Wind Power Generation With a Parawing on Ships, a Proposal

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It is proposed that electric power be generated from wind by pulling a ship. A parafoil pulls and tows a ship. Electrical power is generated by hydraulic turbines installed on the ship below the water line. The electric power generated is expended onboard to electrolyze water to produce hydrogen or methanol or to convert carbon dioxide into storable forms of liquid. This paper describes the principle of designing such a system, shows the general features of such a system, and describes in detail an example design which produces 0.8 GW. It is shown that a fleet of such ships operating in two different regions of the sea can produce much more energy than the world needs.

Nomenclature

A_{Ls} : Area producing ship's side-wise lift, m^2.
A_f : Area producing ship's friction drag, m^2.
A_t : Equivalent frontal area of hydraulic turbine, m^2.
A_w : Area of parafoil, m^2.
C_{Dw} : Drag coefficient of parafoil.
C_{fs} : Skin friction coefficient of ship.
C_{Ls} : Coefficient of side-wise lift of ship.
$\frac{dC_{Ds}}{dC_{Ls}^2}$: Derivative of ship's drag coefficient by ship's lift coefficient squared.
C_{Lw} : Lift coefficient of parfawing.
$\frac{dC_{Ls}}{d\alpha}$: Slope of lift coefficient of ship.
D_f : Ship's drag due to friction, N.
D_{Ls} : Ship's drag due to making side-wise lift, N.
D_m : Ship's drag due to wave-making, N.
D_p : Ship's drag due to power production, N.
D_s : Drag of ship, N.
D_w : Drag of parafoil, N.
F_w : The horizontal component of the resultant force produced by parafoil, N.
F_w' : Resultant force produced by parafoil, N.
g : Earth's gravitational constant, m/s^2.
KT : Ship's speed (V_s) in knots.
L_s : Side-wise lift force of ship, N.
L_w : Horizontal component of the lift produced by parafoil, N.
L_w' : Lift produced by parafoil, N.
M : Mass of parafoil, kg.
M_s : Mass of ship, kg.
P : Electrical power generated, W.
RWR: Resistance-to-weight ratio, Eq. (16).
SLR : Speed-to-length ratio, Eq. (15).
V_r : Wind speed relative to ship, m/s.
V_s : Ship's speed, m/s.
V_w' : Absolute wind speed, m/s.
α : Side-slip angle of ship, radian.
β : Angle between the relative wind vector and direction of ship's motion, radian.
β' : Angle between the absolute wind vector and direction of ship's motion, radian.
γ : Angle of elevation of the resultant force vector of parfawing, radian.
δ : Angle between the normal to the direction of ship's motion and F_w,radian.
δ' : Angle between F_w and the direction of ship's motion, radian.
ϵ : Angle between F_w and relative wind, radian.
ϕ : Virtual angle of elevation of parafoil accounting for gravity, Figure 4, radian.
ϕ' : Angle of elevation of parafoil, Figure 4, Radian.
η_H : Thermal efficiency of producing liquid hydrogen.
η_M : Thermal efficiency of producing methanol.
η_N : Thermal efficiency of producing NaHCO2+HCl.
η_t : Efficiency of hydraulic turbine.
ρ_s : Density of sea water, kg/m^3.
ρ_w : Density of air, kg/m^3.

Introduction

Generating electricity by wind power is one way of producing clean energy. The main limitation of wind power is, at least in the way it is practiced today, that the obtainable amount is relatively small. This is mainly because one cannot build the wind turbine tower tall enough. In Figures 1(a) and (b), which was taken from Reference 1, the wind speed at the 180 East/West longitude, i.e. in the middle of the Pacific Ocean, is shown as a function of altitude. The figures show that wind speed increases approximately linearly with altitude. Because wind power generated is proportinal to the cube of the speed of the wind captured, a large amount of wind power could be captured if the wind turbine is placed at a high altitude. But the cost of building a tall wind turbine tower is very high: a simple reasoning leads one to conclude that the cost of such a tower is proportional to the fifth power of its height.

One immediately conceivable idea of placing electricty-generating equipment aboard a flying platform such as a balloon is impractical mainly because power generation accompanies increase in air drag. Because the length of the tether holding the platform is fixed, the drag force brings down the platform. To maintain the tether at a reasonable angle, at 45° say, the lift force of the flying platform must equal the drag force. To produce electrical power of the order of 100 mega-watts, the lift-producing device on the platform must produce a lift force of the order of thousand tons.

