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Investigation of a dynamically positioned floating offshore wind turbine concept

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Abstract. The dynamically positioned wind turbine concept consists of a floating platform equipped with a wind turbine and propellers. In contrast to a conventional floating offshore wind turbine, it has no moorings. Instead, the propellers are used to keep the wind turbine stationary. It may also be equipped with an on-board energy storage system (e.g. batteries, hydrogen, etc.) to avoid grid-connection. This concept is well suited for deployment in the far-offshore, where grid-connection and installation operations are challenging.

As the propellers which are used to control the position of the wind turbine require power supply, the aim of this study is to investigate whether and in what conditions there can be a positive net power production. To this end, we have developed a velocity and power prediction program (VPPP) to estimate the power consumed by the propellers and the power generated by the wind turbine, as a function of wind conditions, and design parameters (e.g. diameter of the wind turbine and characteristics of the propellers rotors). The VPPP is based on Newton's first law of motion. The forces applied on the system are: the wind turbine thrust, the mean wave drift, and the propellers thrust.

Inspired by an existing floating offshore wind concept, an example design has been developed. The diameter of the wind turbine's rotor is 78 m. Its rated power is 2 MW. The wind turbine is mounted on a 40 m square barge. The diameter of the propellers' rotor is 6 m. Using the VPPP, the power performance of this example design has been investigated as function of wind conditions. The maximum generated power is 0.89 MW. It is obtained for a true wind speed of 13.4 m/s. If deployed in the Northern Atlantic Ocean, this design could achieve a capacity factor of 15%, which is low in comparison to the 70% capacity factor which would be achieved by a moored floating offshore wind turbine if deployed at the same location.

Keywords— Dynamically positioned wind turbine, Offshore wind, Capacity factor, Modelling.

1. Introduction

Deployment potential of offshore wind turbines is limited to relatively near-shore areas, because costs associated with grid-connection, moorings and installation, and maintenance increase dramatically with distance from shore [1]. Therefore, if far-offshore wind energy conversion systems are to become feasible, new approaches are required.

The possible concepts include the energy ship (patented in 1982 by Salomon [2]) and the dynamically positioned wind turbine based on the sailing wind turbine concept (patented in 1983



by Vidal [3]). Energy ships are ships propelled by wind power and which generate electricity by means of water turbines attached underneath their hull. Dynamically positioned wind turbines are non-moored floating offshore wind turbines. In both cases, the energy production platforms can be equipped with an on-board energy storage system (e.g. batteries, electrolyzers for hydrogen production and hydrogen storage tanks for storage, etc.) to avoid grid-connection.

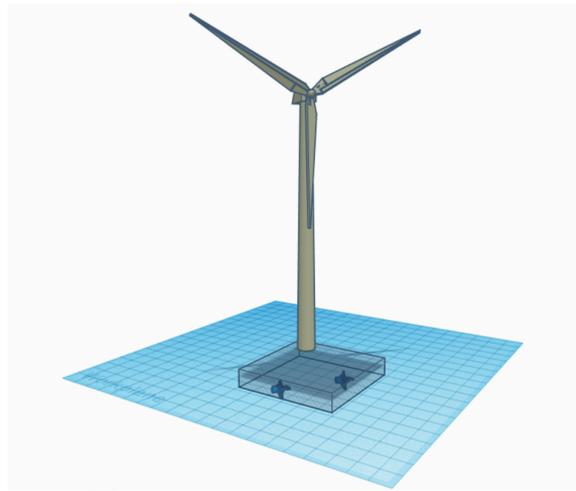


Figure 1. Artist view of a dynamically positioned wind turbine.

Figure 1 shows an artist view of a dynamically positioned wind turbine. It is a floating offshore barge platform equipped with a wind turbine and propellers. The propellers are used to insure that the platform does not drift away: they are controlled such as to deliver a thrust counter-acting the forces generated by the wind and waves. To do this end, part of the power generated by the turbine is consumed by the propellers. Thus, a key question is whether there can be a positive net power production, i.e. whether the consumed power is greater or smaller than the generated power.

In 1986, Blackford reported experiments using a 4 m catamaran on which a 4 m diameter wind turbine was mounted [4]. The wind turbine was used to spin a propeller attached underneath the boat. He showed that using this concept, it is possible to sail directly against the wind. This shows that positive net power production is possible as otherwise he would have not been able to sail against the wind.

