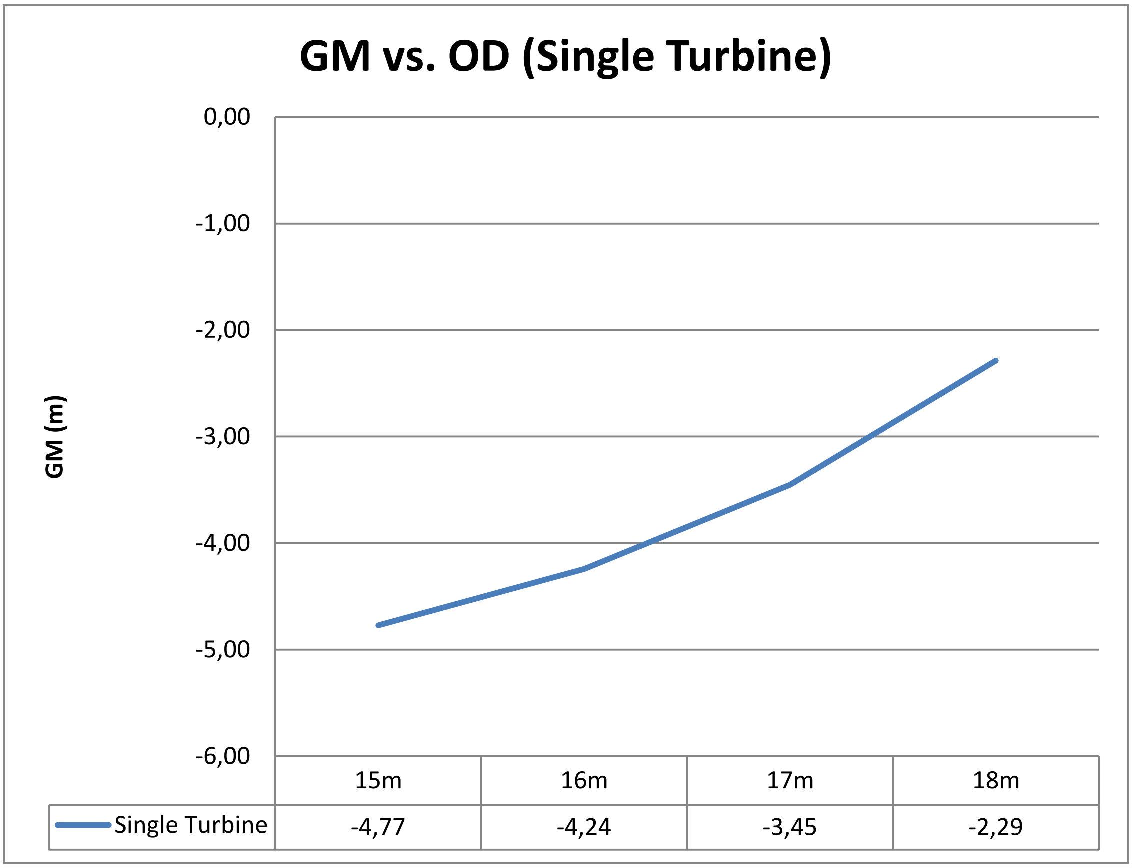


Figure 8: GM in meters versus outer diameter, in meters. With a center of gravity at 10 meters above sea level and a weight of 500 tonnes.

By increasing the OD significantly, the single cylinder tow can become stable (weight of 500t and center of gravity at 110m):

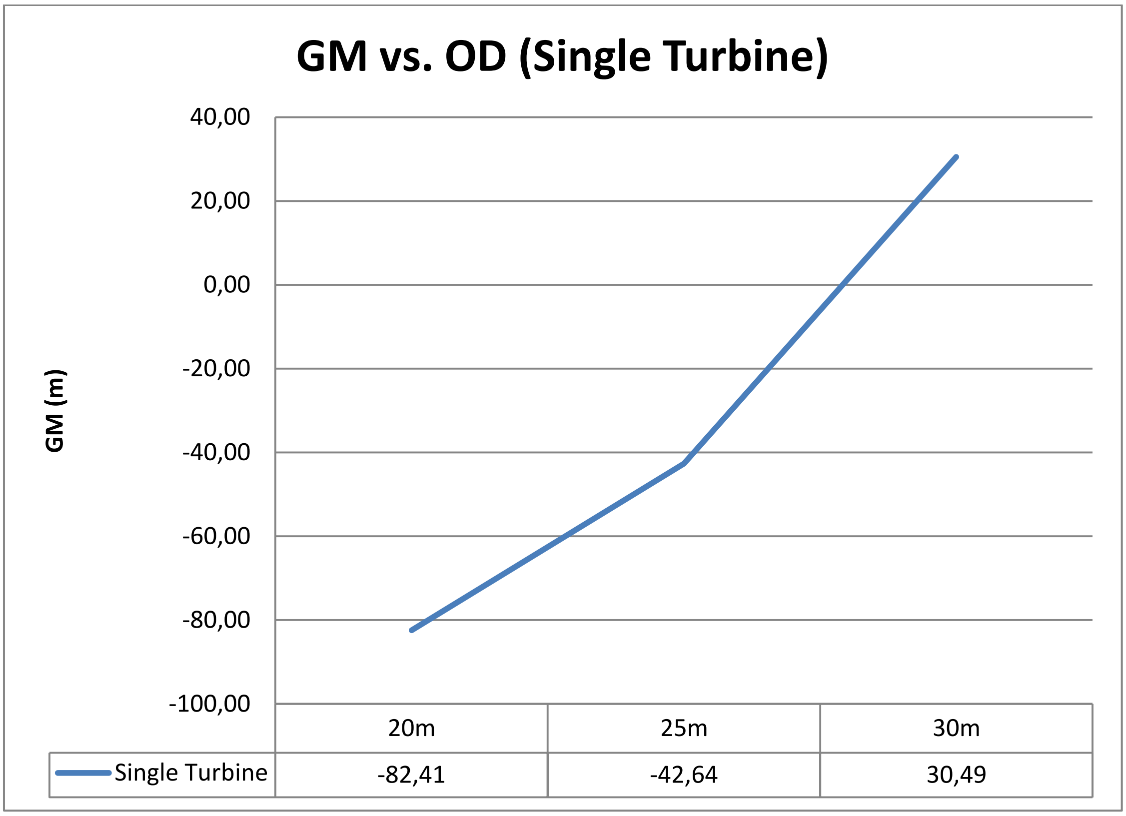


Figure 9: GM in meters versus outer diameter, in meters, of a single wind turbine. Weight of the total wind turbine at 500 tonnes and a center of gravity at 110 meters above sea level.

6.1.8 Discussion of results

As is evident from the results of Figures 1-9, the invention is stable enough with the parameters:

- Outer Diameter - 16 meters
- Leg Length - 8 meters
- Middle Structure Weight - 400 tonnes
- Wind Turbine Weight - 500 tonnes
- Center of Gravity of a Wind Turbine - 110 meters
- Center of Gravity of Middle Structure - 50 meters

Figures 1-9 also show the sensitivity of the GM when varying different parameters. For example, varying the outer diameter of the pontoons by only 1 meter changes stability greatly; even more so than varying the leg length between the center structure and the wind turbine structures.

The results also vary with the position of the center of gravity for the combined structure, however, with the design of the invention as shown in Image 6 and Image 7, this parameter does not affect the stability as severely as it would with a stand-alone design. This is because the distance between the middle structure and the wind turbines makes it a very stable design, effectively increasing the width and therefore increasing the stability value, BM, significantly compared to a design without these distances. However, the center of gravity can affect other factors other than stability, such as roll period etc.

7. Heave, Pitch and Roll

Knowing the Heave, Pitch and Roll periods of the invention is essential for avoiding dynamics during tow and installation. As wave spectra have a specific peak period at different measured significant wave heights, it is very important to know Heave, Pitch and Roll. Knowing these values, a weather window can be suggested for operations i.e. for the transport and installation phases. Image 14 below shows the axis for the different motions/degrees of freedom [8].