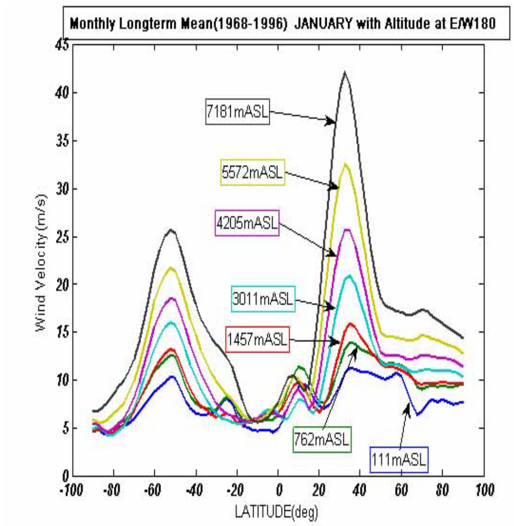

Figure 1. Wind speed as a function of altitude at 180 East/West longitude.[1] (a) In the month of January as a function of latitude. The legends signify altitudes in meters above sea level.

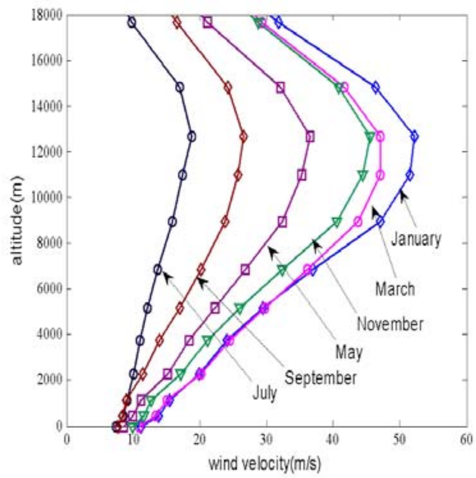

Figure 1. (b) Between the latitudes of 35 and 40° in various months.

There has been several proposals to tap the high altitude wind energy using a generator placed on the ground.[2−4] In these proposals, the flying element, which consists of one or more wings, is made to tow a tether line. The tether line makes a linear translational motion and drives an electric generator. The ideas differ in the way the linear motion of the tether is made to drive the generator. But, because there is a limit on how far the tether can translate, the tether must be made to reciprocate or rewind in all of these ideas. The difficulty in reciprocation renders these schemes impractical. None of these schemes have yet been put into practical use.

In this paper, we propose an alternative scheme which should be much easier to be realized. We propose that the wing, which is in reality flexible and is called parafoil, is made to pull and tow a ship. The tether line that connects the wing to the ship is of fixed length, and no relative translational motion is made. Such a system already exists as Skysails(http://www.skysails.info) shown in Figure 2. In the present proposal, the ship is equipped with hydraulic turbines below the water line. The turbines drive an electric generator and produces electrical power. The scheme is sketched conceptually in Figure 3.

Figure 2. The Skysails system in which a parafoil pulls a ship. (http://www.skysails.info).

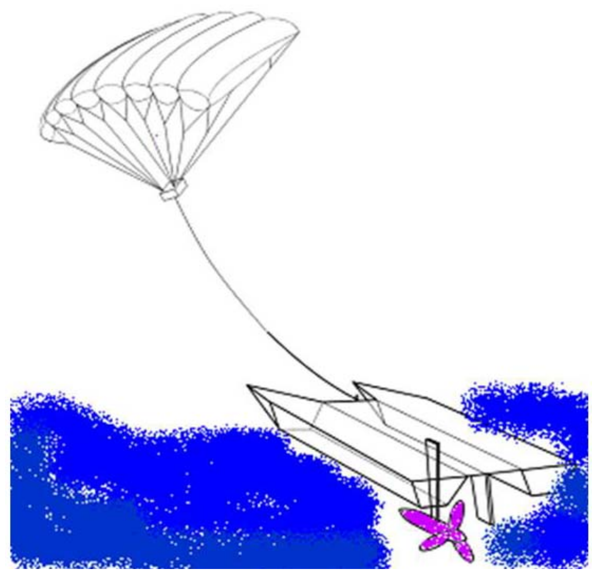

Figure 3. Principle of wind power production by pulling a ship using a parafoil.

The power so produced is converted into a chemical form by electrolyzing seawater. As will be described in detail later, two different chemical processes are possible. In the first possible process, water is split into hydrogen and oxygen. Hydrogen is either liquefied and sold directly or combined with carbon dioxide to produce methanol. In the second possible process, electrolysis of sea water is made for the sole purpose of converting carbon dioxide into storable forms of liquid. These liquidous products are stored in tanks onboard the ship. The cargo is unloaded regularly either at a port or to a courier tanker. The liquids can be stored in the depth of an abandoned mine for perpetuity. In both these processes, carbon dioxide can be obtained either directly from the atmosphere or from terrestial plants as an industrial byproduct in the form of dry ice. In both these processes, energy is obtained from the wind without increasing atmospheric carbon dioxide.

