Wind Trawler: operation of a wind energy system in the far offshore environment

A M Annan¹, M A Lackner¹ and J F Manwell¹

¹ Department of Mechanical Engineering, University of Massachusetts Amherst, Amherst, MA 01003, USA
aannan@umass.edu, lackner@ecs.umass.edu, manwell@ecs.umass.edu

Abstract. A great untapped wind resource lies within the deep oceanic environment far from shore. Considering the technological and economic challenges of fixed offshore wind platforms to operate at great offshore depths and distances, we propose that this resource best be exploited by the use of a mobile floating wind-and-hydro power producing plant, termed the Wind Trawler. This paper explores preliminary design considerations for wind turbine, hydro turbine, and hull to optimize power performance ensure stability. The wind speed is modelled using long term averages from hindcast software to compare power production of a Wind Trawler and fixed wind turbine in the offshore environment.

1. Introduction
Currently, most global offshore wind deployments are sited in shallow or transitional (<50 m) water depths, typically within 50 km to shore, [1], and use substructures that are fixed-mounted directly to the seabed. A large concentration of the global wind resource, however, is in deeper waters farther from shore. Of the U.S.’ technically viable offshore resource potential, 59% is in deep water (>60 m), which is unsuitable for fixed substructures [2]. Considering the coasts specifically, along which over half of the U.S. population resides, 28.1% of the east coast resource and 97.5% of the west coast’s resource lie in deep water. In Europe, the North Sea is home to 90% of the world’s installed offshore wind development, and 66% of its technically available resource is in deep water [3]. In Japan, at least 80% of the resource is in deep water.

As society transitions from an energy system supplied primarily by fossil fuels to one supplied predominantly by renewable sources, offshore wind development will need to extend to deeper waters and farther from shore, spurring the need for substructures which can accommodate such depths. To access deeper waters, floating substructures are under development, with a few pre-commercial projects now installed and operating, and large-scale development likely to occur in the coming decade [4]. Floating substructures have additional technical and economic challenges, however, including mooring system assembly and installation in the unpredictable ocean environment, costs of electricity transmission, and cost of maintenance, all of which scale with offshore depth or distance.

Considering the energy transition more broadly, increased penetration of intermittent renewables poses challenges to the grid, in terms of satisfying baseline and peak power. Storable and dispatchable fuels may have an important role in filling a power void during low production levels. In addition, although the energy transition forecasts an almost complete electrification of the global energy supply, there is a continued need for energy sources in applications where electrification is difficult or impractical [5]. These applications range from chemical or agricultural industry feedstocks to marine and long-distance rail transportation fuel. For example, hydrogen is expected to serve as a versatile and multi-purpose energy source. It is already utilized in some situations for powering vehicles and as
a supply for ammonia, due to an increased demand for agricultural fertilizer as the global population continues grow. In light of the technical and economic challenges faced by offshore wind development in deep waters far from shore, as well as the need for dispatchable sources of energy in the energy transition, there is an opportunity to address both challenges with an innovative offshore wind concept—the Wind Trawler. The Wind Trawler is a floating, unmoored, and mobile-platform concept that generates energy in deep waters far from shore and produces dispatchable, storable hydrogen (or possibly ammonia, though this option is not considered in this paper). The Wind Trawler may mitigate (site investigation, permitting) or eliminate (mooring, transmission costs) certain challenges and costs of floating offshore wind, while producing a flexible fuel with high value in the global energy market. The Wind Trawler differs from conventional fixed-foundation wind turbines and floating offshore wind turbines (FOWTs) both in the form of the energy it delivers (fuel rather than electricity) and in its system architecture (floating unmoored hull, hydro turbines, fuel production). A conceptual Wind Trawler configuration considered for this paper is shown in Figure 1.1. The system consists of a turbine (here shown as downwind) mounted on a floating and unmoored hull that is steered via two hydrokinetic turbines, and powers a hydrogen fuel synthesis and storage plant.

The goal of this paper is to present design considerations of a Wind Trawler with respect to the interactions of hull, wind turbines, and hydro turbines in a simplified dynamic offshore environment to generate power and store energy during steady state operation for varying ambient wind conditions. Once the configurations of the wind turbine, hydro turbine(s), and hull are specified to optimize power production, the performance in realistic wind conditions is compared to a fixed wind turbine close to shore.