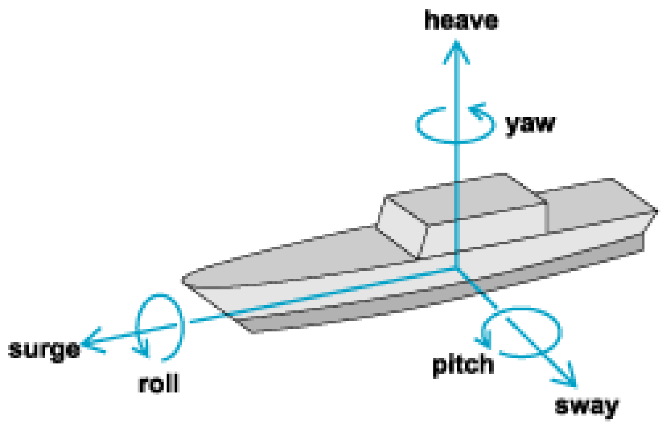


Image 14: Annotations on the different degrees of freedom for a vessel, with reference to [8].

Selected parameters for calculation of Heave, Pitch and Roll are:

Turbine Weight	500,00	tonnes
Turbine Waterplane Area	63,62	m^2
Pontoon Waterplane Area	137,44	m^2
Pontoon Outer Diameter	16,00	m
Leg length	8,00	m
Middle structure weight	400,00	tonnes
Middle structure waterplane area	63,62	m^2

With above parameters, the moment of inertia in each phase is		
Moment of Inertia (no wind turbine connected)	130653,98	m^4
For one wind turbine connected	130976,04	m^4
For two wind turbines connected	186263,41	m^4
For three wind turbines connected	186585,47	m^4

Displacement		
...of one wind turbine + pontoon	486,38	m^3
...of two wind turbines + pontoons	972,76	m^3
...of three wind turbines + pontoons	1459,14	m^3
...of middle structure	389,11	m^3
...of one pontoon (no ballast)	68,09	m^3

The formula for calculating the heave period, T_h, of the invention, reference to[8]:

$$T_h = 2\pi \cdot \sqrt{\frac{m_{total}}{\rho_w \cdot g \cdot A_w}},$$

where

A_w: *Total waterplane area of the invention*

ρ_w: *Density of sea water*

m_{total}: *Total mass of the invention + added mass due to motion in water* (1.2*mass)

g: *Gravity constant*

Figure 10 shows the results of calculations on Heave. With the lowest value at 2,28 seconds and highest at 3,57 seconds.

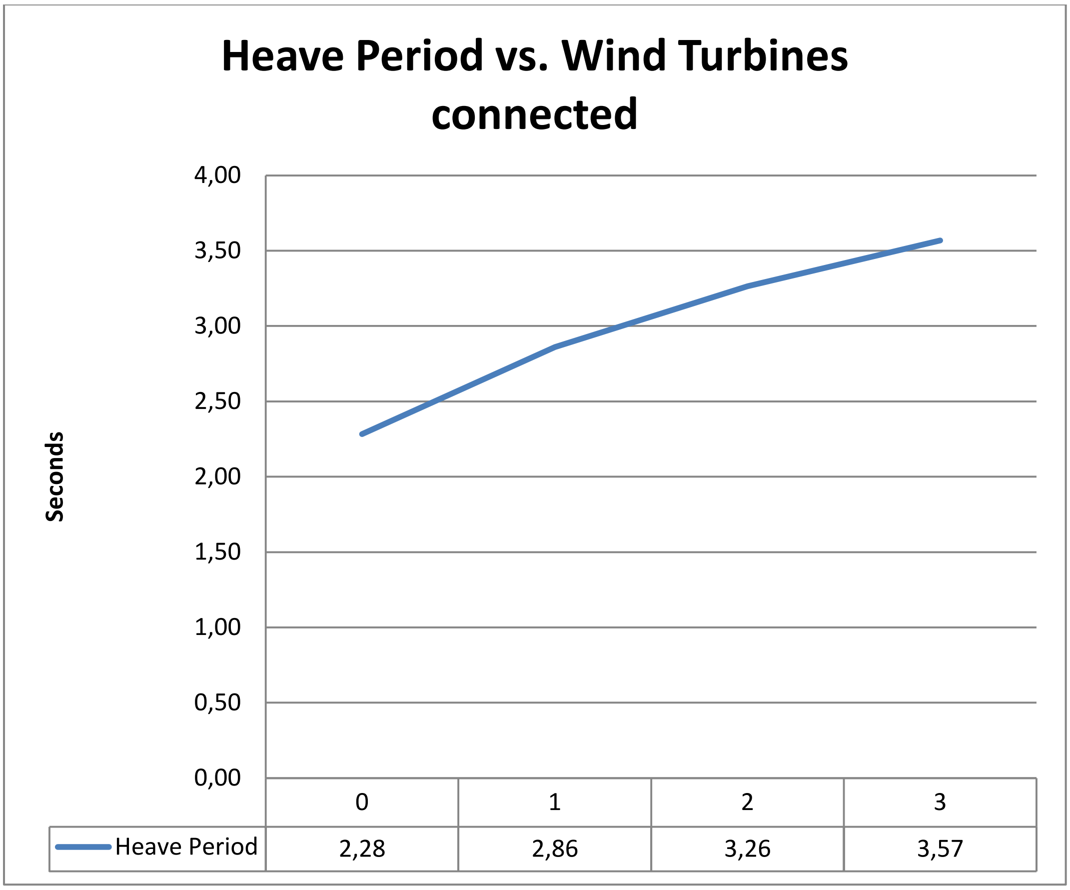


Figure 10: Results of calculation of Heave. Vertical axis is seconds while the horizontal axis is amount of connected wind turbines.

Image 15 below shows the different axis used to calculate Pitch and Roll periods for the invention. Annotations are in degrees.