The laws of force balance applicable to such a system are first delineated in this paper. Then how to make the system is proposed. A sample calculation is carried out for a large system to produce power in the order of a gigawatt. Calculation is made to show that the scheme can potentially produce several times more energy than the world needs.

Force Balance Relationships

In order for the system to function under the steady-state condition, the forces produced by the parafoils must be balanced by the forces produced by the ship. The force components associated with the parafoil are shown schematically in Figure 4.

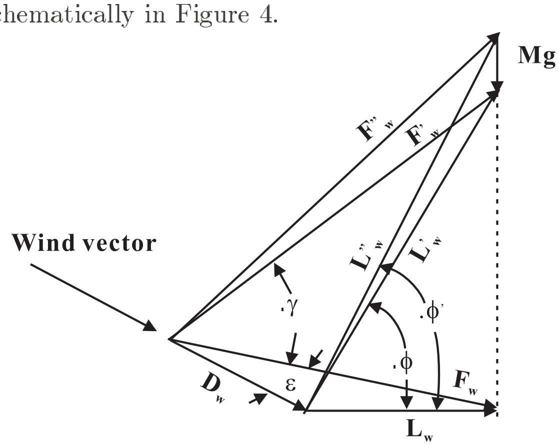

Figure 4. Force vectors for the parafoil.

The parafoil produces lift L''_w

$$L''_w = 0.5 C_{Lw} \rho_a V_r^2 A_w \tag{1}$$

and drag D_w

$$D_w = 0.5 C_{Dw} \rho_a V_r^2 A_w \tag{2}$$

shown in Figure 4, producing the net force F''_w

$$F''_w = \sqrt{L''^2_w + D^2_w}.$$

Here, V_r is the wind velocity relative to the moving ship. The lift and drag coefficients of the parafoil are assumed in the present work to be 1.5 and 0.3, respectively. The weight of the parafoil Mg changes this lift into the net lift L'_w given by

$$L'_w = \sqrt{L''^2 - (Mg\sin(\phi))^2} - Mg\sin(\phi) \tag{3}$$

Here, ϕ is the angle of elevation of the L'_w vector shown in Figure 4. M is stipulated here to include the mass of the tether line. L'_w and D_w produce the resultant force F'_w

$$F'_w = \sqrt{L'^2_w + D^2_w} \tag{4}$$

The angle of elevation of the F'_w vector, γ, is the direction of tension of the tether line holding the parafoil, and is given by

$$\gamma = \sin^{-1}(L'_w \sin(\phi)/F'_w) \tag{5}$$

The horizontal component of the force F'_w, F_w, makes an angle ϵ against the drag force D_w,

$$\epsilon = \tan^{-1}(L_w/D_w) \tag{6}$$

The force components associated with the ship are shown schematically in Figure 5. The wind blows toward the ship at an angle β' with respect to the direction of ship's motion with a speed V_w, when the ship is moving at an infinitesimally small speed. When the ship moves with a finite speed V_s, the relative speed of the wind V_r is

$$V_r = \sqrt{[V_w\cos(\beta') + V_s]^2 + (V_w\sin\beta')^2}. \tag{7}$$

The direction of the wind with respect to the ship in motion becomes

$$\beta = \tan^{-1}\frac{V_{\mathrm{w}}\sin(\beta')}{V_w\cos(\beta') + V_s}. \tag{8}$$

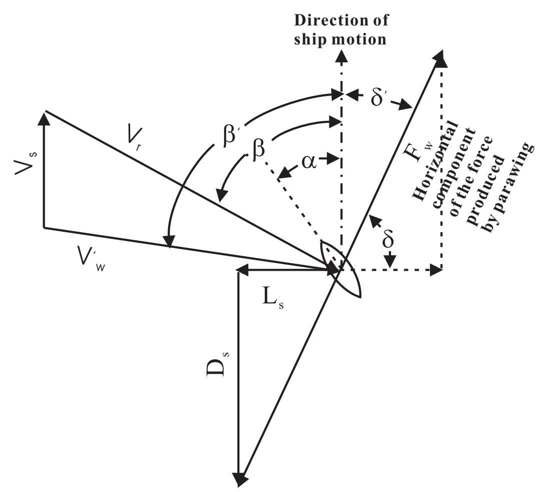

Figure 5. Force vectors for the ship.