2. Background and Motivation

2.1. Wind Turbine Propulsion of Ships

The combination of a wind turbine and a mobile platform has been investigated in prior literature to identify more efficient methods of ship propulsion, as well as to demonstrate that a wind turbine-propelled ship can navigate directly upwind, using only its own generated power [6]. It was shown that for the same tanker hull, a wind turbine-propelled ship was more efficient and produced less heeling moment than a wingsail with a sail area equivalent to the wind turbine rotor disk area. A wind turbine’s stability when mounted on a ship is dependent on the thrusts and moments imposed on the Trawler center of mass, detailed in Section 4.3. Instead of propulsion as the primary objective, the concept presented in this paper prioritizes energy generation using wind and hydro turbines.
2.2. Wind Trawler Similar Concepts

Concepts similar to the Wind Trawler have been proposed, which produce hydrokinetic power in lieu of, rather than in addition to, wind power. Instead of using wind turbine thrust as the propulsion mechanism, efforts such as the FARWIND project [7] and sailing hydrogen-producing ships modelled at University of California Davis use conventional wingsails to produce motion, and use submerged hydrokinetic turbines to generate hydro power proportional to the water velocity of the ship. The FARWIND project indicates that one of the key advantages to a mobile offshore renewable energy system is the ability to meteorologically predict the wind and navigate towards the strongest resource, significantly boosting capacity factor (CF). Authors at the University of California Davis [8] highlighted the advantage of optimizing performance of the sailing ship independent of scale using non-dimensional ratios of turbine rotor area to sail area, and vessel wetted area to sail area.

3. Preliminary Design

3.1. Wind and Hydro Turbine Control System

At any instant, the Wind Trawler turbines’ rotors are normal to, and the hull’s longitudinal axis is parallel to, the ambient wind. Assuming still water (i.e. no current), the propulsive mechanism for the Trawler is wind turbine thrust. The thrust in turn produces the Trawler’s water velocity experienced by the hydro turbines and in the same direction of the wind. Also resulting is a relative wind speed at the wind turbine that is less than a ambient. From one-dimensional momentum theory, a Wind Trawler’s wind turbine and hydro turbine thrust can be written as:

\[ T_{\text{wnd}} = \frac{1}{2} C_{t,\text{wnd}} \rho_a A_{\text{wnd}} (U_{\text{wnd}} - V_{\text{tr}})^2 \]

\[ T_h = \frac{1}{2} C_{t,h} \rho_w A_h V_{\text{tr}}^2 \]

Similarly, the turbines’ mechanical power can be written as:

\[ P_{\text{wnd}} = \frac{1}{2} C_{p,\text{wnd}} \rho_a A_{\text{wnd}} (U_{\text{wnd}} - V_{\text{tr}})^3 \]

\[ P_h = \frac{1}{2} C_{p,h} \rho_w A_h V_{\text{tr}}^3 \]

Where \( T_{\text{wnd}} \) is wind thrust, \( C_{t,\text{wnd}} \) is the wind thrust coefficient, \( \rho_a \) is the sea air density, \( A_{\text{wnd}} \) is the wind turbine rotor area, \( U_{\text{wnd}} \) is the ambient wind speed, \( V_{\text{tr}} \) is the Trawler’s velocity in water, \( T_h \) is the hydro turbine thrust, \( C_{t,h} \) is hydro thrust coefficient, \( \rho_w \) is the seawater density, \( A_h \) is the hydro turbine rotor area, \( C_{p,\text{wnd}} \) is the wind turbine power coefficient, and \( C_{p,h} \) is the hydro turbine power coefficient. Both wind and hydro turbines are variable speed and pitch regulated. Typical thrust and power curves for a horizontal axis turbine are shown in Figure 3.1. The parameters are normalized to generalize trends independent of a particular turbine’s configuration of rated power, rated flow (water or wind) speed, axial induction factor, and rotor area. Thrust and power coefficients are constant at \( C_{t,0} \) and \( C_{p,0} \) respectively for flow speeds ranging from cut-in to rated. As expected, rated power and maximum thrust are obtained at rated flow speed. For flow speeds greater than rated, the generator maintains rated power, and therefore a drop in power coefficient \( C_p \) as well as \( C_t \) must accommodate an increase in wind speed. Thrust also decreases since it is proportional to the square, rather than the cube, of the flow speed.
3.2. Force Balance and Dimensionless Coefficients