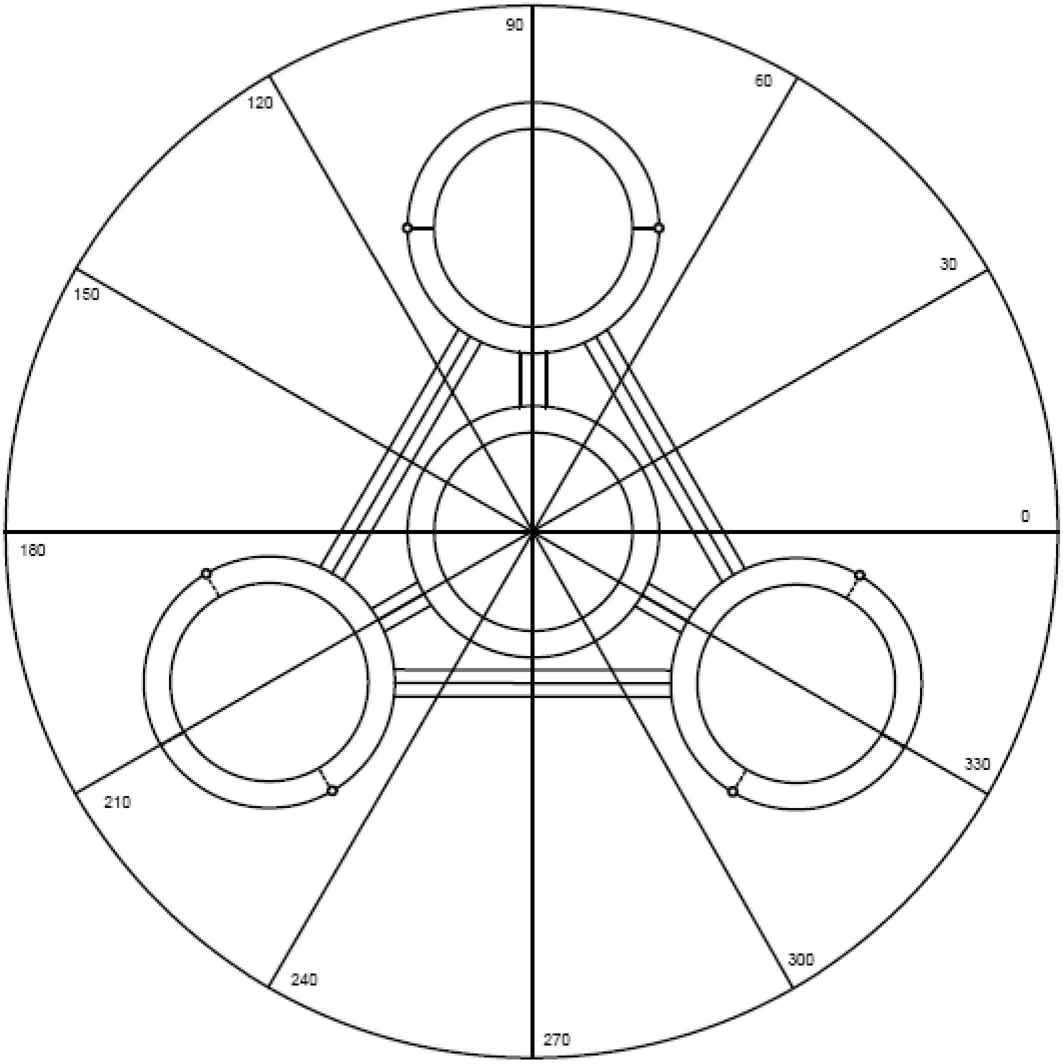


Image 15: Drawing showing the axis taken into account when calculating Pitch and Roll periods for the invention, 0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300 and 330 degrees.

The formula for calculating the roll period, T_{roll}, of the invention, reference to [2], [7] and [8]:

$$T_{roll} = \frac{2\pi \cdot k}{\sqrt{g \cdot GM}},$$

where

$$k = \sqrt{\frac{I}{A_W}}$$

$I: Moment\ of\ Inertia$

$k: Radius\ of\ Gyration$

Axes taken for calculation are the ones shown in Image 15. Axis 1 (0° and 90° in image 15)is used when only 1 wind turbine is connected (1 on the horizontal axis) and Axis 2 (120° and 300° in image 15) is when 2 wind turbines are connected (2 on the horizontal axis). While varying the amount of wind turbines connected, these periods change, as shown in Figure 11 below.

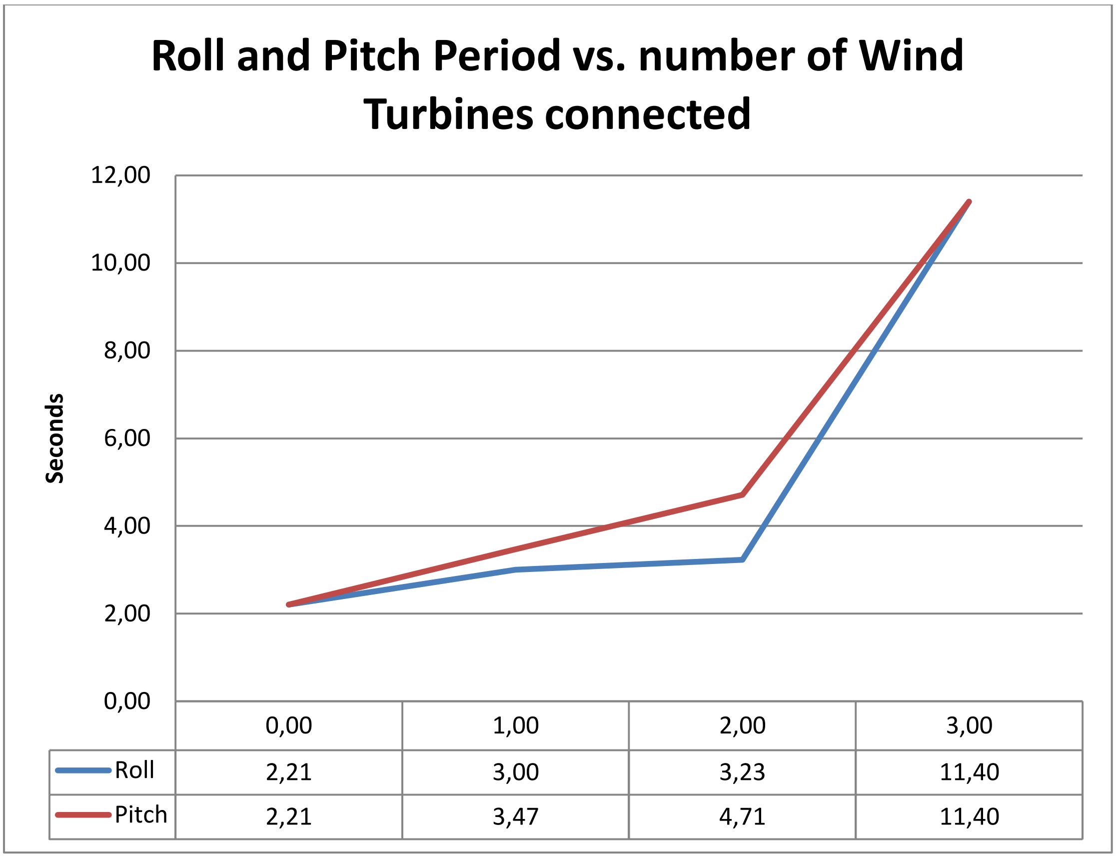


Figure 11: Roll and Pitch period in seconds. Horizontal axis describes the amount of wind turbines connected, while the vertical axis is in seconds.

7.1 Comments

The heave period is rather low for such a large design; however, it also means that it can be used in conditions where the waves have higher periods. The roll and pitch periods experience a steep drop from 3 wind turbines connected to 2 wind turbines connected, this is due to the drop in GM for the parameters used for these calculations. Wave periods of 4-6 seconds are quite common in the North Sea, and as such, the design can be used safely in these conditions. Tow out or installation cannot take place for wave periods above 6-8 seconds due to the high roll period when 3 wind turbines are fully assembled.

7.2 Additional measures

If there is a need to increase the heave period, mass can be added by providing more pontoons, which are not necessarily located around the wind turbines. These can be filled with ballast water. Furthermore, as an effect of added pontoons, stability can be controlled even more by strategically placing them as suggested in Image 16 below.

