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Comparison of the capacity factor of stationary wind turbines and weather-routed energy ships in the far-offshore

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Abstract. Offshore wind energy technology has developed rapidly over the last decade. It is expected to significantly contribute to the further increase of renewable energy in the global energy production in the future. However, even with floating wind turbines, only a fraction of the global offshore wind energy potential can be harvested because grid-connection, moorings, installation and maintenance costs increase tremendously as the distance to shore and the water depth increase. Thus, new technologies enabling harvesting the far offshore wind energy resource are required. To tackle this challenge, mobile energy ship concepts have been proposed. In those concepts, electricity is produced by a water turbine attached underneath the hull of a ship propelled by the wind using sails. It includes an on-board energy storage system since energy ships are not grid-connected. Thus, the ships route schedules could be dynamically optimized taking into account weather forecast in order to maximize their capacity factors (CF). The aim of this study is to investigate how high the capacity factors of energy ships could be when using weather-routing and compare them to that of stationary wind turbines that would be deployed in the same areas. To that end, a modified version of the weather-routing software QtVlm was used. Velocity and power production polar plots of an energy ship that was designed at LHEEA were used as input to QtVlm. Results show that capacity factors over 80% can be achieved with energy ships and stationary offshore wind turbines deployed in the North Atlantic Ocean.

Keywords. Offshore wind energy, Energy ship, Capacity factor, Weather-routing

1. Introduction

The capacity factor CF (%) is a key metric to quantify the energy performance of a power generation source. It is defined as the ratio between the effective average power over a given period and the nominal power. In terms of energy, this corresponds to the ratio of the actual electrical energy produced by a system over a given period of time to the energy it would have produced if it had operated at its nominal power during the same period.

In [11], Capps & Zender showed that the average capacity factor for 5MW offshore wind turbines for locations characterized with class 3 wind speeds and water depth smaller than 200m is in the order

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of 38 to 49%. In practice, capacity factors of 40 to 50% have been reported for offshore wind farms [1]. They are significantly greater than land-based installations; thanks to higher wind speeds in open ocean areas in comparison to areas over land [2]. However, these CF are for offshore wind farms that are located near-shore. To date, it is unclear whether even greater CF can be achieved by deploying wind energy plants further offshore.

Moreover, an alternative technology for far-offshore wind energy conversion is the energy ship. In energy ships, electricity is produced by a water turbine attached underneath the hull of a ship propelled by the wind using sails. Energy ships include an on-board energy storage system (e.g a Power-to-Liquid production plant for renewable fuel production [3]) since energy ships are not grid-connected. Energy ships being mobile, their route schedules can be dynamically optimized taking into account weather forecast in order to maximize their CF. Although the concept is clear, to our knowledge, there has not been yet a study that investigates the CF of weather-routed energy ships.

Obviously, the most relevant criterion for comparing energy ships and stationary offshore wind turbines is the levelized cost of energy. However, it is not possible to perform such a comparison at present because there is not yet a cost model available for energy ships (because this new concept is in the very early stages of development). Therefore, in this study, it is assumed that the rated velocity of the energy ships is similar to that of current offshore wind turbines which allows the capacity factors of those two technologies to be compared.

2. Data

2.1. Wind speed data

In this study, 10m wind speed data for years 2015, 2016 and 2017 is used. It was obtained from the ERA-Interim dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis.

2.2. Offshore wind turbine power curve

In this study, we considered a 5MW horizontal axis wind turbine. Figure 1 shows the power curve that was used. The nominal wind speed is 11.4 m/s. The cut-in wind speed is 4 m/s and the cut-off wind speed is 25 m/s. It corresponds to a bottom-fixed offshore wind turbine. It has been assumed that the effect of the motion of the platform supporting the wind turbine on its energy performance is negligible.