More recently, Annan et al. investigated the Wind Trawler concept [5], which is a mobile floating wind-and-hydro power producing plant. Using a numerical model, they showed that this concept can achieve similar capacity factors to that of nearshore fixed offshore wind turbines. The key difference between their concept and the concept investigated in the present study is that their concept is not stationary (it drifts with the wind) which can be a challenge for operations.

To our best knowledge, there has not been yet an investigation of the performance of a dynamically positioned offshore wind turbine concept. Thus, it is the aim of this paper.

In the remainder of the present paper, we first describe a Velocity and Power Prediction Program (VPPP) which allows the velocity and energy performance of a dynamically positioned wind turbine to be investigated as function of the design parameters and the environmental conditions. We then use it to analyze the performance of an example design of the proposed dynamically positioned floating offshore wind turbine concept.

2. Methods

2.1. Equation of motion

In this study, it is assumed that the wind turbine is attached to a barge platform. The dimensions of this barge are inspired by the "Floatgen" concept, which performance and stability were demonstrated at sea. The static angle as well as the dynamic effects resulting from the linear wave-structure interactions are expected to be small [6]. Therefore, these phenomena can be neglected and the generalised equation of motion reduces to the equation of equilibrium (Newton's first law). In addition, assuming that the wind turbine's rotor area is always perpendicular to the wind direction, Newton's first law of motion is further reduced to a single equation written along the true wind direction:

$$T_T + F_d + T_P = 0, \quad (1)$$

where, T_T , F_d and $T_P = T_{P1} + T_{P2}$ respectively correspond to the wind turbine thrust force, mean wave drift force and propellers thrust force. Those forces are detailed in the following sections.

2.2. Wind turbine mathematical model

The thrust force on the wind turbine is evaluated using the apparent wind speed, which depends on both the true wind speed W and the platform's velocity U . In this study, the platform is dynamically positioned, thus its velocity is approximately 0. Therefore, the apparent wind speed V is equal to the true wind speed W .

According to [7], the thrust force on the wind turbine is,

$$T_T = \begin{cases} \frac{1}{2}\rho_a A_T C_T V^2 & \text{if } V_{\text{cut-in}} \leq V < V_{\text{cut-out}} \\ 0 & \text{otherwise} \end{cases}, \quad (2)$$

where, ρ_a is the density of the air at standard atmospheric conditions, A_T is the wind turbine rotor's area, C_T is the wind turbine thrust coefficient, $V_{\text{cut-in}}$ is the cut-in wind speed (i.e. the wind speed for which that turbine starts operating) and $V_{\text{cut-out}}$ is the cut-out wind speed (i.e. the wind speed for which the wind turbine stops operating because the wind is too strong). The wind turbine thrust coefficient is expressed as,

$$C_T = 4af_c(1 - a), \quad (3)$$

where a denotes the induction factor and f_c is the tip-hub losses correction factor. f_c is a value between 0 and 1 ($f_c = 1$ corresponds to the ideal case of no losses [8]). In this study, $f_c = 0.9$. For $V_{\text{cut-in}} \leq V < V_{\text{rated}}$, the optimal induction factor is $a = 1/3$. For wind velocities above the rated wind speed ($V_{\text{rated}} \leq V < V_{\text{cut-out}}$), the induction factor is the solution of,

$$\frac{1}{2}\rho_a A_T C_T (1 - a)V^3 - \frac{P_{\text{rated}}}{\eta_T} = 0, \quad (4)$$

where P_{rated} and η_T respectively denotes the rated power of the wind turbine and the efficiency of the drive-train and generator. Finally, the power generated by the wind turbine is,

$$P_T = \eta_T \times 2\rho_a A_T f_c a(1 - a)^2 V^3 \quad (5)$$

Figure 2 shows the thrust and power as functions of the wind speed at the nacelle height for the wind turbine considered in this study (i.e. 78 m rotor's diameter). It can be seen that the thrust is maximum (approximately 300 kN) for the rated wind speed (11.4 m/s). The rated power is approximately 2 MW.

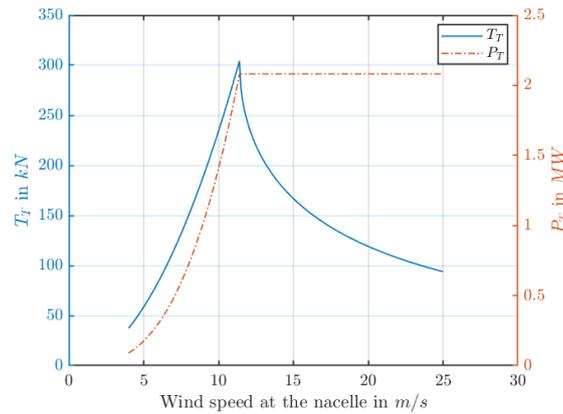


Figure 2. Thrust force and electrical power of the wind turbine considered in this study as function of the wind speed at the nacelle height.