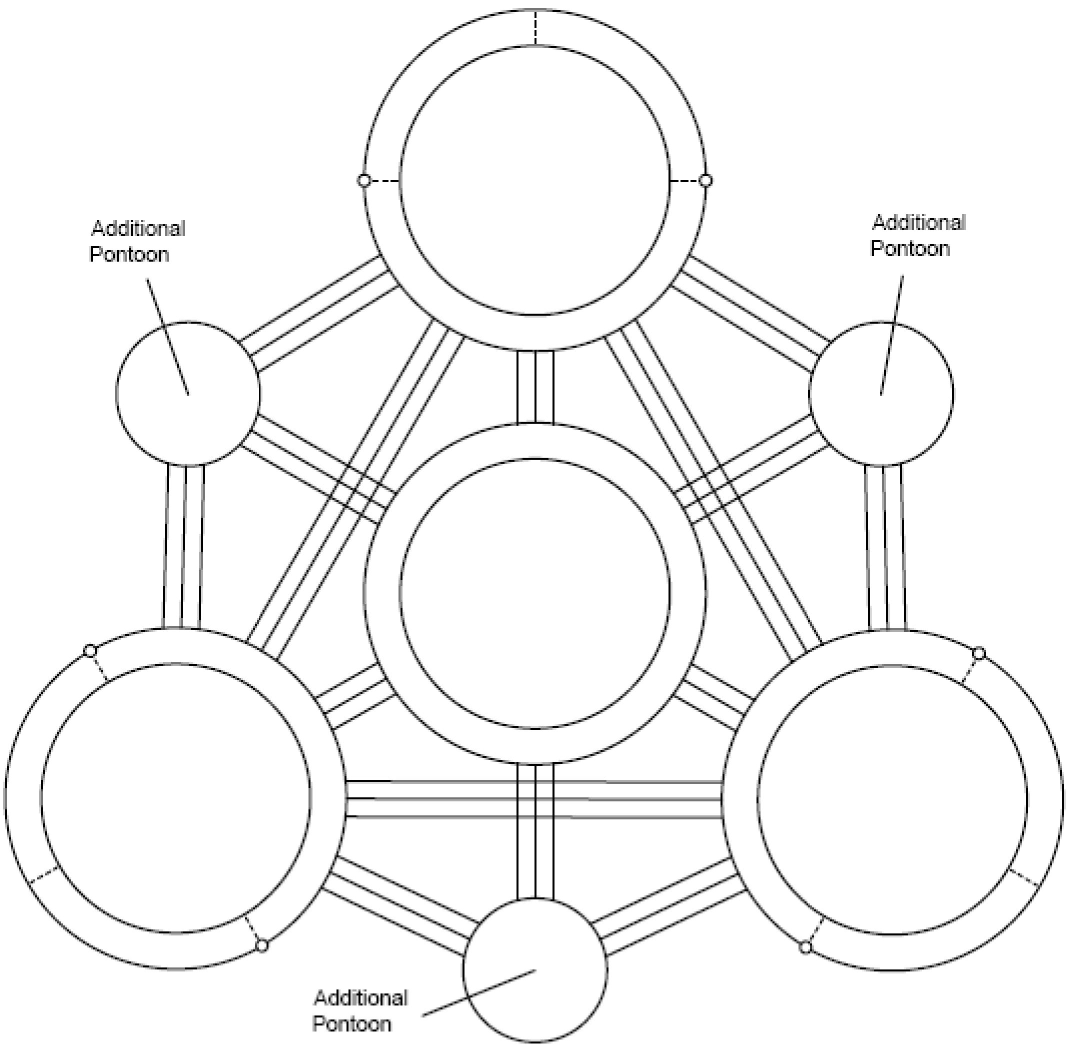


Image 16: Suggested placements of suggested pontoons for ballasting during operation. By dynamically pumping sea water in and out of the added pontoons, additional stability can be assured.

8. Transport

When the wind turbines are assembled and connected to the invention inshore, they proceed to get towed out to a specified location for installation.

The pontoons have joints to allow them to open for assembly after the installation has been completed (see image 17). They automatically lock when a wind turbine is guided into it (see image 18).

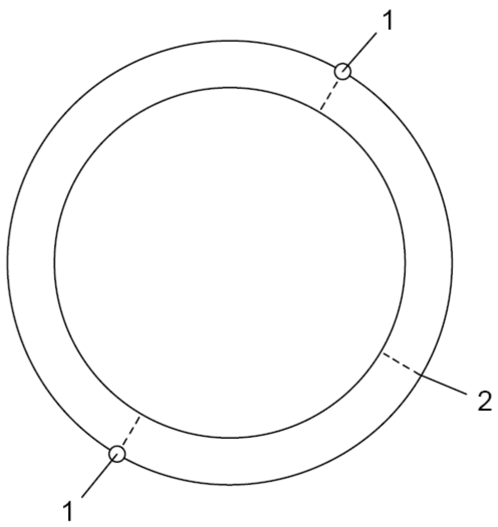


Image 17: Shows a pontoon in locked position.

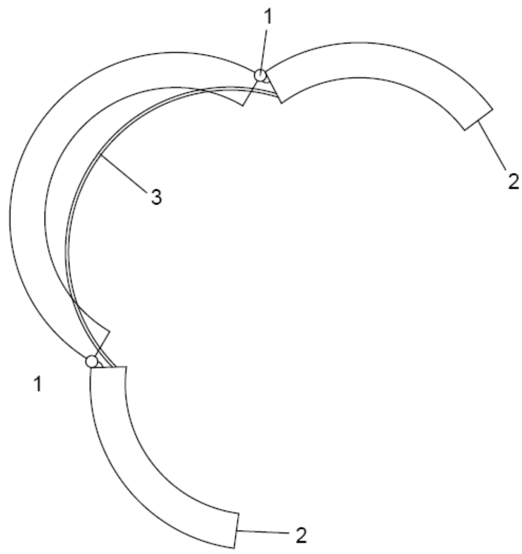


Image 18: Shows a pontoon when it is open.

Explanation of images 17 and 18:

Image 11 shows a locked pontoon with joints (1) to allow for it to open. At the point annotated (2), there is a connective joint which automatically locks when the joints are connected to each other. When a wind turbine is guided into an open pontoon (image 18), it will push on the trigger (3) which will cause the pontoon to automatically lock (image 17) when the wind turbine is safely placed in the pontoon.

The hydraulic arms shall be connected such that they can compensate for heave and still allow movement in the vertical direction, while the connecting legs between the middle structure and the wind turbines shall be sufficiently rigid and have enough strength to take the forces during tow out.

8.1 Weather Windows

Suggested weather windows for installation are when the significant wave heights, H_s, are around 2-3 meters [17] (see image 19). Sea states higher than the ones described can resonate severely with the structure, however, there is not much danger in case of significant wave heights of less than 3 m as the energy is low in that range (see chapter 8.2).

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Table 1
Twenty-nine-year scatter diagram for the northern North Sea

H_s/T_p	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10	10–11	11–12	12–13	13–14	14–15	15–16	16–17	17–18	18–19	19–20	20–21	21–22	22–23	23–24	24–25	25–26	26–27	27–28	28–29	29–30	Sum
0.25	1	0	38	35	53	69	101	116	74	43	29	25	17	8	7	8	2	5	6	0	0	0	1	0	0	0	0	0	0	0	638
0.75	0	0	9	50	331	822	1186	1187	1175	919	461	297	110	35	35	17	12	5	7	4	0	3	1	0	0	0	1	0	1	0	6668
1.25	0	0	4	27	458	1219	2059	1986	2148	1782	1060	804	407	193	126	49	29	14	8	4	1	2	0	3	0	1	4	0	0	0	12,388
1.75	0	0	0	1	112	894	1820	2344	2166	1911	1250	892	552	309	190	73	35	12	8	4	3	0	0	2	0	1	3	0	0	0	12,582
2.25	0	0	0	0	11	296	1253	1781	1964	1663	1282	924	614	309	247	83	27	22	7	2	2	0	1	0	0	2	3	0	0	0	10,493
2.75	0	0	0	0	0	71	604	1333	1857	1665	1067	955	668	310	285	116	41	18	5	3	2	2	0	0	1	4	1	1	0	0	9009
3.25	0	0	0	0	1	6	219	835	1375	1431	911	785	554	368	246	122	54	25	8	1	1	1	0	1	0	0	0	0	0	0	6944
3.75	0	0	0	0	0	0	48	427	983	1176	832	655	453	282	239	119	50	23	9	2	0	0	0	0	0	1	0	0	0	0	5299
4.25	0	0	0	0	0	0	5	165	642	997	672	549	426	194	199	97	41	30	9	3	0	1	0	0	0	0	0	0	0	0	4030
4.75	0	0	0	0	0	0	2	39	344	715	588	514	339	195	140	61	44	27	6	5	1	0	0	0	0	0	0	0	0	0	3020
5.25	0	0	0	0	0	0	0	4	109	468	555	457	289	162	120	41	31	16	6	4	0	0	0	0	0	0	0	0	0	0	2262
5.75	0	0	0	0	0	0	0	1	34	211	382	308	249	100	97	41	16	17	6	0	0	0	0	0	0	0	0	0	0	0	1462
6.25	0	0	0	0	0	0	0	0	9	92	221	232	190	106	62	18	16	3	4	2	2	0	0	0	0	0	0	0	0	0	957
6.75	0	0	0	0	0	0	0	0	0	30	143	209	151	73	59	24	8	4	2	0	0	0	0	0	0	0	0	0	0	0	703
7.25	0	0	0	0	0	0	0	0	0	7	44	126	103	61	47	21	6	8	1	1	0	0	0	0	0	0	0	0	0	0	425
7.75	0	0	0	0	0	0	0	0	0	0	20	69	79	43	32	11	5	3	1	0	0	0	0	0	0	0	0	0	0	0	263
8.25	0	0	0	0	0	0	0	0	0	0	9	32	50	34	30	11	5	1	0	0	0	0	0	0	0	0	0	0	0	0	172
8.75	0	0	0	0	0	0	0	0	0	0	3	18	31	25	16	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	105
9.25	0	0	0	0	0	0	0	0	0	0	1	5	26	20	20	4	1	1	0	1	0	0	0	0	0	0	0	0	0	0	79
9.75	0	0	0	0	0	0	0	0	0	0	0	3	6	10	8	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	32
10.25	0	0	0	0	0	0	0	0	0	0	0	3	4	13	6	5	1	0	1	0	0	0	0	0	0	0	0	0	0	0	33
10.75	0	0	0	0	0	0	0	0	0	0	0	0	6	2	3	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	14
11.25	0	0	0	0	0	0	0	0	0	0	0	0	2	2	5	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	11
11.75	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
12.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
12.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
Sum	1	0	51	113	966	3377	7297	10218	12880	13110	9530	7862	5326	2855	2220	938	430	235	94	36	12	9	3	6	1	9	12	1	1	0	77,593

Image 19: Scatter diagram of observed waves in the northern part of the North Sea [17].