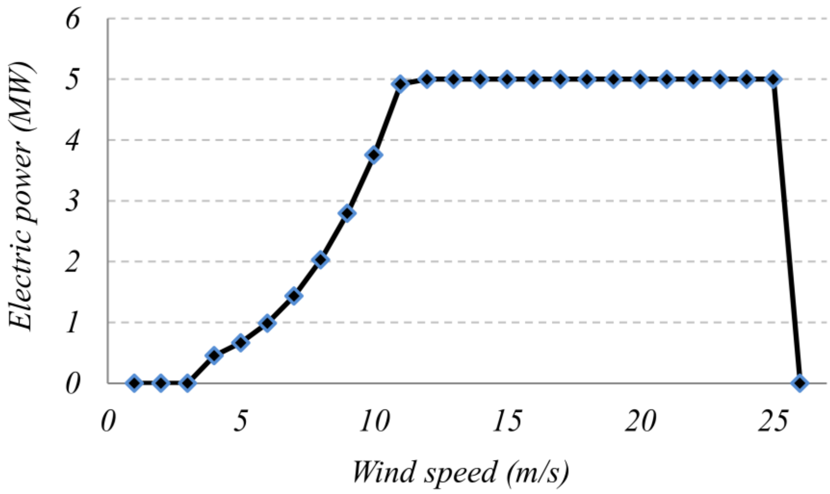

Figure 1. Power curve for the 5MW wind turbine

2.3. Boat Speed and Power Polar

A preliminary design of an energy ship has been developed at LHEEA. It is a 80m long catamaran fitted with four (27m tall, 4m diameter) Flettner rotors, which correspond to the dimensions of the rotors of the “e-ship 1” ship [12]. The performance of the energy ship is characterized by polar plots for its speed and power production. Those plots relate the speed of the boat (U) or the produced power to the true wind speed (TWS) and true wind angle (TWA). They have been obtained using an in-house velocity and power performance program (VPPP) [5]. The polar plots are shown in Figure 2. The rated power of 1MW was chosen in order to allow a fair comparison to the wind turbine. Indeed, it is achieved for a true wind speed of 20 knots (10.2 m/s) which is close to the nominal wind speed of the wind turbine (11.4 m/s). Moreover, note that the wind speed for the wind turbine is the wind speed at hub height, whereas the wind speed for the energy ship is at 10m.

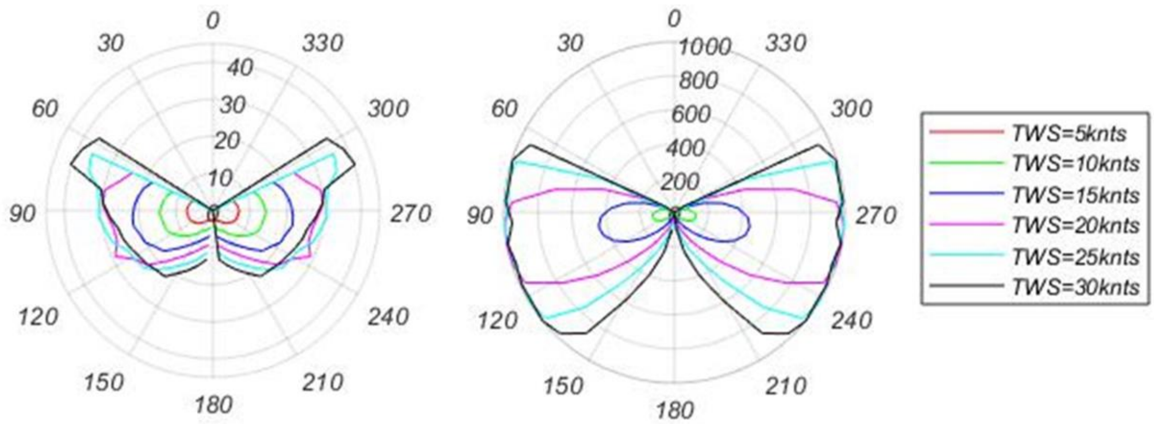

Figure 2. Polar plots for the velocity (left, in knots) and power production (right, in kW) for the energy ship of 1 MW rated power; 6 different true wind speeds (TWS) are shown in both plots ranging from 30 knots (outer curve), then 25 knots, 20 knots, 15 knots, 10 knots and 5 knots (innermost curve); for power production polar plot, the innermost curve of 5 knots TWS hardly to be seen because only 10 kW power were produced.