To estimate power production from a Wind Trawler, the Trawler’s relative velocity in the water must be determined such that a steady state equilibrium exists. For still water relative to a fixed reference frame, the Trawler is in steady state equilibrium when forces from wind thrust, hydro thrust, and hull resistance are in balance. This force balance can be written as:

\[ N_{wnd} \frac{1}{2} C_{t,wnd} \rho_{a} A_{wnd} [U_{wnd,rel}]^2 = N_h \frac{1}{2} C_{t,h} \rho_w A_h V_{tr}^2 + \frac{1}{2} C_{R, tr} \rho_w A_{tr} V_{tr}^2 \]  \hspace{1cm} (3.2.1)

\[ N_{wnd} \] is the number of wind turbines, \( U_{wnd,rel} = U_{wnd} - V_{tr} \) is the relative wind velocity at the wind turbine, \( N_h \) is the number of hydro turbines, \( C_{R, tr} \) is the tanker coefficient of resistance, and \( A_{tr} \) is the tanker hull wetted area. The number of wind turbines and hydro turbines on a Wind Trawler configuration is considered a design variable for this general analysis, though likely designs would have 1 wind turbine and 2 hydro turbines.

Dimensionless coefficients are introduced to reduce the number of physical parameters, and to make the analysis easily scalable for wind turbine, hydro turbine, and Trawler configurations.

\[ C_h = \frac{N_h \frac{1}{2} C_{t,h} \rho_w A_h}{N_{wnd} \frac{1}{2} C_{t,wnd} \rho_{a} A_{wnd}} \]  \hspace{1cm} (3.2.2a)

\[ C_{tr} = \frac{\frac{1}{2} C_{R, tr} \rho_w A_{tr}}{N_{wnd} \frac{1}{2} C_{t,wnd} \rho_{a} A_{wnd}} \]  \hspace{1cm} (3.2.2b)
The force balance (3.2.1) is rewritten in terms of dimensionless coefficients:

\[ [U_{\text{wind}} - V_{\text{tr}}]^2 = [C_h + C_{tr}] V_{\text{tr}}^2 \]

\( V_{\text{tr}} \) and \( U_{\text{wind},\text{rel}} \) can be expressed as a linear function of \( C_h \& C_{tr} \),

\[ V_{\text{tr}} = \frac{1}{1 + \sqrt{[C_h + C_{tr}]/C_{tr}}} U_{\text{wind}} \]  

(3.2.3a)

\[ U_{\text{wind},\text{rel}} = \frac{\sqrt{C_h + C_{tr}}}{1 + \sqrt{[C_h + C_{tr}]/C_{tr}}} U_{\text{wind}} \]  

(3.2.3b)

Since neither the hydro turbine nor the wind turbine configuration is specified, it is advantageous to normalize both Trawler speed and relative wind speed each by the respected rated flow speed of the turbines, and present them as functions of \( C_h, C_{tr} \), as well as dimensionless parameters of ambient wind speed \( U_{\text{wind}} \) and ratio of rated wind speed to rated hydro speed \( U_{\text{wind,r}} \). Dimensionless ambient wind speed is useful since it may represent a typical ambient wind speed found in a geographic location relative to a wind turbine’s design rated speed.

\[ \frac{V_{\text{tr}}}{U_{\text{h,r}}} = \frac{1}{1 + \sqrt{[C_h + C_{tr}]/C_{tr}}} \frac{U_{\text{wind}}}{U_{\text{wind,r}}} \]  

(3.2.4a)

\[ \frac{U_{\text{wind},\text{rel}}}{U_{\text{wind,r}}} = \frac{\sqrt{C_h + C_{tr}}}{1 + \sqrt{[C_h + C_{tr}]/C_{tr}}} \frac{U_{\text{wind}}}{U_{\text{wind,r}}} \]  