The angle between F_w and the direction of ship's motion will be named δ'. Its complement, $\delta = \pi/2$ - δ', is given by

$$\delta = \epsilon + \beta - \pi/2 \tag{9}$$

The two components of F_w, the component parallel to the direction of ship's motion and the component perpendicular to it, $F_w\sin(\delta)$ and $F_w\cos(\delta)$, must be balanced by ship's drag D_s and ship's side-wise lift L_s

$$F_w\sin(\delta) = D_s \tag{10}$$

$$F_w\cos(\delta) = L_s \tag{11}$$

There are four components in ship's drag D_s. They are:

$$\begin{aligned} \mathrm{D_s} = &\text{drag due to skin friction} \\ &+\text{drag producing lift} \\ &+\text{drag making wave} \\ &+\text{drag due to electric power generation} \\ &= D_f + D_{Ls} + D_m + D_p \end{aligned} \quad . \qquad (12)$$

Of these, D_f and D_{Ls} can be expressed as

$$D_f = 0.5 C_{fs} \rho_s V_s^2 A_f \qquad (13)$$

$$D_{Ls} = 0.5 \frac{dC_D}{dC_L^2} C_L^2 \rho_s V_s^2 A_L \qquad (14)$$

The wave-drag[5] has traditionally been expressed as a function of the so-called speed-lenth-ratio SLR defined as

$$SLR = \frac{KT}{\sqrt{LWL}} \qquad (15)$$

where KT is ship's speed in knots (nautical mile per hour) and LWL is length of water line in feet. A quantity named resistance-to-weight-ratio RWR is defined as

$$RWR = \frac{\text{wave drag}}{\text{weight of the ship}} \qquad (16)$$

The relationship between RWR and SLR is well known.[5] In the range of SLR less than 1.34, it can be represetned approximately by

$$RWR = 0.009572(SLR)^2 + 0.00194(SLR)^4 \qquad (17a)$$

For SLR greater than 1.34, it is approximated here by

$$\begin{aligned} RWR = 0.000041 + 0.038(SLR) - 0.13(SLR)^2 \\ +0.15(SLR)^3 - 0.06(SLR)^4 \\ +0.0079(SLR)^5 \end{aligned} \qquad (17b)$$

Installation of what is known as bulbous bow[6] reduces this wave drag by about 15%. As a result, the wave-making drag is

$$D_m = 0.85 \times RWR \times [M_s g - L'_w \sin(\phi)] \qquad (18)$$

The hydraulic turbine is assumed to be designed to produce the maximum power by operating at the so-called Betz's limit condition.[7] This is achieved by the duct surrounding the turbine. At this condition, the flow velocity passing through the turbine is 2/3 of the ship's speed V_s, and the flow speed far downstream of the turbine is 1/3 of the ship's speed. This leads to the drag expression

$$\text{Drag} = D_p = (4/9)\rho_s A_t V_s^2. \qquad (19)$$

The work done per unit time to the electrical power generating system by the drag, i.e. drag power, becomes

$$\text{Drag power} = (2/3) D_p V_s \qquad (20)$$

By multiplying the overall thermal efficiency η_t, which is the product of the turbine efficiency and generator efficiency, one obtains the electrical power generated, P:

$$P = \eta_t \times (2/3) D_p V_s = 0.2963 \eta_t \rho_s V_s A_t \qquad (21)$$

The efficiency η_t is assumed in the present work arbitrarily to be 0.85.

The side-wise lift of the ship L_s needed in Eq. (11) can be written approximately as

$$L_s = 0.5 \frac{dC_{Ls}}{d\alpha} \alpha \rho_s V_s^2 A_{Ls}$$

The calculation of the force-balance condition starts by specifying the parameters A_w, ϕ, M, M_s, V'_w, C_{Lw}, C_{Dw}, the altitude of the parafoil (which determines ρ_w), $dC_{Ls}/d\alpha$, and dC_{Ds}/dC_{Ls}^2. The quantities to be determined are V_s, α, and the most appropriate value of the turbine area A_t. There are only two force balance equations, Eqs. (10) and (11). The most appropriate value of A_t is that value which maximizes P. Sollutions are obtained by the use of a Newton-Raphson root finder. Once these three quantities are determined, all other parameters can be calculated as well as the quantities of liquid hydrogen, methanol, or the storable liquid containing carbon dioxide that can be produced.

Chemical Processes

Using an existing technology, the electrical energy P can be converted into chemical energy in the form of electrolysis

$$H_2O + 286 \text{ kJ/mol} \rightarrow H_2 + 0.5O_2 \qquad (22)$$

with a thermal efficiency varying from 53 to 73% (Ref. 8). A mean value of 63% is used in the present calculation. For methanol (CH_3OH) production, process (22) is followed by

$$CO_2 + 3H_2 + 50 \text{ kJ/mol} \rightarrow CH_3OH + H_2O. \qquad (23)$$

The thermal efficiency of the combined process varies from about 52 to 73% (Ref. 9). A mean value of 62% is assumed in the present work. In producing methanol, CO_2 is removed. This rate is calculated here also.