3. Data

3.1. Route optimization using QtVlm

Weather routing was performed using the QtVlm software [7]. It is a free navigation and weather routing software designed for sailing boats. It also enables viewing grib files (weather data files) at different geographical and temporal resolution.

3.2. Optimization criterion

In the standard version of QtVlm, the optimization criterion is the travel duration from the starting point A to the arrival point B. QtVlm uses the isochrones method to find an optimal route. The isochrones method [4] is a practical deterministic method for finding the minimum time route obtained through varying ship headings while assuming constant engine power [8]. The software includes the possibility to further improve the travel duration by optimizing the location of the nodes of the optimal route using the simplex method.

A dedicated version of QtVlm was developed in order to be able to optimize the capacity factor over the route instead of the travel duration. The new optimization criterion is defined by:

$$C_F = \frac{\int_0^T \tilde{P}(t)dt}{(T+6)P_{rated}}$$

With:

- C_F is the capacity factor
- T is the route duration (in hours)
- $\tilde{P}$ is the power produced by the energy ship
- P_{rated} is the rated power of the ship

The 6 hours in the denominator of the optimization criterion account for the time necessary to unload the stored energy, and to prevent the optimization from converging to very short routes.

An important constraint to take into account in the optimization process is the limited energy storage capacity aboard the ship. Thus, we introduced the filling ratio F that we define as the ratio of the energy stored in the energy reservoir $E = \int_0^T \tilde{P}(t)dt$ to the reservoir capacity, E_{max}. We assume that the reservoir capacity is 7 days and 6 hours (174 hours) at rated power (E_{max}=174P_{rated}). Thus, the filling ratio is:

$$F = \frac{\int_0^T \tilde{P}(t)dt}{174P_{rated}}$$

To take into account the limited storage capacity, the produced power is set to 0 if the filling ratio reaches 1. If not, the produced power is obtained by interpolating in the power production polar plot (Figure 2) as function of the true wind speed and true wind angle at the ship location ($\tilde{P} = P(TWS, TWA)$) except during maneuvers. It is assumed that maneuvers (which correspond to events during which the axis of the ship crosses the axis of the wind) last for 15 minutes. During maneuvers, the produced power and ship velocity is reduced to 25% of the power and velocity in the polar plots.

Finally, the produced power $\tilde{P}$ is given by:

$$\tilde{P}(t) = \begin{cases} 0 \; if \; F \geq 1 \\ 0.25P(TWS, TWA) \text{ during maneuver} \\ P(TWS, TWA) \text{ otherwise} \end{cases}$$

3.2.1.Optimization method

The optimization process requires the specifications of a starting point and an arrival point for the energy ship. It has been assumed that those points are one and the same point. This is because we assume that the energy ship meets in this location a platform or a tanker for unloading the stored energy.

We selected a point where there appears to be favorable wind conditions. The chosen location is at N 54, 516660; W 27,551844. It is in the North Atlantic storm track which offers high density of wind resource [2][10][11].