(3.2.4b)

Where \( \frac{V_{\text{tr}}}{U_{\text{h,r}}} \) is the ratio of Trawler velocity to rated hydro speed, and \( \frac{U_{\text{wind},\text{rel}}}{U_{\text{wind,r}}} \) is the ratio of relative wind speed to rated wind speed. Normalized hydro power \( P_{h,\text{norm}} \), wind power \( P_{\text{wind,norm}} \), and total power \( P_{\text{tot,norm}} \) can also be written in terms of dimensionless parameters.

\[ P_{h,\text{norm}} = \frac{N_h P_h}{N_h P_{h,r}} = \frac{N_h}{N_h} \frac{1}{2} C_{p,h} \rho_w A_h [V_{\text{tr}}]^3 \frac{V_{\text{tr}}}{U_{h,r}}^3 \]  

(3.2.5a)

\[ P_{\text{wind,norm}} = \frac{N_{\text{wind}} P_{\text{wind}}}{N_{\text{wind}} P_{\text{wind,r}}} = \frac{N_{\text{wind}}}{N_{\text{wind}}} \frac{1}{2} C_{p,\text{wind}} \rho_w A_{\text{wind}} [U_{\text{wind},\text{rel}}]^3 \frac{U_{\text{wind},\text{rel}}}{U_{\text{wind,r}}}^3 \]  

(3.2.5b)

\[ P_{\text{tot,norm}} = \frac{P_{\text{tot}}}{P_{\text{tot,r}}} = \frac{N_{\text{wind}} P_{\text{wind}} + N_h P_h}{N_{\text{wind}} P_{\text{wind,r}} + N_h P_{h,r}} = \left[ \frac{[C_h + C_{tr}]^{1.5} + C_h}{U_{\text{wind,r}}^{1.5} + U_{h,r}} \right] \frac{V_{\text{tr}}}{U_{h,r}}^3 \]  

(3.2.5c)

where \( P_{\text{wind,r}}, P_{h,r}, P_{\text{tot,r}} \) are the rated wind turbine, hydro turbine, and total wind-and-hydro combined power capacities respectively of the Trawler.
3.3. Hydro Turbine Design
For any given Wind Trawler hull configuration, the hydro turbine design can optimize power performance. From Eqs. (3.2.2a & 3.2.2b), both $V_{tr}$ and $U_{wnd,rel}$ are expressed as linear functions of ambient wind speed normalized by the rated speeds of the hydro turbines and wind turbines respectively. $C_h$ and $C_{tr}$ can be optimized with respect to each other in order to obtain rated hydro power simultaneously to rated wind power, such that the Trawler system can obtain the total combined power capacity. The normalized equations for $U_{wnd,rel}$ and $V_{tr}$ in eqns. (3.2.4a) and (3.2.4b) can be rearranged and made equal to unity (and eventually each other):

$$\frac{V_{tr}}{U_{h,r}} = \frac{1}{1 + \sqrt{C_h + C_{tr}}} \frac{U_{wnd}}{U_{wnd,r}} = 1$$

$$\frac{U_{wnd,rel}}{U_{wnd,r}} = \frac{\sqrt{C_h + C_{tr}}}{1 + \sqrt{C_h + C_{tr}}} \frac{U_{wnd}}{U_{wnd,r}} = 1$$

Combining, one can solve for $C_h$ in terms of $C_{tr}$ and the ratio of rated turbine flow speeds $\frac{U_{wnd,r}}{U_{h,r}}$ such that the Trawler obtains its total combined power capacity:

$$[C_h + C_{tr}] = \left[\frac{U_{wnd,r}}{U_{h,r}}\right]^2$$

(3.2.6)

These general equations will be applied to a specific configuration in section 4.