As is evident by image 19, the highest percentage of waves for an H_s of 2-3 meters occurs when the wave period is around 8-10 seconds, however, waves with higher periods may occur for the same H_s. Special care should be taken in any case when tow out and installation proceedures are underway.

8.2 Energy of low period waves resonating

As mentioned in chapter 8.1, the energy produced when the structure resonates with low period waves is reasonably low not to cause damage to the invention, as shown in figure 12 below:

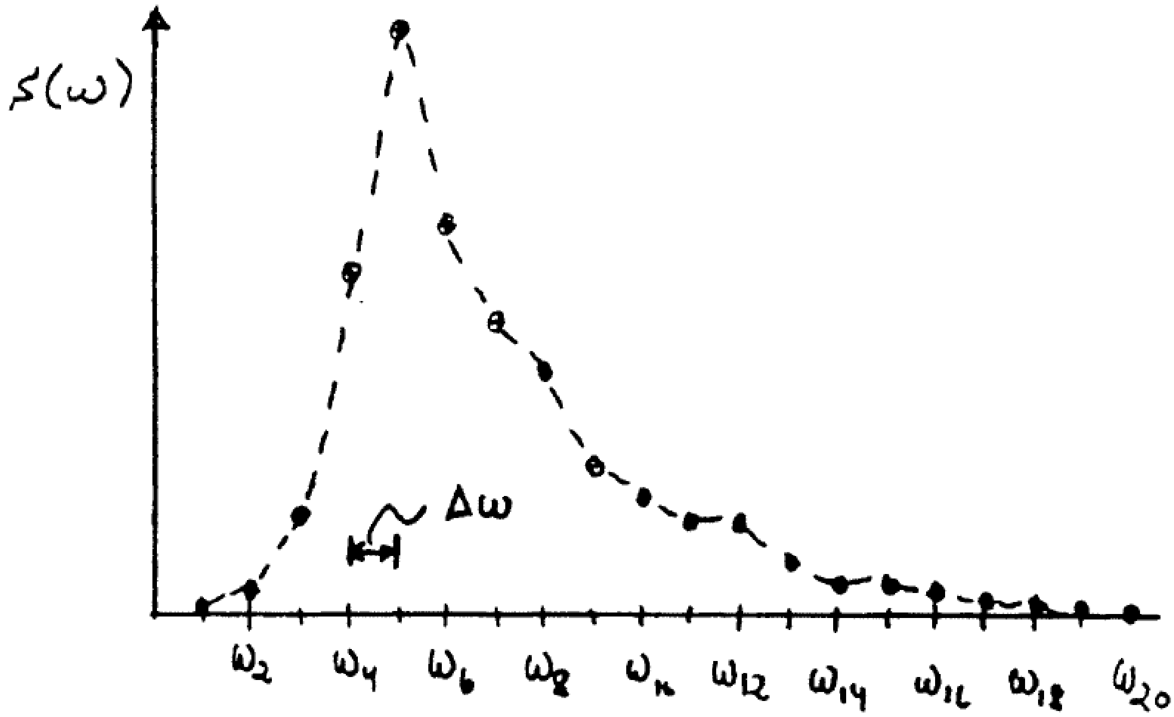

Figure 12: Energy of harmonic waves where S(ω) is the energy and the ω ranging from 0-20 [18].

Important to note here that:

$$\omega_2 = 0.2\,,\ \omega_4 = 0.4, \dots \dots\ \omega_{20} = 2.0$$

where

$$\omega = \frac{2\pi}{T} \qquad [18]$$

So, for a period, T, of around 4 seconds, we get

$$\omega = \frac{2\pi}{4} = 1.571$$

wich corresponds to a value just below ω_{16} on figure 12 ($\omega_{16} = 1.6$), and as is evident by the figure, S(ω) is rather low. Furthermore, the lower the period, T, is, the higher ω gets and the energy is not harmful to the invention.

9. Installation

To make the installation process easier, it is proposed to use slide frames installed in the pontoons carrying the wind turbines. In combination with ballasting and the hydraulic arms (see Image 8), this assembly will represent a very accurate method of installing the wind turbines.

Once one wind turbine is installed, the pontoon that circumferences it is ballasted accordingly and the vessel proceeds to install the others and finally return to shore.

A step-by-step representation of installing the first wind turbine is shown in below in image 20.

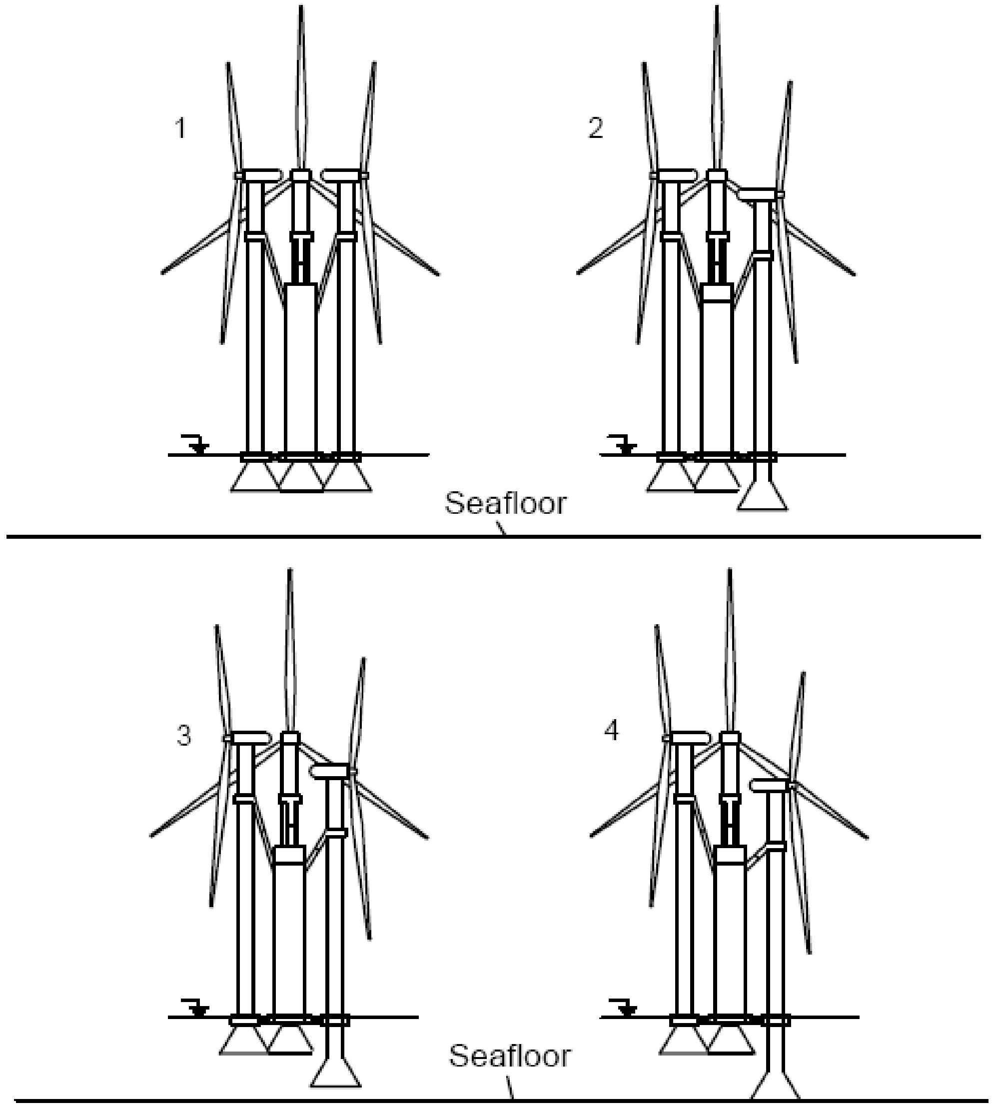

Image 20: Step-by-step representation of installing a wind turbine.