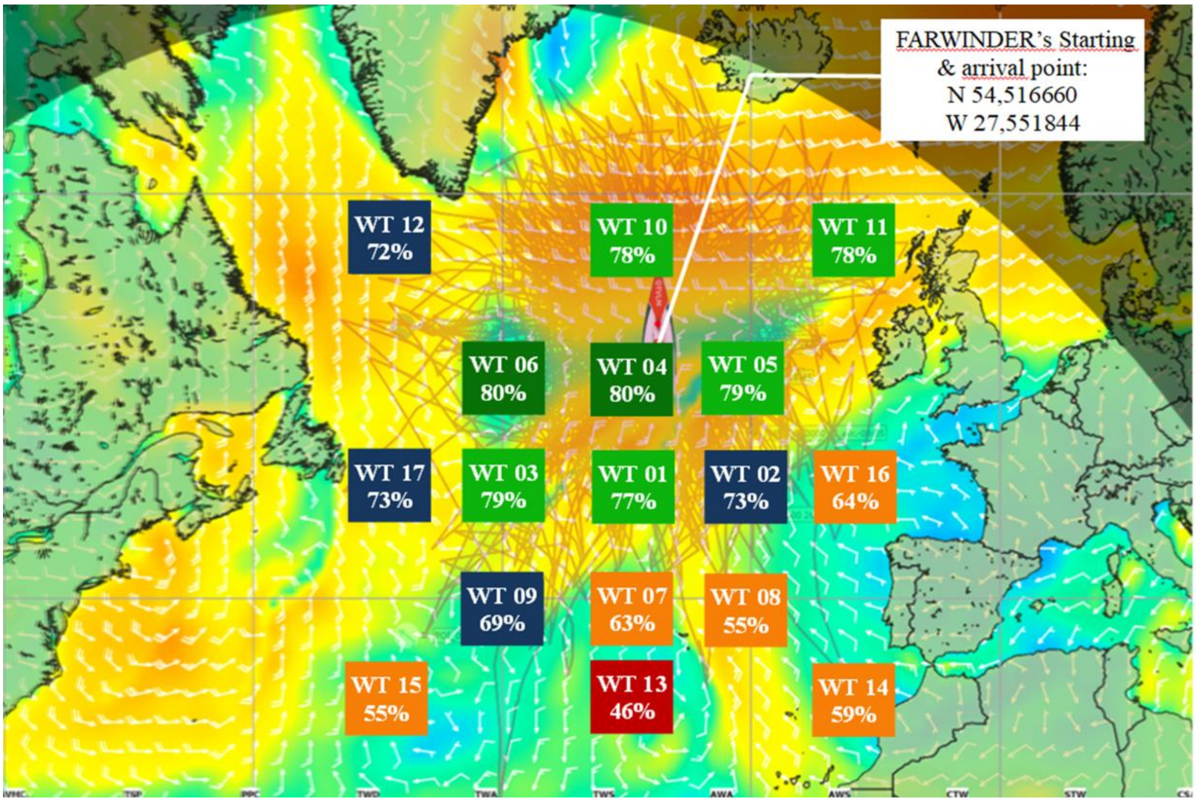

Figure 3. Tested locations for the wind turbines and average capacity factor over the three years of 2015, 2016 and 2017

Then, in order to initialize the optimization, six points of interest (POIs) are placed around the boat. The seventh POI is located back to the starting point.

The first step of the optimization is to optimize the position of the six first POIs. This is done using the simplex method which is available in QtVlm. Then, additional POIs are added on the optimized route and the optimization algorithm is re-run. This process is repeated until no further significant gain is achieved for the capacity factor.

Then, the data from the route logbook and route comparator table is saved, the new starting date time is set to the arrival time of the last route plus 6 hours (to account for the time necessary to unload the stored energy), and the optimization process is started again in order to calculate the new optimal route for the next period. This process allowed us to calculate an optimized capacity factor over the three years of 2015, 2016 and 2017.

3.3. Floating wind turbine capacity factor using QtVlm

The assessment of the capacity factors for stationary 5MW floating offshore wind turbines hypothetically deployed in the North Atlantic ocean also has been performed using the QtVlm software. In that case, the polar plot for the velocity were set to zero and the polar for the power was derived from the wind turbine power curve (Figure 1). Extrapolated wind data at the altitude of the hub (90m) using power law profile [13] has been used to calculate the CF for stationary wind turbine.