4. Design of Wind Trawler for Specified Wind Turbine

4.1. Selection of Wind Turbine

The Wind Trawler is primarily a wind powered machine, since the wind turbine provides most of the total power generated and the driving thrust as it drifts. The DTU 10 MW Reference Wind Turbine [9] is a state-of-the-art wind turbine conceptual design used for research and is used in this paper. It has a rated power of 10 MW, radius of 89.15 m, rated wind speed of 11.4 m/s, tower height of 119 m, tower mass of 605,000 kg, and rotor nacelle assembly (RNA) mass of 675,000 kg. Rated thrust coefficient $C_{t,wnd}$ is 0.82 and rated power coefficient $C_{p,wnd}$ is 0.475.

4.2. Hull Design for Pitch Stability and Buoyancy

A tanker hull form was chosen for this work based on existing designs, though future work will consider an optimized hull form for this application. The tanker provides basic design parameters expected to be appropriate for the Wind Trawler, including the capacity for energy (fuel) storage. For a tanker, the basic geometry is typically characterized by the length between perpendiculars $L_{pp}$, the beam (width) $B$, the draught $T$ (distance from average still waterline level to the keel), and the depth $D$ (distance from the deck line to keel) [10]. Considering stability and buoyancy of the tanker in water, the total mass of water displaced by the tanker and cargo the displacement $\nabla$ must be equal to the total mass of the tanker and cargo $M_{tr}$:

$$\nabla = M_{tr}$$

(4.2.1)

Approximations for $\nabla$ exist in literature, but any case depends on length, beam, and draught:

$$\nabla \approx C_B L_{pp} BT$$

(4.4.1b)
The block coefficient $C_B$ gives the approximate ratio of a hull’s actual water displacement to volume of a theoretical rectangular prism with the same length, draught, and beam. It is hull form dependent, and here a value of 0.8 is used, which is typical for a tanker [11].

An existing tanker design does not necessarily account for the mass of the wind turbine as part of its deadweight, and ultimately the dimensions of the tanker can be scaled accordingly. Assuming that the original fuel storage system can be replaced with a hydrogen synthesis and storage system with negligible effect, the original displacement of the tanker can be scaled according to the additional mass of the wind turbine with the expression:

$$\frac{\nabla}{\nabla_0} = 1 + \frac{M_{WT}}{\rho_w \nabla_0} \quad (3.4.2)$$

where $\nabla_0$ is the original displacement and $M_{WT}$ is the mass of the wind turbine. To maintain geometric similarity of the scaled tanker, a linear dimension scaling parameter $\xi$ is introduced such that:

$$\nabla = \xi^3 \nabla_0$$

$$\xi = \left[1 + \frac{M_{WT}}{\rho_w \nabla_0}\right]^\frac{1}{3}$$

The Damen 3000 LNG reference tanker was selected for the preliminary design [12], since its specified deadweight is similar to the mass of the wind turbine. From an originally specified length of 99 m, beam of 11.3 m, and draught of 3.25 m, the original tanker displacement $\nabla_0$ is estimated as 2910 $m^3$ and assuming a density of 1035 kg/m$^3$ for seawater, a displacement mass of 3,012,000 kg. The additional wind turbine mass of 1,280,000 is 42.5 % of the displacement, and to keep a geometrically similar tanker, the length, beam, and draught must scale by $\xi = [1.425]^\frac{1}{3} = 1.125$, or 12.5%. The scaled tanker possesses length of 111.4 m, beam of 12.7 m, and draught of 3.66 m.

The Wind Trawler hull must also provide stability in the often-unpredictable ocean environment. The wind and hydro turbines are assumed to be oriented along the hull’s longitudinal (surge) axis and therefore oriented in the direction of the ambient wind. Still water is assumed and there are no environmental forces considered in sway (lateral) or heave (vertical). Roll stability is often a critical consideration for a ship’s operation at sea, however it is neglected under the present assumptions, since no forces acting on the Trawler in this analysis induce rolling tendency. The pitch overturning moment, which is maximized at the rated wind turbine thrust $T_{wind,max} = 1.5 MN$, occurs at rated wind speed $U_{wind,r}$ for the DTU 10 MW turbine. This thrust produces a pitch overturning moment $M_{OT}$ of 17.8 MN*m about the center of mass of the hull, which is assumed at the intersection of $L_{pp}$, $B$, and $T$ midpoints. The line of action of the hull resistance and hydro turbine thrust is assumed to intersect the hull center of buoyancy so as not to produce additional overturning moment. Stability of the tanker occurs when the restoring moment $M_R$ balances the overturning moment at a pitch angle $\theta_y$:

$$M_R = GM_y \theta_y \nabla \rho_w g = M_{OT}$$

Where $g$ is the acceleration due to gravity of 9.81 m/s$^2$, and $GM_y$ is the metacentric height, a measure of initial static stability of the hull. The overturning moment from wind thrust as well as restoring moments of the hull are shown in the free body diagram of Figure 4.1.