2.3. Mean wave drift mathematical model

The sea water is coupled with the thin atmospheric boundary layer in such a way of exchanging heat, momentum and water mass at the air-water interface. Dynamically, the turbulent fluctuation of the atmospheric pressure at the free surface generates small, unstable waves known as capillary waves, which grow with time and ultimately lead to fully developed ocean waves [9]. The wave energy distribution of a fully developed sea can be represented by the Pierson-Moskowitz spectrum,

$$S(f) = \frac{\alpha_{PM} g^2}{(2\pi)^4 f^5} e^{-\beta_0 \left(\frac{g}{2.154\pi W_{10} f} \right)^4}, \quad (6)$$

where $\alpha_{PM} = 0.0081$, $\beta_0 = 0.74$ and f is the frequency of the propagating waves, g is the gravitational acceleration and W_{10} is the true wind speed at 10 m altitude [10].

The non-linear action of waves on the platform generates a wave-structure interaction force. It has a steady component which is the average drift force. It can be estimated according to,

$$F_d = \int_0^\infty \Phi(h) S(f) df, \quad (7)$$

where $\Phi(h)$ is the drift force response amplitude operator. This operator can be calculated using potential theory-based numerical codes. In this study, the software DIODORE has been used [11].

In addition to the average drift force, first order and second order wave-structure interaction effects also generate dynamic loads at various frequencies. As the present study focus on the steady response, they are not considered.

For sake of simplicity, the irregular wave is replaced by a regular wave of period equal to the spectrum peak period and carrying the same amount of energy. Its amplitude is given by,

$$\mathcal{A} = \frac{\mathcal{H}_s}{2\sqrt{2}}, \quad (8)$$

where \mathcal{H}_s is the specific wave height and given by,

$$\mathcal{H}_s = 4 \sqrt{\int_0^\infty S(f) df}. \quad (9)$$

Figure 3 shows a comparison of the average drift force calculated using Eq. 7 (blue curve) and the equivalent drift force calculated from the equivalent regular wave ($F_{d,eq} = \Phi(h)\mathcal{A}^2$, red curve). One can see that the equivalent drift force approximates very well the average drift force. As it is much quicker to calculate, this approach has been retained in this study.

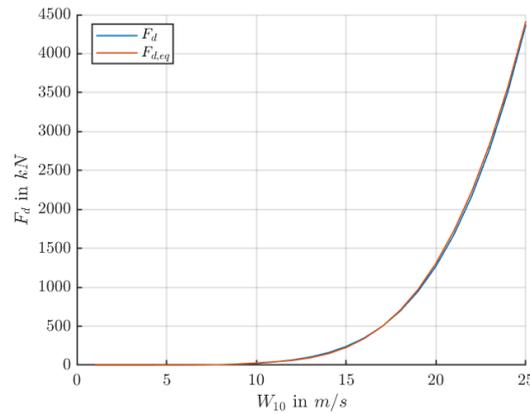


Figure 3. Comparison of the average drift force and its approximation calculated from the equivalent regular wave as function of W_{10} and for a and in the direction of the true wind.

2.4. Propellers mathematical model

The propulsion force delivered by the two identical propellers is,

$$T_P = \rho_w n^2 D_P^4 (K_{T,P1} + K_{T,P2}), \quad (10)$$

where ρ_w is the seawater density at standard atmospheric conditions, n is the propeller's rotational velocity, D_P is the disc diameter of each propeller and $K_{T,P1} = K_{T,P2} = K_T$ are the propellers thrust coefficients evaluated using a polynomial fit of the experimental results for the Wageningen B-series screw propellers [12]. They depend on the advance coefficient given by

$$J = \frac{U}{nD_P}, \quad (11)$$

as well as the pitch to diameter ratio $\frac{\xi}{D}$, the blade area ratio $\frac{A_E}{A_o}$ and the number of blades Z . Thus, assuming a uniform inflow equals to the velocity of the platform (U), the thrust coefficients is expressed as,

$$K_T = f\left(J, \frac{\xi}{D_P}, \frac{A_E}{A_P}, Z\right). \quad (12)$$

For more details, the reader is referred to [12]. The power consumed by the propellers is expressed as function of the propellers' torque such as,