4. Results and discussion

4.1. Capacity factor of offshore wind turbines installed in the North Atlantic ocean

Figure 3 shows the results for the capacity factor of stationary offshore wind turbines hypothetically deployed in the North Atlantic Ocean. Seventeen different locations (indicated by the boxes in Figure 3) were considered, covering part of the North Atlantic Ocean between 30° to 60° North and 0° to 60° West. The starting and arrival point for the energy ship is also shown in the Figure 3.

One can see that the capacity factor varies significantly depending on the location of the wind turbine. The smallest capacity factor (46%) is obtained for wind turbine #13 which is one of the most southernly located turbine. The greatest capacity factor 80% is obtained for wind turbines #4 and #6 which are located in the northern part of the area, close to the starting point of the energy ship.

Overall, it can be seen that the capacity factor is primarily driven by the longitude, and secondly by the latitude. Wind turbines deployed northern than 45° N have capacity factors greater than 75% except in the West of the area (72% for wind turbine #12). Close to 45° N, the capacity factor varies from 64% to 79% depending on the latitude. It can be observed that the capacity factor decreases with getting closer to Europe (64% for wind turbine #16). The smallest capacity factors are obtained for the four wind turbines located on the most southern line (46% to 59%).

4.2. Optimization of the capacity factor of the energy ship

Table 1. Results for the optimization of the capacity factor of the 1MW energy ship.

Year	-	2015	2016	2017
Annual average CF	%	81	83	81
Best CF over one route	%	95	95	94
Worst CF over one route	%	46	55	60
Average route duration	Day (s)	6	6	6
Longest route duration	Day (s)	15	11	11
Shortest route duration	Day (s)	1	2	2
Longest route distance	NM	7480	6073	5730
Shortest route distance	NM	907	1140	1576
Average filling ratio at the end of the routes	%	68	71	69

Table 1 shows the results for the optimization of the capacity factor of the energy ship over the years 2015, 2016 and 2017. One can see that the annual average of capacity factor is very high. It consistently exceeds 80% for the three years. The average over the three years is greater than 81%. It reaches 83% for the best year which is 2016.

The best capacity factor achieved over one route is in the order of 95%, which means that route optimization enabled the energy ship to sail in highly favorable conditions over the whole duration of the route. More important, it can be seen that the worst capacity factor over one route over the three years is still very high (46%). Indeed, it is comparable to the capacity factors that have been reported for existing offshore wind farms [1].

Finally, the average filling ratio over the three years is 69% and the average route duration is 6 days. Thus, it seems that the assumed energy storage capacity (7 days and 6 hours at rated power) is sufficient. However, this needs to be confirmed by running sensitivity studies for the effect of storage capacity on the capacity factor and route duration.