For a buoyant structure, $GM_y$ is dependent on the distance from keel to the center of buoyancy (center of displaced water volume) $KB$, the distance from center of buoyancy to metacenter $BM$, and the distance from keel to center of gravity (center of mass of Wind Trawler) $KG$:

$$GM_y = KB + BM - KG$$
Referencing from the keel of the hull, $KB$ is approximated as $T/2$, or half the tanker draught of 1.83 m. $KG$ is determined as the mass-weighted sum of the center-of-mass heights of the tanker, wind turbine tower, and wind turbine RNA as 29.82 m. $BM$ is calculated from the second moment of area of the tanker at the waterline $I_{yy}$ and tanker displacement using the expression:

$$BM = \frac{I_{yy}}{\nabla}$$

By approximating the tanker waterplane area as an ellipse with aspect ratio equal to the ratio of tanker length to beam, then $I_{yy} = 8.86 \times 10^5 m^4$ and $BM = 212 m$. Therefore $GM_y = 184 m$, and a restoring moment equal to the maximum overturning wind turbine moment is obtained when the Wind Trawler pitches at an angle $\theta_y = 1.89^\circ$. This satisfies typical specified maximum pitch (or heel for offshore wind platforms) angle limits for offshore wind turbine platforms of 5° [13] to prevent drastic reductions in annual energy production (AEP) due to a reduced rotor area, and to prevent significant tower bending moments.

The scaled Trawler hull satisfies the additional buoyancy required to mount a wind turbine and the restoring moment when the wind turbine is under maximum thrust conditions. The performance of the Wind Trawler for the selected hull can now be estimated. First, the wetted area of the hull $A_{tr}$ is determined, which can be approximated using the displacement, length, and draught of the hull [14]:

$$A_{tr} = 1.025 \left( \frac{\nabla}{T} + 1.7L_{pp}T \right) = 3770 m^2$$

The coefficient of resistance $C_{R, tr}$ is dependent upon the hull form, and a typical value for tankers is 0.003 [15]. Although assumed constant for this analysis, future work must consider $C_{R, tr}$ variability with water speed and its dependence upon waves and hull features such as keels. Therefore the dimensionless Trawler coefficient representing a stable configuration is:

$$c_{tr} = \frac{1}{2} \frac{C_{R, tr} \rho_w A_{tr}}{C_{t, wnd} \rho_a A_{wnd}} = 0.425$$

Figure 4.1. Overturning moment $M_{OT}$ caused by $T_{wind, max}$ about the center of buoyancy of the Trawler $Z_b$. $H_{wind}$ is the height of the wind turbine tower. $M_R$ is the restoring moment. $T_h$ is the hydro thrust, and $R_{tr}$ is the water resistance of the hull.
assuming an air density $\rho_a$ of 1.225 kg/m$^3$. In this configuration, the hydro turbines provide $60x \left( \frac{C_h}{C_{tr}} \right)$ the resistance of the hull.