To solely remove carbon dioxide, the following processes can be followed:

$$NaCl + H_2O + 212 \text{ kJ/mol} \rightarrow NaOH + 0.5Cl_2 + 0.5H_2 \qquad (24)$$

$$NaOH + CO_2 - 70 \text{ kJ/mol} \rightarrow NaHCO_3 \qquad (25)$$

$$0.5Cl_2 + 0.5H_2 - 92 \text{ kJ/mol} \rightarrow HCl \qquad (25)$$

These processes are equivalent to

$$\mathrm{NaCl} + \mathrm{H_2O} + \mathrm{CO_2} + 50\mathrm{kJ/mol} \rightarrow \mathrm{NaHCO_3} + \mathrm{HCl} \quad (26)$$

The process thus produces sodium hydrogen carbonate $NaHCO_3$ and hydro-chloric acid HCl. The overall efficiency of this process is not known at present. It is arbitrarily assumed here to be 0.3.

How To Make and Operate It

Parafoil

Parafoil is a commonly used terminology for a flexible wing. It is made of a water-tight light-weight fabric such as ripstop nylon.[10] The largest parafoil built to date is that used for NASA's X-38 shown in Figire 6, which had a total area of 696.8 m^2 (Refs. 11 and 12). Briddles run from the nodes between each cells to the tether lines as seen in the Figure. Each cell is equipped with an inlet valve which allows air in but keeps water out. Lift-to-drag ratio was 3.5 for the X-38, but is typically five or higher in modern parafoils. It was assumed to be 5 in the present work.

Figure 6. Frontal view of the parafoil for X-38.[12]

Cables run through in the span-wise direction. By pulling the cables, the parafoil is contracted. It can be inflated on the ground by pressurizing with an air pump. In air, the ram pressure acting at the leading edge can inflate the parafoil. From the floating position, a parafoil can be made airborne either by tugging the tether lines or lifting it with a small pilot chute. The parafoil can be pitched or yawd by pulling the tether lines and bridles.

For X-38, there were many bridles as seen in Figure 6. For a very large parafoil envisioned in the present work, such large number of bridles may be undesirable. The number of bridles may be reduced by using the so-called inflatable beams which run in the span-wise direction, as shown schemmatically in Figure 7.

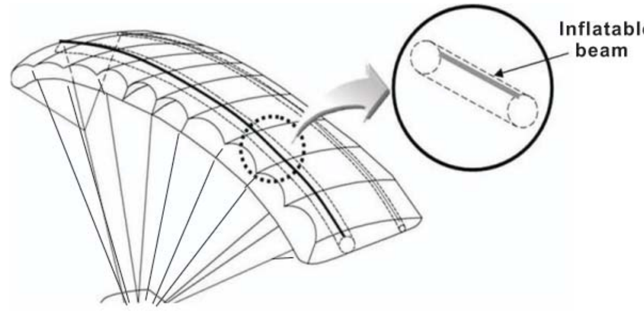

Figure 7. Schematic of an inflatable beam.

The tether lines are assumed to be made of a material named Dyneema,[13] which has a tensile strength of 3.520×10^4 MPa with a safety factor of 2. This material is lighter than water and thus floats on the water.

The mass of the parafoil can be estimated as follows: Examination of the small parafoils for use in sports flight reveals that its mass is roughly proportional to the aerodynamic force it encounters, i.e., it follows the formula

$$\text{Parafoil mass} = C\rho_w V_r^2 A_w \ \text{kg.} \qquad (22)$$

The coefficient C can be determined from the X-38 data as follows. According to Bennett and Fox[11], the mass of the parafoil package for X-38 was 564.7 kg. According to Madsen and Cerimele[12], the ratio between the mass of the parafoil alone and the mass of the package was 0.857. Thus, one deduces that the mass of the parafoil for X-38 was $564.7 \times 0.857 = 483.7$ kg. The parafoil area A_w was 696.8 m^2, and the relative wind speed V_r was 63.25 m/s. These relationships lead to a C value of 0.00152. This value was used for the performance calculation in the present work.

The Ship

The ship is assumed to be catemaran, i.e., has two hulls. The two hulls are separated by a distance equal to the length of the hulls. Between the two hulls, a bridge exists, and turbine-generator pods are hung below the bridge, as shown schematically in Figure 8.

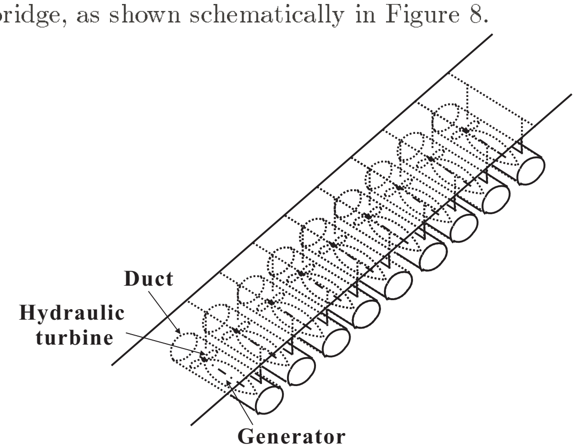

Figure 8. Turbine-generator pod arrangement.