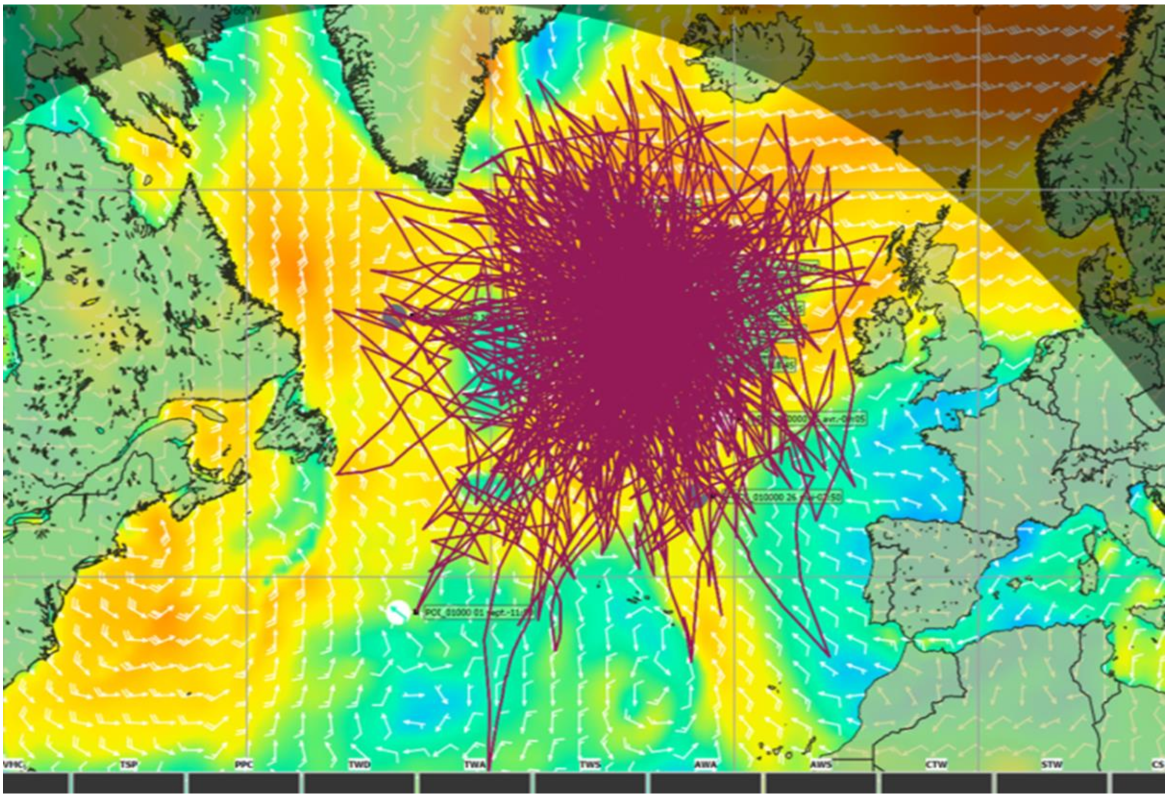

Figure 4. Traces of the optimized routes followed by the energy ship over the three years of 2015, 2016 and 2017

Figure 4 shows the superimposition of the traces of all the optimized routes followed by the 1MW ship over the three years. It shows that the ship's trajectories cover a large part of the North Atlantic Ocean. The trajectories appear to be random; no typical pattern can be identified.

However, it seems that most of the time, the ship sails in the area corresponding to the North Atlantic storm track, where wind is known to be high. This area is also known for the harsh sea conditions. Harsh sea conditions are known to reduce the velocity of marine vessels in comparison to their capabilities in calm water. This effect has not yet been taken into account in the velocity and power polar plots for the energy ship performance.

Finally, we recall that a six hours gap between the arrival time of one route and the starting time of the next route is assumed to account for the time required to unload the stored energy from the energy ship to the platform or a tanker. This has an effect on the average capacity factor. Indeed, as the average route duration is 6 days, it can be estimated that the cost of the unloading operation is 360 hours per year. It corresponds to a loss of 4% of capacity factor in comparison to a case for which this time would have been used to produce energy at rated power.

5. Conclusion

In this study, we compared the capacity factors of energy ships to stationary offshore wind turbines that would be deployed far-offshore in the North Atlantic Ocean. The capacity factor of the energy ships is optimized using weather-routing.

We found that energy ships can achieve very high capacity factor. Indeed, it exceeds average 82% for the three years of 2015, 2016 and 2017. In comparison, the greatest capacity factor for the stationary offshore wind turbine is also high, 80%.

Therefore, this study highlights that moving further offshore will increase significantly the CF of stationary wind turbine. Furthermore, with the same available wind resources and over the same geographical area, an energy ship also may increase even more the CF. However, this promising result for the capacity factor of energy ships needs to be refined. It includes sensitivity studies as function of the storage capacity aboard the energy ships and the rated power, also taking into account the effect of sea conditions on energy ships' performance.

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