Step 1 shows the invention in position for installation. Steps 2 and 3 shows the invention gradually lowering a wind turbine with help from the hydraulic arm connected. Step 4 shows the invention after lowering one wind turbine to the sea bed just before releasing the pontoon supporting it. However, upon nearing the sea bed with the wind turbine foundation, the jacking system utilized will have hydraulic modifications. According to Prof. O. T. Gudmestad, the company Aker Solutions are developing such designs. If there are no hydraulic modifications, the foundation of the wind turbine may hit the sea bed at a high velocity and the wind turbine may potentially sustain damage.

After the wind turbine has been safely installed, the pontoons surrounding the wind turbine is disconnected, followed by the hydraulic arm supporting it.

9.1 Heave Compensation

When the wind turbine is to be installed, waves can cause heave, roll and pitch when the installation process is ongoing. To reduce this effect, it is proposed to use heave compensators at the hydraulic arms (see Image 21). These would work by significantly reducing the vertical motion of the connected wind turbine, making installation much easier and safer to execute. It also allows for installation in rougher seas and weather conditions. In meetings with Prof. O. T. Gudmestad it was revealed that Aker Solutions have heave compensation systems that can be utilized.

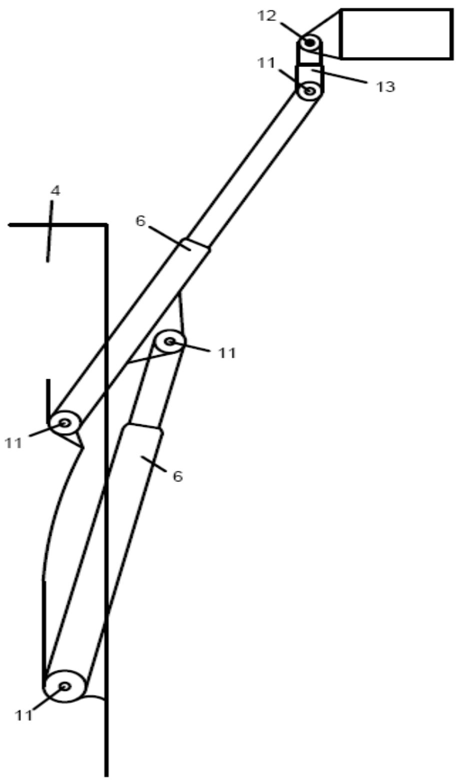

Image 21: Shows a side view of the hydraulic arm connected to a wind turbine.

Explanation of image 21:

Each wind turbine is connected to the middle structure (4) by a hydraulic arm (6, 11, and 12). The hydraulic arm could consist of three hydraulic pistons – two to support the forces during transport and installation (6) and one installed for heave compensation (13). The joint connecting the longest hydraulic arms (6) can rotate freely, while the joint (11) connecting the longest hydraulic piston (6) with the one meant for heave compensation (13), only allow for the longest piston to rotate freely. The hydraulic piston meant for heave compensation (13) shall stay locked in a vertical position, only allowing for movements in the vertical direction, namely the heave motion. The joint at the top (12) allows for no movement.

10. Conclusions

The invention is stable with these given parameters:

- Outer Diameter - 16 meters
- Leg Length - 8 meters
- Middle Structure Weight - 400 tonnes
- Wind Turbine Weight - 500 tonnes
- Center of Gravity of a Wind Turbine - 110 meters
- Center of Gravity of Middle Structure - 50 meters

From these parameters, it is very likely that this proposed invention can be built and used in the North Sea. Even though the natural period for Heave is low and Pitch and Roll high when three wind turbines are connected, the energy during the resonance is not high enough to cause damage to the structure (given of course it has sufficiently strong joints etc), except for the Pitch and Roll periods when three wind turbines are connected. In response to the latter situation, special care should be taken on tow out and one should only do tow out when the weather windows suggested in chapter 8.1 are satisfied.

11. Suggestions for further work

Suggestions for further work includes everything needed to be undertaken to have this invention become a reality. These steps are (but not limited to):

- Patent write-up
- Calculation of Strength and Durability
- Estimated Cost
- Cost effective analysis
- Estimation of the lifetime of the invention
- Scaled prototypes
- Empirical studies

Basically, the above list describes everything that is needed to have this invention constructed and used for the towing and installation of offshore wind turbines.

The work shall start with a thorough Feasibility study to document the feasibility of the concept.

12. References

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[17] Torgeir Moan et al.:

“Uncertainty of wave-induced response of marine structures due to long-term variation of extratropical wave conditions”, 18th of October 2005, Norwegian University of Science and Technology.

[18] Lecture on Description of Sea Waves by Professor Ove T. Gudmestad, University of Stavanger.

13. Appendix 1: Data and Calculations

NOTE: Shows only the two first values at each parameter. The excel sheet on the CD which follows contains the original Excel sheet used.

You can adjust each parameter to influence the outcome of stability	-	-
x OD vary (leg length 6 meters)	20,78	19,92
x Leg vary (16 OD)	22,52	21,65
x Leg vary (15 OD)	21,65	20,78
Leg Length	10,00	9,00
Data for Wind-Turbine		
Height	160,00	
Weight	500,00	450,00
Center of Gravity	160,00	150,00
Radius (at sea level)	4,50	
Area (at sea level)	63,62	

Data for Middle Structure		
Height	100,00	
Weight	400,00	
Center of Gravity	50,00	
Radius (at sea level)	4,50	
Area (at sea level)	63,62	
Draft (with pontoon)	2,40	
	18	17
Data for Pontoons around each Wind-Turbine and Middle Structure		
Radius (Inner)	4,50	
Radius (Outer)	9,00	8,50
Height	3,91	
Weight	70,00	
Area (at sea level)	190,85	163,36
Draft (with wind-turbine connected) weight vary	2,91	2,65
Draft (with wind-turbine connected) OD vary	2,91	3,39
Draft (without ballast and wind-turbine)	0,36	
Draft (with middle structure connected) weight vary	2,40	
Draft (with middle structure connected) OD vary	2,40	2,80
Varying outer diameter		
Moment of Inertia (no wind turbine connected)	184541,72	145061,52
For 1	184863,78	145383,58
For 2	240151,15	196185,93
For 3	240473,21	196507,99

Varying Leg length (15 OD)

Moment of Inertia (no wind turbine connected)	115002,76	106690,11
For 1	115324,82	107012,17

For 2	175288,06	162299,54
For 3	175610,12	162621,60

Varying Leg length (16 OD)

Moment of Inertia (no wind turbine connected)	151270,68	140756,16
For 1	151592,74	141078,23
For 2	216422,70	201041,46
For 3	216744,76	201363,52

Moment of Inertia (no wind turbine connected)
For 1
For 2
For 3

Displacement		
…of one wind-turbine + pontoon	486,38	437,74
...of two wind-turbines + pontoons	972,76	875,49
...of three wind-turbines + pontoons	1459,14	1313,23
…of middle-structure + pontoon	389,11	
…of one pontoon around a wind turbine (no ballast)	68,09	
Varying OD (leg length 6 m, wind turbine weight 500 t, CoG 110)		
No wind turbines connected		
Global G	28,61	
KG	31,00	31,41
KB	1,20	1,40
BM	311,00	244,46
GM	281,19	214,46
One wind turbine connected		
Global G	63,10	63,10
KG	65,49	65,89
KB	1,20	1,40
BM	182,73	143,71
GM	118,44	79,21
Two wind turbines connected	-	-
Global G	77,06	
KG	79,45	79,85
KB	1,20	1,40
BM	160,31	130,96
GM	82,06	52,51
Three wind turbines connected		
Global G	84,61	-
KG	87,01	87,41
KB	1,20	1,40