The general configuration of the catemaran is dictated mainly by the method of stowing and deploying the parafoil. Conceivably, several different methods are possible. Here, one such method is shown. In this method, the parafoil sits on a platform located between the two hulls. The platform rides an escalater. The escalater can raise the platform to the up-position or lower it to the down-position as shown schematically in Figure 9. When the platform is in the down-position, it is below the water line, and the parafoil floats over the water. The ship slips away using its own power leaving the parafoil behind as shown. The parafoil will be inflated fully in this position. The parafoil can then be made airborne either by tugging it or by using a pilot chute.

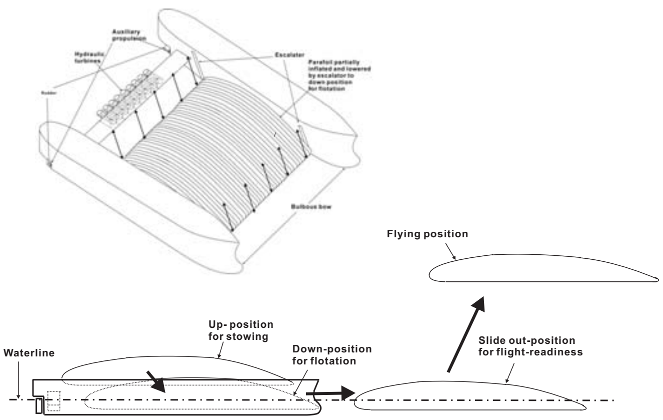

Figure 9. General layout of the ship and the procedure for deployment of the parafoil.

The ship is assumed to continually produce either liquid hydrogen, methanol, or sodium hydrogen carbonate and hydro-chloric acid, and store the product. As will be shown later, hydrogen and methanol produced in one month will be of the order of 100,000 tons. When electric power is expended solely to remove carbon-dioxide, producing sodium hydrogen carbonate and hydro-chloric acid, operation over three days produces approximately 100,000 tons of the liquids. The ship can either enter a port and transfer the load, or do so to a courier tanker.

As will be shown later, the most optimum direction for ship's motion is the normal to the wind vector. Within one 24-hour day, such a ship will travel a few hundred kilometers. At the end of such a sailing day, the ship will have to make a U-turn. The ship must thus make a figure of eight maneuver every 24 hours or so.

In order to make a U-turn, the load on the electrical generator should be turned off so that the turbines idle. The angle of attack of the parafoil should be reduced so that the lift of the parafoil only supports its own weight. If wind direction is unfavorable, the ship will have to use its own power to tow the parafoil. This operation must be made also when the wind speed is absolutely zero. For this reason, the minimum relative air speed for the parafoils to stay aloft, and the propulsive power needed for it are calculated.

Sample Calculation

A sample calculation is made here for one large such system. The ship is assumed to have hulls 300 meters in length, separated by 300 m. The total parafoil area is 600,000 m^2, meaning a span of 2000 m and a chord of 300 m. The ship's displacement is 100,000 tons empty, and 200,000 tons fully laden, so that the average mass is 150,000 tons. The results of these calculations are shown in Figures 10(a) and (b), and Tables 1.

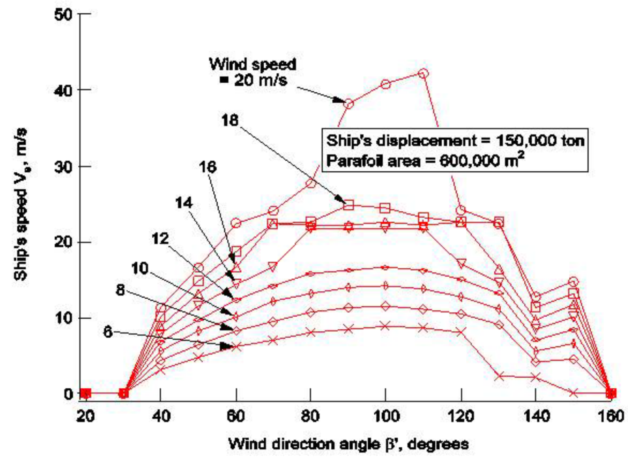

Figure 10. A 150,000 ton ship with parafoil area of 600,000 m^2 flying at the altitude of 1000 m. (a) Ship's speed.