4.3. Hydro Turbine Design for Wind Turbine and Hull Configuration

For a ratio of rated wind to hydro speeds $\frac{U_{wnd,r}}{U_{h,r}} = 5$ (a reasonable assumption for a rated wind speed near 10 m/s and rated hydro speed near 2 m/s) and dimensionless hull coefficient $C_{tr} = 0.425$ derived in Section 4.2, Figure 4.2 shows the effect of varying $C_h$ on normalized wind, hydro, and total power. $C_h$ is directly related to hydro turbine rotor area, and the effect of increasing hydro rotor area relative to wind turbine rotor area is to produce more resistive thrust against the wind thrust for any ambient wind speed below rated. A greater relative wind at the wind turbine, and thus greater wind power is generated. For the hydro turbines however, a greater relative wind means that the Trawler velocity and therefore hydro power is less. The optimum $C_h$ occurs when total normalized power is maximum, and the normalized wind power is equal to normalized hydro power, occurring at $C_h = 24.575$ for the current hull. Assuming the thrust coefficients of the wind and hydro turbine are equivalent to each other at rated conditions, $C_{tr}$ is independent of their value. So that the Wind Trawler can steer using the hydro turbines, $N_h$ is chosen as two, one on the starboard side and one on the port side of the hull. Rearranging eqn. (3.2.2a), this corresponds to a hydro-wind rotor area ratio $\frac{A_h}{A_{wnd}} = 1.5\%$ and radius of 10.9 m for a single hydro turbine.

![Figure 4.2. Normalized Wind, Hydro, and Total Trawler Power vs. Dimensionless Hydro Coefficient $C_h$.](image)

**Figure 4.2.** Normalized Wind, Hydro, and Total Trawler Power vs. Dimensionless Hydro Coefficient $C_h$. $\frac{U_{wnd}}{U_{wnd,r}} = 1.0$, $C_{tr} = 0.425$, and $U_{ratio} = 5$.

5. Operation in a Hypothetical Offshore Environment

The total power $P_{tot}$ generated by the Wind Trawler is a sum of the contributions by the wind and hydro turbines:

$$P_{tot} = P_{wnd} + N_h P_h$$
Both $P_{wnd} = \frac{1}{2} C_{p,wnd} \rho A_{wnd} (U_{wnd} - V_{tr})^3$ and $N_h P_h = \frac{1}{2} C_{p,h} \rho A_h [V_{tr}]^3$ are dependent upon the Trawler velocity according to the force balance of eq. (3.2.1), which includes wind thrust, hydro thrust, and hull resistance. Trawler power and velocity are plotted in Figure 5.1 for ambient wind speeds ranging from the cut-in to cut-out speeds of the wind turbine. The Wind Trawler produces approximately 70% of the fixed turbine power for ambient wind speeds in between cut-in and rated. Trawler velocity in this range increases linearly according to eq. (3.2.3a), and relative wind at the wind turbine according to eq. (3.2.3b). The effect of relative wind is that rated Trawler conditions are met at an ambient wind speed greater than the specified rated wind speed, as indicated by the shift of the wind power curve to the right from the fixed turbine’s curve (Figure 5.1 left). For wind speeds from rated (11.4) to 13.7 m/s, the fixed turbine power is constant at rated unlike the Trawler, whose wind and total power increase, eventually exceeding fixed wind power at ~ 12.9 m/s. At 13.7 m/s ambient wind, both the Trawler’s wind and hydro turbines reach rated conditions and thus Trawler power is maximized. At this point, Trawler velocity (also the water speed at the hydro turbines) is maximized. For greater wind speeds, Trawler turbine thrust and power coefficients are no longer held constant and decrease, since Trawler’s wind and hydro turbines must also decrease thrust to maintain rated power levels (referencing Figure 3.1). An iterative and interpolative solver was developed in the MATLAB computing software to solve for post-rated conditions, subject to the force balance eq. (3.2.1) and the turbine control systems.

A Wind Trawler has an advantage over conventional wind power development in that its mobility allows it to navigate to the strongest wind resource. This advantage is especially evident near coast lines, as the mean wind speed typically increases significantly with distance from shore, and wind power scales with the cube of the wind speed.

![Figure 5.1. (Left) Wind Trawler Power Curves: Total, Wind, & Hydro as well as Fixed DTU-10MW Wind Turbine Power vs. Increasing Ambient Wind Speed. (Right) Trawler Velocity.](image)

Using a hindcast meteorological dataset provided by MERRA [16], the long-term mean wind speed was sampled at several distances from shore off the coast of Portland, Maine, and plotted in Figure 5.2 along with a least-squares quadratic fit to the data. The data indicates how the wind speed varies with offshore distance and provides a general sense of the change in wind speed with depth since the offshore distance and depth are often correlated.