$$P_P = 2\pi n Q_{P1} + 2\pi n Q_{P2}, \quad (13)$$

where $Q_{P1} = Q_{P2} = Q_P$ and expressed as,

$$Q_P = \rho_w n^2 D_P^5 K_Q, \quad (14)$$

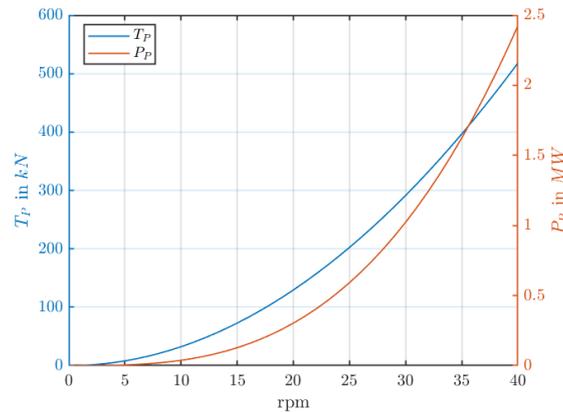


Figure 4. Propellers' thrust force T_P and consumed power P_P as function of the rotational velocity, for an inflow velocity of 0 m/s , corresponding to the case of dynamically positioned floating platform.

with K_Q denoting the torque coefficient of the propeller.

Figure 4 shows the thrust force and the power consumption as function of the rotational velocity for the propellers, each having the following characteristics: 6 m diameter, 1.4 pitch diameter ratio, 0.3 blade area ratio and 3 blades. One can notice that when increasing the rotational velocity, the thrust force and the consumed power are also increased.

2.5. Net power production

In the dynamically positioned wind turbine concept, part of the electric power generated by the wind turbine P_T (equation 5) is used to power the propellers P_P (equation 13). The remaining net power production P_{net} is stored in an energy storage system. Thus,

$$P_{net} = P_T - P_P. \quad (15)$$

2.6. Velocity and power prediction program

A velocity and power prediction program has been developed in Matlab. It solves the equilibrium equation described in section 2.1. It allows evaluating the rotational velocity of the propellers, their power consumption, the wind turbine power generation and the net power production.

3. Results

3.1. Power curve

Figure 5 shows the wind turbine generated power, propellers power consumption, net power production and propellers rotational velocity as function of the wind speed at the nacelle height. A net positive power is achieved for a wind velocity in the range 4 m/s to 18.3 m/s . The peak power (0.89 MW) is achieved for a wind speed (at the nacelle height) of 13.4 m/s . Beyond 18.3 m/s , the propellers' power consumption becomes greater than the generated power resulting in negative net power. Hence, overall, the range and the magnitude of net positive power achieved by this concept is less than that achieved by a conventional floating offshore wind turbine.

Moreover, Figure 5 shows that the propellers' rpm, hence, the power consumption increases with increasing wind speed because of increasing wave drift and wind turbine thrust forces, except in the range of wind speed between 11.4 m/s and 13.4 m/s . This decrease can be

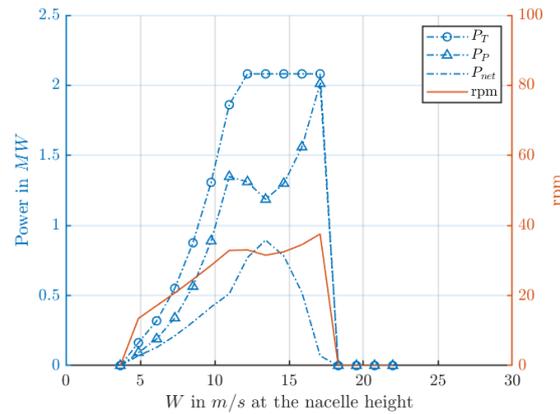


Figure 5. Power curve of the dynamically positioned wind turbine.

explained by the fact that the wind turbine thrust decreases for wind speeds greater than 11.4 m/s . Nevertheless, despite the wind turbine thrust is still decreasing beyond 13.4 m/s wind speed, the propellers' power consumption increases because of the increasing wave drift force.

3.2. Sensitivity to the wind turbine and propellers dimensions

In this section, the sensitivity of the net power production to the wind turbine and propellers dimensions is studied. The wind turbine diameter is varied between 10 m and 110 m with an increment of 10 m . The hub heights is defined according to the rotor's diameter based on the data provided by [13]. The propellers' diameter is varied between 3 m and 10 m with an increment of 1 m . The true wind speed is set to 11 m/s at 10 m elevation above sea level.