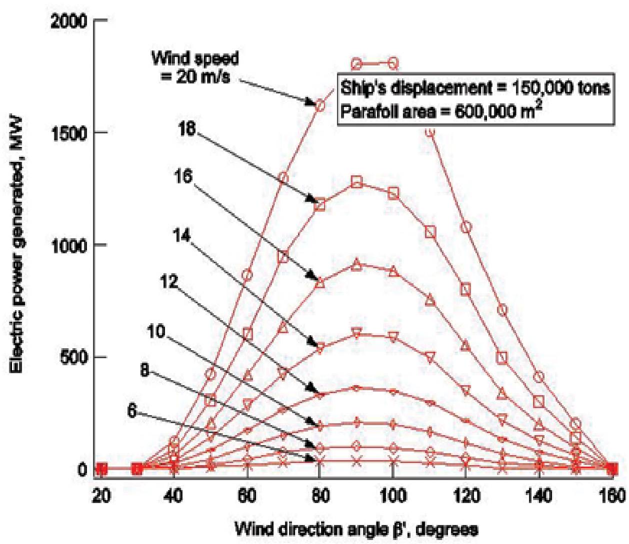

Figure 10. (b) Electric power generated.

In Figure 10(a), one sees that the ship's speed can exceed the wind speed. This happens because the force pulling the ship is mostly the lift force produced by the parafoil. Figure 10(b) shows that the electric power generated increases with the wind speed, as expected. The highest power output results when the wind blows from the 90° direction. The power generated exceeds 1.5 GW.

In Table 1, the details of the calculated results are presented for one operating condtion. The ship is sailing at the East/West 180° longitude between the latitudes of 35 and 40° in the month of February. Its parafoil is flying at the altitude of 1481 m, and the wind speed is 15.37 m/s, the mean value for the month of February.

Table 1. Representative design parameters of the wind-power ship.

Item	Value
General	
parafoil altitude, m	1481
Air density at the altitude ρ_a, kg/m^3	1.073
Wind speed V_w, m/s	15.37
parafoil area A_w, m^2	600,000
Energy flow in air $0.5\rho_a V_w^3 A_w$, MW	1753
Mass of parafoil M, ton	1020
Minimum air speed to stay aloft, m/s	4.55
Power to tow parafoil at min speed, MW	9.11
Power to push ship at min speed, MW	2.32
Assumed input parameters:	
Ship's average displacement M_s, ton	150,000
Wind direction w/r to ship β', deg	90
parafoil angle of elevation ϕ, deg	30
parafoil lift coefficient C_{Lw}	1.5
parafoil drag coefficient C_{Dw}	0.3
turbine-generator efficiency	0.85
H_2 production efficiency	0.63
methanol production efficiency	0.62
$NaHCO_3$+HCl production effieincy	0.30
Output parameters:	
Optimum turbine frontal area A_t, m^2	268.6
Ship's speed V_s, m/s	22.6
Relative wind speed V_r, m/s	27.4
Tether line tension F_w', ton	37,110
Vertical component of parafoil's lift, ton	18,190
Horiz component of wind force F_w, ton	32,350
Tether line elevation angle γ, deg	29.3
Ship's lift-to-drag ratio angle δ, deg	21.0
Ship's side-slip angle α, deg	5.38
Speed-length-ratio SLR	1.403
Power-producing drag D_p, ton	6400
Wave-making drag D_m, ton	2485
Friction and lift drag D_f+D_{Ls}, ton	1230
Total drag of ship D_s, ton	11,590
Power going into turbine assembly, MW	947.3
Power converted into electricity, MW	805.2
Chemical parameters:	
H_2 production rate, ton/month	9,217
Methanol production rate, ton/month	114,200
Rate of CO_2 consumption in methanol production, ton/month	84,190
Rate of CO_2 removal in $NaHCO_3$ production, ton/3 days	55,110
Rate of $NaHCO_3$ production, ton/3 days	105,200
Rate of HCl production in $NaHCO_3$ production, ton/3 days	45,660
Miscellaneous:	
Total cross section area of tether line, cm^2	3,310
Length of tether lines,m	3022
Weight of tether lines, ton	700
Average underwater cross section area, m^2	500
Average draft, m	15.8
Wet area of the hull, m^2	28,460

In the Table, the average underwater cross sectional area is calculated by dividing the submerged volume by the length of the hull. The average draft is calculated by assuming that the submerged portion of the hull has a rectangular cross section, the width being twice the draft. The average draft and the wet area are those corresponding to this case. These values indicate that the assumed values of A_{Ls} and A_f are reasonable.

The minimum airspeed needed to stay aloft is the speed that produces a lift equal to the weight of the parafoil system. The power needed to tow the parafoil to that speed, in the absence of wind, is seen to be very small compared with the level of output of the system. The power to push the ship to that speed is also quite small. The total power needed is the sum of the two powers.

As seen in the Table, the weight of the parafoil is a relatively small fraction of the lift force the parafoil produces. The total force in the tether lines is about 37,000 tons. Even with this high tension load, the calculated weight of the tether lines is still comparatively small.