BM	121,18	99,02
GM	35,37	13,01

Varying Leg length (OD 15)		
No wind turbines connected	-	-
Global G	28,61	
KG	31,00	31,41
KB	1,20	1,40
BM	193,81	179,80
GM	164,00	149,79
One wind turbine connected		
Global G	63,10	-
KG	65,49	65,89
KB	1,20	1,40
BM	113,99	105,78
GM	49,70	41,28
Two wind turbines connected	-	
Global G	77,06	
KG	79,45	79,85
KB	1,20	1,40
BM	117,01	108,34
GM	38,76	29,89
Three wind turbines connected		
Global G	84,61	
KG	87,01	87,41
KB	1,20	1,40
BM	88,49	81,95
GM	2,68	-4,06

Varying Leg length (OD 16)		
No wind turbines connected		
Global G	28,61	
KG	31,00	31,41
KB	1,20	1,40
BM	254,93	237,21
GM	225,12	207,20
One wind turbine connected		
Global G	63,10	
KG	65,49	65,89
KB	1,20	1,40
BM	149,84	139,45
GM	85,55	74,96
Two wind turbines connected	-	
Global G	77,06	

KG	79,45	79,85
KB	1,20	1,40
BM	144,47	134,20
GM	66,22	55,75
Three wind turbines connected		
Global G	84,61	
KG	87,01	87,41
KB	1,20	1,40
BM	109,22	101,47
GM	23,41	15,46

Varying weight of one wind turbine (OD 16 m leg length 6 m)		
No wind turbines connected		
Global G	28,61	
KG	31,00	
KB	1,20	
BM	254,93	
GM	225,12	225,12
One wind turbine connected		
Global G	63,10	61,02
KG	65,49	63,82
KB	1,20	1,20
BM	140,39	147,02
GM	76,10	84,39
Two wind turbines connected		
Global G	77,06	74,97
KG	79,45	77,77
KB	1,20	1,20
BM	140,39	147,02
GM	62,14	70,45
Three wind turbines connected		
Global G	84,61	82,74
KG	87,01	85,53
KB	1,20	1,20
BM	140,39	147,02
GM	54,58	62,68

Varying Center of Gravity		
No wind turbines connected		
Global G	28,61	
KG	31,00	
KB	1,20	
BM	254,93	
GM	225,12	225,12

One wind turbine connected		
Global G	84,28	80,05
KG	86,68	82,44
KB	1,20	1,20
BM	140,39	140,39
GM	54,91	59,15
Two wind turbines connected		
Global G	106,82	100,87
KG	109,21	103,26
KB	1,20	1,20
BM	140,39	140,39
GM	32,38	38,33
Three wind turbines connected		
Global G	119,02	112,13
KG	121,41	114,53
KB	1,20	1,20
BM	140,39	140,39
GM	20,18	27,06

Heave (Leg Length 9 meters, CoG W 110 m, CoG MS 50 m, OD 16 m)		
0	2,28	2,28
1	2,86	2,80
2	3,26	3,17
3	3,57	3,44

Roll	0,00	1,00
k	15,15	16,96
	2,21	3,00
k	15,15	13,91
	2,21	3,47

Legs connecting Middle Structure and Wind-Turbines		
Misc. Data		
Density of sea water	*1028 kg/m^3*	

Center of mass (axis is through middle structure) for different leg length	OD of 16 meters	
2 turbines connected		
x	10,99	10,57

1 turbine connected		
x	0,00	0,00
y	11,02	10,59

2 Turbines situation		
Distance off-center of wind turbine, same direction as above	2,01	1,93
Area semi circle (smallest)	56,32	57,79
Area semi circle (largest)	144,74	143,27
Distance to mass centres from new axis, around y axis. X direction		
Small semi circles	1,48	1,51
Large semi circles	4,21	4,13
Moment of Inertia around new axis	197930,27	183734,66
Two wind turbines connected		
Global G	28,61	28,61
KG	31,93	31,93
KB	1,66	1,66
BM	138,42	128,49
GM	108,15	98,22

1 Turbine Situation		
Moment of Inertia for new axis	228571,703	211362,955
One wind turbine connected		
Global G	63,10	63,10
KG	65,49	65,49
KB	1,20	1,20
BM	225,93	208,92
GM	161,64	144,63

13.1 Formulas for x, X1 and X2 as displayed in Images 10-13 [9]

$$\boldsymbol{x = sin30^\circ \cdot (OD + L)}$$

$$\boldsymbol{X1 = \frac{2 \cdot (sin30^\circ \cdot (OD + L) \cdot m_p) + (OD + L) \cdot (m_t + m_p)}{4 \cdot m_p + m_t + m_m}}$$

$$\boldsymbol{X2 = \frac{2 \cdot (sin30^\circ \cdot (OD + L) \cdot (m_t + m_p)) + (OD + L) \cdot m_p}{4 \cdot m_p + 2 \cdot m_t + m_m}}$$

where

m_p : *weight of one pontoon*

m_t : *weight of one wind turbine*

m_m : *weight of the middle structure*

L : *leg length*

OD : *Outer Diameter*

14. Appendix 2: Original Description of Invention

SIJOIJBUd SUIRATON JEREN I
SNIHVION SNOI78ND

Towing and installation of offshore wind-turbines

Presented at Jæren tingrett on 2 February 2011

Notary Public

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At present, the state of art of towing and installing of offshore wind-turbines is to tow each turbine individually with heavy-duty equipment, such as large jackups or offshore cranes, which makes for a costly operation. The claims and designs described in this document aim to reduce time spent on tow-out and installation, thereby also reducing the cost.

The design is intended for easy tow-out and installation of offshore wind-turbines. This is done by towing 3 or more turbines out at the same time, to reduce the time spent towing and to increase stability during tow.

Having a main structure to support the 3 or more turbines during tow, as well as having a truss system connecting the turbines together, will make the tow stable and the wind-turbines easier to install – due to the main structure is intended to have hydraulic arms to assist both in stability and installation.

Image 1.1 shows a cross-sectional view of the design, excluding the top half. In the middle is a structure which contains hydraulic arms and floats on a barge/pontoon. The outer circles describes the wind-turbine (inner circle) and the pontoons locked around its base (outer circle). The lines in between are a connective truss system for stability.

Image 1.2 shows a side view, excluding the bottom part of the invention, with hydraulic arms from the middle structure connected to each wind-turbine in higher elevations for stability and control.

The design is presented as shown in image 1.1 and image 1.2 and is described in more detail below.

The major aspects of the design mentioned below are to have 3 or more wind-turbines [3] in one tow, and that the contraption is reusable.

The invention has a main structure in the middle [1], which supports the wind-turbines [3] at higher elevations, by hydraulic arms [4] connecting them together. From image 1.1 and image 1.2, it is evident that there are 3 wind-turbines [3] in tow, where each turbine [3] is connected to eachother and the main structure [1] by a truss, or box, system [2], connected to each at the ends [9].

Around each turbine [3], at water level, there is a connective joint [5] and pontoons [8]. The turbine [3] connects to this joint [5] by guiding it in to the opening, and the joint [5] will automatically lock around the turbine [3]. In this way, it makes assembly for transport faster and simpler.

The joint [5] can easily be opened to free the turbine [3] for installation. The connective, hydraulic arms [4] is, other than keeping the tow stable, intended to aid in installation by staying connected, possibly until the wind-turbine [3] is installed on bottom, when the joint [5] is opened. By, for example, having the main structure [1] fitted with a crane floating on a barge, the installation procedure will be far less complicated than if there were separate cranes to do this work.

The pontoons [8] will be fitted with pumps to adjust the ballast during tow and comissioning. For example, when a turbine [3] is released for installing, water can be pumped into, and out of, the pontoons [8] to stabilize the system.

The pontoons [8] and the truss, or box, system [2] are connected such that it gives free way for opening and easy assembly for the wind-turbine [3].

The hydraulic arms [4] can be adjusted in hight and length by a joint [6] and telescopic joints [10] respectively. This is needed as each wind-turbine [3] is different in height and diameter. Proceeded to be clamped [7] on at the turbine tower.