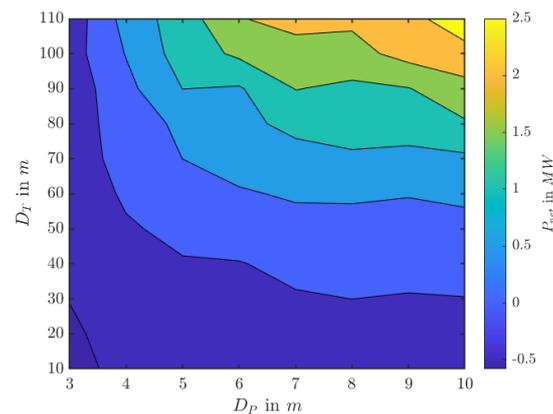


Figure 6. P_{net} as function of the propellers' diameter D_P and the turbine's diameter D_T .

Figure 6 shows the net power production as function of the wind turbine diameter (D_T) and propellers diameter (D_P). One can see that the generated net power increases with increasing wind turbine and propellers' diameters.

It appears that the smaller the propellers' diameter, the larger the wind turbine diameter is required to achieve positive net power production. The reason is that propellers with large

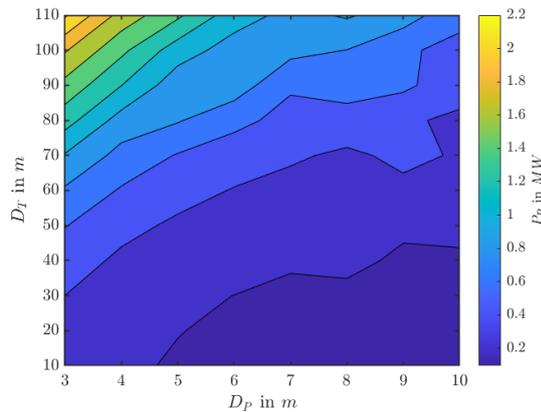


Figure 7. Power consumed by the propellers.

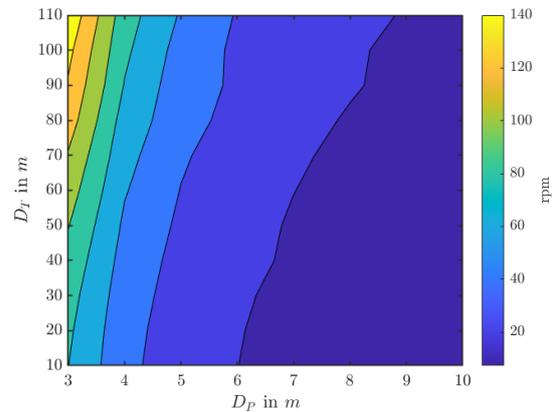


Figure 8. Propellers' rotational velocity.

diameters are more energy efficient than small propellers. This is shown in Figures 7 and 8, which respectively represent contour plots of the propellers power consumption P_P and rotational velocity as function of D_P and D_T .

In this study, the diameter of the wind turbine is 78 m diameter and the diameter of the propellers is 6 m. Figure 6 shows that propellers of even greater diameter can increase the net power production. Nevertheless, the investigation of the capacity factor is next conducted for propellers of 6 m because they are believed to be quite big already.

3.3. Capacity factor of dynamically positioned wind turbines operating in the far offshore

In this section, the capacity factor of dynamically positioned wind turbines that would be deployed in the far-offshore is estimated and compared to hypothetical moored floating wind turbines deployed in the same locations. Following Abd-Jamil et al. [14], average capacity factors over the years 2015, 2016 and 2017 have been estimated. The wind data was obtained from the ERA-Interim data-set provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) [15].

Results for moored floating wind turbines are shown in figure 9, showing that very high capacity factors, in the range of 40% to 70%, could be achieved. These results are in agreement with capacity factors estimates derived by Dupont et al. [16]. For the sake of comparison, it can be noted that the average capacity factor for offshore wind farms currently operating in Europe is 37% [17]. For the dynamically positioned wind turbine concept, this capacity factor is reduced to a maximum of 15% compared to the hypothetical moored system. This can be related to the smaller rated power range and the addition of propellers which consume power.

4. Conclusion

In this paper, the concept of dynamically positioned wind turbines was investigated. A model was developed which enables the velocity and power performance of a dynamically positioned wind turbine to be estimated as a function of environmental conditions.