The effective frontal area of the turbines is well within the realizable range. The relative wind speed is substantially greater than the wind speed. This is because the ship is moving with a substantial speed. The speed-length-ratio is below 1.4. The power generated is about 0.8 GW, a value comparable to the output of a standard-size nuclear power plant.

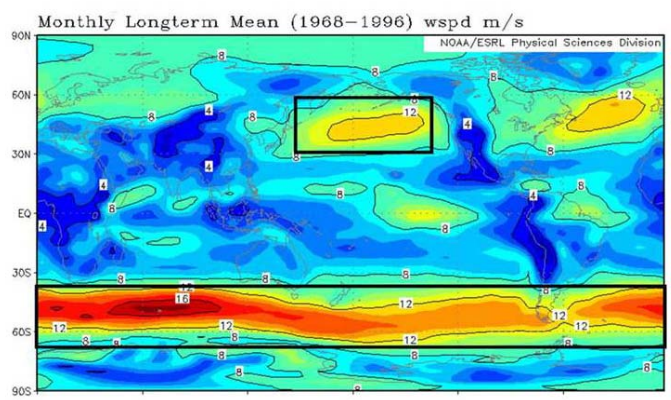

Figure 11. Worldwide distribution of yearly-averaged wind speed at the altitude of 1481 m (Ref. 1), and two most promising regions of operation of wind-power-ships.

Application

Figure 11 shows the global distribution of the yearly-averaged wind speed at the altitude of 1481 m. The averaging is taken over the period from 1968 to 1996. Two regions of strongest wind in the northern hemisphere are in the temperate zones (latitude between 30 and 60°) at the middle of the Pacific and Atlantic Oceans. In the southern hemisphere, the strongest wind blows approximately uniformly over the entire temperature zone.

Of these three best zones, the zone in the Atlantic Ocean coincides with one of the busiest shipping lanes. Therefore, it would be prudent to avoid the Atlantic zone. Thus, one can envision operating the wind-power-generating ships in the northern Pacific zone and the southern temperate zone indicated by the bold lines in Figure 11. If we assume that one such ship operates at one degree intervals in latitude and longitude, corresponding approximately to 100 km intervals, between N30 and N60 latitudes and between E130 and W120 longitudes in the northern hemisphere, and between S40 and S70 and E0 and E360 in the southern hemisphere, these ships will produce electrical power listed in Table 2. The annual average of these values is 3,237 GW as indicated.

Table 2. Average electrical power produced by month by a fleet with inter-ship distance of 100 km, MW.

Month	Northern hemisphere	Southern hemisphere
January	901,755.1	1,897,695.9
February	857,106.6	2,157,184.3
March	770,416.5	2,463,150.9
April	568,041.5	2,733,871.4
May	431,518.3	2,888,752.9
June	321,054.1	3,023,367.9
July	260,542.5	3,206,253.0
August	268,416.8	3,272,112.6
September	351,930.1	3,151,766.3
October	521,808.4	2,858,977.1
November	756,849.4	2,316,362.1
December	899,427.3	1,970,093.7
sum	6,908,867.0	31,939,588.0
	Total Sum	38,848,455.0
	Mean	3,237,371.2

The experience with existing windmills shows that wind mills can operate at their optimum performance when the spatial intervals between windmills are equal to or greater than 5 times the wind turbine diameter. Using this rule, we can assume that a 20 km interval is sufficient between neighboring ships. At these intervals, we can obtain 25 x 3,237 GW = 81 TW of power output. This power level is six times the global energy requirement since the average total worldwide power consumption was 15 TW in 2004.

The above results indicate that the potential performance of the proposed system is substantial. The force balance laws are satisfied with hardware systems seemingly within our ability to produce: man-made floating structures have been built to a size of the order of one kilometer and to a mass of over million tons.

The only unproven technology is the technology of making and operating large parafoils. As mentioned, the largest parafoil made to date has an area of only about 700 m^2. Parafoils have not been made to a larger size perhaps because there were no such needs. When we recognize the need, one may be able to make such large parafoils.

Conclusions

A proposal is made that a parafoil is made to pull a ship, which produces electric power using hydraulic turbines. The electric power is to be used to electrolyze water and thereby produce either hydrogen, or methanol by combining with carbon dioxide, or to convert carbon dioxide into storable liquids. The force balance equations dictating the design of such a system are delineated, and sample calculations are carried out. The calculation shows that, using a ship of a size that has been built in the past, a giga-watt order electrical power may be harvested by this system. If such ships are deployed at 20 km intervals over two temperate zones, one in the middle of the Pacific Ocean in the northern hemisphere and the other in everywhere in the souther hemisphere, the total power produced will be many times that needed by the world.

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