As previously mentioned, by having a design with 3 wind-turbines [3] rather than less, the tow will be very stable. However, the possibility of 4 or more wind-turbines will also have to be taken into consideration. Issues may rise such as weight, allocated space in dock or at inshore site, for assembly and how complex the middle structure [1]will have to become.

For deployment:

- Tow-out: Assemble inshore by locking in the turbines at designated areas on the structure, lock on hydraulic arms and proceed to tow-out to installation area.
- Installation: Release joints around the turbines and, with help from the hydraulic arms, proceed to install the turbines.
- Maintenance: The invention can be aided further by the hydraulic arms and additional pontoons for stability during maintenance.
- Decomissioning: Reverse installation.

From this description, the invention makes it possible to have the tow-out and installation of offshore wind-turbines seem trivial compared to what is currently state of art. In essence, this invention gives mobility and reduces time for comissioning and decomissioning of offshore wind-turbines, thereby also reducing the cost significantly.

Advantages.

1. By connecting 3 or more turbines together, the tow out will become more stable.
2. As with point 1, but will also reduce time spent on tow overall.
3. The invention will reduce the cost of tow-out and installation of offshore wind-turbines.
4. The invention is reusable.
5. The invention will trivialize what is now state of art in offshore wind-turbine towing and installation.

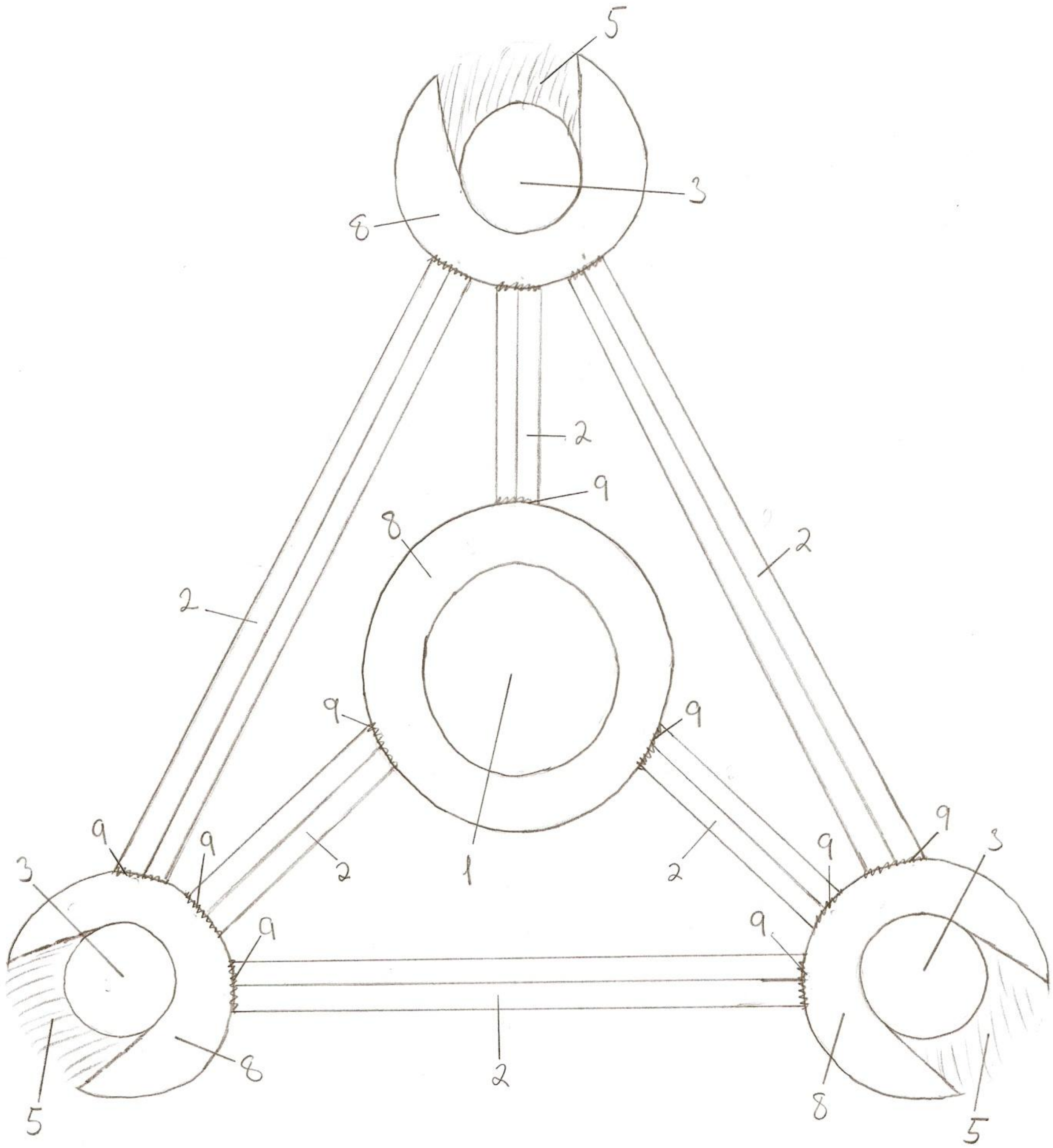

Image App 2.1

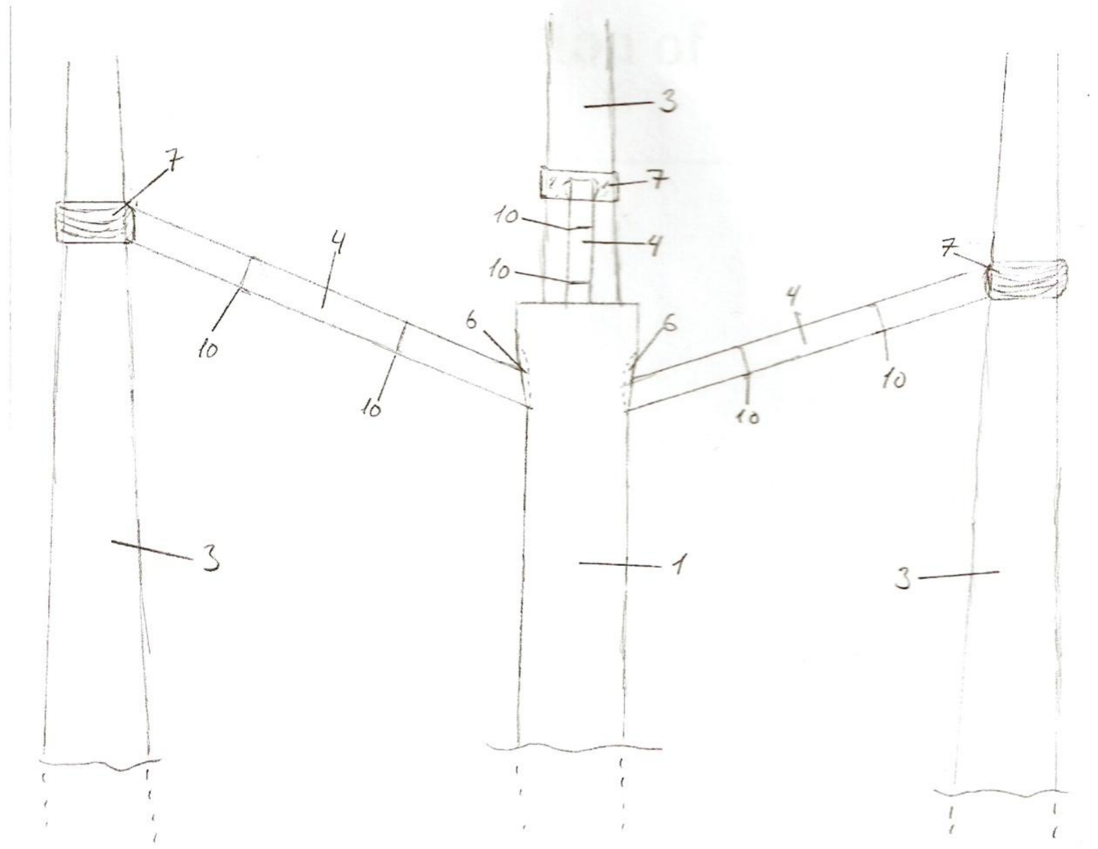

Image 1. 2

Image App 2.2