Using this model, it was shown that a positive net power can be achieved for an example design (2 MW wind turbine mounted on a 40 m square barge equipped with two propellers of 6 m diameter) for wind speeds ranging between 4 m/s and 18.3 m/s at the nacelle height (that is between 3.28 m/s and 15 m/s at 10 m elevation). For the proposed operation of this concept, in which the rotational velocity of the propellers is controlled to maintain the position of the wind turbine, a capacity factor of 15% can be achieved if deployed in the North Atlantic Ocean. This does not preclude the possibility that other design parameters and platform types as well

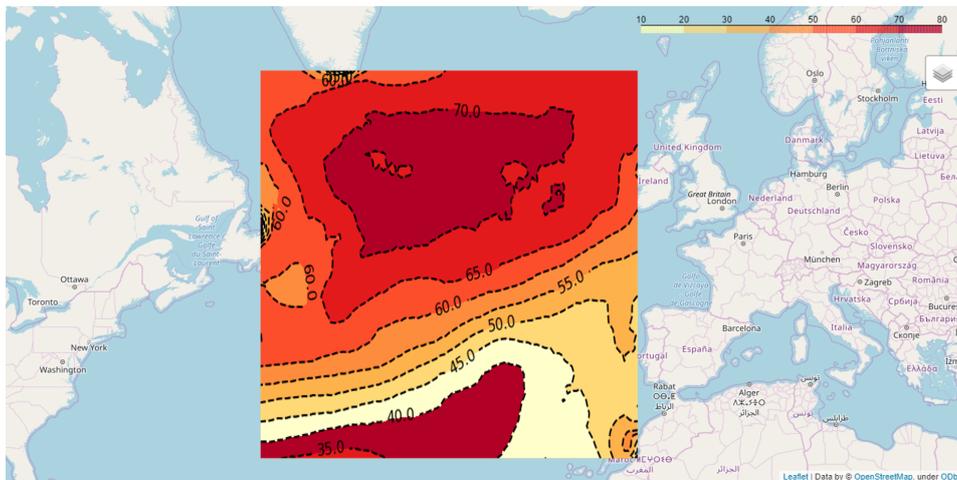


Figure 9. Mean capacity factors - from 2015 to 2017 - of a hypothetical 2 MW moored floating offshore wind turbines deployed in the North Atlantic Ocean.

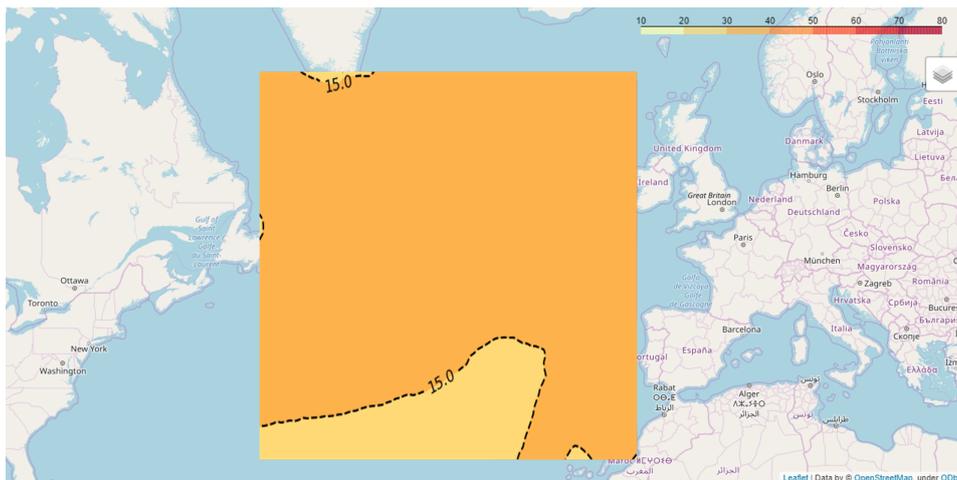


Figure 10. Mean capacity factors - from 2015 to 2017 - of a 2 MW dynamically positioned floating offshore wind turbines deployed in the North Atlantic Ocean.

as propellers types may be considered so that resisting forces are minimized, which may lead to greater capacity factors.

Finally, with respect to energy cost, significant savings in CAPEX can be expected for dynamically positioned wind turbines, as they require neither moorings nor anchors. In addition, this concept is well suited for far offshore applications, where grid-connection is challenging. However, dynamically positioned wind turbines require on-board energy storage and a means to transport energy to the end users. They would also need very reliable propellers. Therefore, further research is required regarding the type and the cost of the energy delivered to end users.

Acknowledgments

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