Energy production of a wind energy system at a particular site can be estimated using that site’s mean wind speed applied to the Rayleigh probability distribution and the wind speed power curve of the system. The Rayleigh probability distribution $p(U)$ has been widely utilized for wind speed in practice and literature [17], and can be used to estimate the mean power $\bar{P}$ according to $\bar{P} = \int_0^\infty p(U) P(U) dU$. 

\[ \bar{P} = \int_0^\infty p(U) P(U) dU. \]
where $P(U)$ is the power as a function of the ambient wind speed (according to Figure 5.1). The annual energy production $AEP$ measured in kWh is then $AEP = \bar{P} [kW] * 8760 [\text{h}]$ and the capacity factor $CF$:

$$CF = \frac{\bar{P}}{\bar{P}_{\text{wind},r}}$$

provides a measure of the average power production of a wind energy system during a period compared to an idealized situation in which the system is producing rated wind power constantly. $CF$ is calculated for increasing distance from the shore of Portland, Maine for both the Wind Trawler and fixed DTU-10MW wind turbine and plotted in Figure 5.3.

The figure indicates that at distances currently feasible for fixed wind turbines (0-60 km) [3], the Wind Trawler is not expected to perform as well as a fixed wind turbine. Within this region, it must operate ~40 km farther from shore to achieve the same estimated energy production as a fixed wind turbine. However, the Trawler’s siting is not (theoretically) limited by distance from shore or depth like the fixed wind turbine, and it can achieve as high as 44% capacity 240 km from shore, 9% greater than the maximum fixed wind turbine $CF$. What must also be accounted for in future work is the energy consumed by the Wind Trawler when transporting fuel and then navigating to its operating position, which will increase with distance offshore.
6. Conclusions and Future Work

A preliminary design of a Wind Trawler configuration using dimensionless parameters has been proposed. The Trawler hull was selected to provide stability considering the pitch overturning moment during maximum wind thrust conditions. Hydro turbines were sized such that rated hydro power is achieved simultaneously to rated wind power. Capacity factor (CF) for a Wind Trawler operating in a range of distances offshore from a known location was compared to that achieved by a fixed wind turbine operating in distances typical for conventional offshore substructures near shore. A Rayleigh distribution was assumed for the mean wind speed.

Near shore, the Trawler does not perform as well as a fixed wind turbine since its motion in the direction of the ambient wind induces a relative wind and decreased wind power. However, the Trawler can operate farther from shore than the fixed wind turbine and experiences a boost in CF since the mean wind speed and therefore generated wind power continues to increase with distance from shore past where it is feasible for fixed substructures. The Trawler achieved a maximum 10% greater CF than a fixed wind turbine.

This analysis is limited in its consideration of Trawler hydrodynamics and stability in realistic ocean conditions. These conditions drive the need for stability in all translational and rotational degrees of freedom. The power production of a Wind Trawler is dependent upon, for example, forces exerted by waves on the Trawler hull. Significant waves may necessitate Trawler shutdown (e.g. storms) if stability is compromised, while the wave direction becomes important since it will affect the resultant Trawler water speed and ultimately relative wind at the wind turbine. The exact costs of a Wind Trawler are not known, but an attempt to compare to those of a typical offshore wind turbine is necessary in future work.

We expect that instead of electric transmission and substructure/mooring dominating the costs, the Trawler costs may be dominated by the hull’s construction and hydro turbines. Since the Trawler stores and therefore must deliver the fuel energy it produces, future work must also consider the energy expenditures during transport of the fuel to the point of delivery which will have an impact on the net amount of energy delivered. The effect on net energy delivered by certain hydrogen storage parameters such as the overall conversion efficiency of seawater to hydrogen, energy storage capacity and hydrogen density must also be weighed. These are expected to affect Trawler rate of fuel storage, and therefore drift duration, drift distance, and ability to navigate to the strongest wind resource available.

Figure 5.3. Capacity factor (CF) for fixed DTU-10 MW wind turbine operating at distances from shore typical for deployed fixed wind turbines, and for a Wind Trawler equipped with DTU-10 MW wind turbine and two 1 MW hydro turbines. Wind speed averages are calculated from the Quadratic expression of Figure 5.1.
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