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ME 472

Techno-Economic Analysis of Airborne Wind Energy Systems

Airborne wind energy (AWE) is a sustainable energy technology that harnesses winds at altitudes higher than those of conventional horizontal-axis wind turbines. At elevations of 200 to 400 meters, winds are not subject to surface friction, an effect that slows near-surface wind speeds significantly. With access to greater kinetic energy, AWE systems pose the potential for high power outputs. Additionally, these systems appear to avoid many of the issues that arise from the construction, land use, and public acceptance of conventional wind renewables.

The fundamentals of the technology are as follows: a large kite tethered to a grounded power station is blown into high-altitude winds, spinning an electrical generator as the tether is unreeled. Once the kite is approaching maximum altitude, it is flown in figures of eight to maintain tension and power generation. The generator then acts like a motor and reels the kite in to finish the cycle. This automated “pumping” cycle is a recurring theme in AWE systems, albeit with variations. Since the technology’s inception in the 1970s, researchers have explored airborne turbine-driven generators attached to helium balloons and rigid kites resembling model airplanes, shown below in figure 2 (Diehl). Due to its simplicity and current market dominance, however, this report will focus on the setup featuring a flexible sail tethered to a grounded power station, depicted in figure 1.

Figure 1: Onshore airborne wind energy system with flexible kite (SkySails).

Figure 2: Offshore airborne wind energy system with rigid kite (Makani).

SkySails, a German company that has been around for over 20 years, is the first in the world with AWE systems that are ready for order. They have demonstrated their product’s feasibility in multiple power-generating applications ranging from providing power for small islands to trans-oceanic freight ships. Their kite systems “can substitute as much as two megawatts from the ship’s engine and reduce fuel consumption by up to ten tons of fuel per day” (SkySails Power). Their claims for their newest onshore unit are summarized in table 1 below.

Table 1: Technical data for the SKS PN-14 SkySails AWE Power

TECHNICAL DATA SKS PN-14	
Average cycle power / rated power [1]	100-200 kW
Kite size (laid out) [1]	90-180 m²
Operating wind range	3-25 m/s
Tether length	800m
Tether diameter	14 mm
Ground station	30 ft container

SkySails also claims that their technology is much less resource-intensive than traditional wind turbines in just about every aspect, from raw materials to deployment. Being theoretically capable of generating more power due to access to higher wind speeds, their system emerges as a sustainable and economically viable alternative to traditional wind. Their claims are to be further investigated and analyzed, specifically the quoted power rating for their system's given dimensions, through an energy analysis. Then, the economics of the technology will be analyzed by calculating the system's levelized cost of electricity (LCOE), or the dollar amount it costs to produce a kilowatt (kW) of electricity. These numbers will provide a better idea of how powerful the technology is and will indicate whether the company's claims are sound.

Background

First, it is important to briefly discuss the theory behind the concept of AWE. As previously mentioned, wind speeds at higher altitudes tend to be increased due to the lack of surface friction effects. Near the ground, it is common for winds to blow at a couple miles per hour, whereas in the Jetstream (four to eight miles up), winds can reach 300 miles per hour. Historically, wind turbines have been placed on Earth's surface, but the higher power densities that come with stronger and steadier high-altitude winds certainly leave something to be desired. Wind power is one of the few renewables that, in theory, is large enough to provide all the world's energy. Motivating this idea, the theoretical global limit of wind power at high altitude was estimated to be around 4 times higher than at ground level (Marvel). In a more practical sense, uncovered in a power estimate for a tethered airfoil is the cubic relationship between wind velocity v_w and power P, given by

$$P = \frac{2}{27}\rho A v_w^3 C_L (\frac{C_L}{C_D})^2, \tag{1}$$

where A is the area of the kite, C_L and C_D the lift and drag coefficients, and ρ the air density (Loyd). Under idealized assumptions, equation 1 is to be used in the energy analysis that follows. So, why hasn't the wind industry put all its money into developing these high-wind technologies? Because the future of wind will be determined by economic and technical constraints, not theoretical geophysical limits.

Technical Analysis

Applying table 1 to equation 1 using Engineering Equation Solver (EES) offers a valid estimate that can prove or disprove SkySails' power rating claim. With the following assumptions and inputs shown in table 2, a power output of about 83 kW is calculated.

Table 2: Input variables and power calculation (EES).

$C_D = 0.25$	$A = 90$ [m^2]	$P_{wind} = 83200$ [W]
$C_L = 1$	$\rho_{air} = 1.2$ [kg/m^3]	
$C_{ratio} = 4$	$v_w = 10$ [m/s]	

Although this result is below their stated 100-200 kW power rating, this isn't too far off, especially considering the wind speed used was 15 meters per second (m/s) slower than the maximum rated speed for the tether, and lift and drag coefficients based on other experiments and research were assumed (Borobia-Moreno et al). In fact, using this model for power does not require much of an increase in wind speed or kite area to reach the rated 100-200 kW, shown in the plots below.

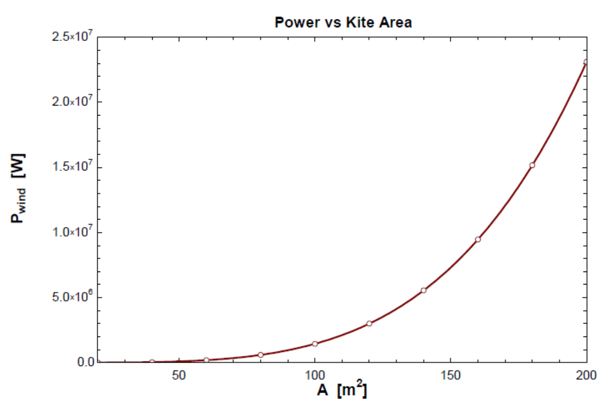

Figure 3: Power output as a function of kite area (EES).

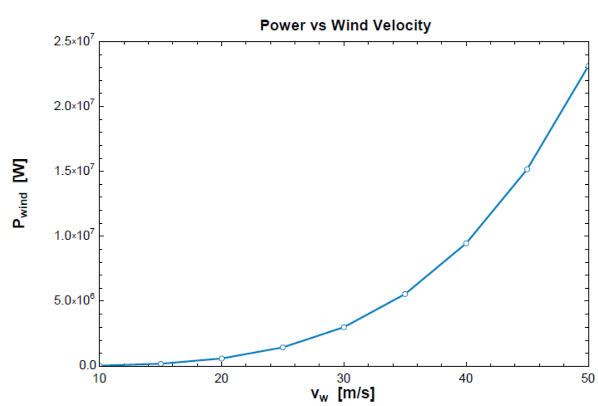

Figure 4: Power output as a function of wind speeds (EES).

This is attributed to the assumptions made for this simplified power model that limit the ability to assess the performance losses of tether drag, especially those experienced at increased wind speeds. Nonetheless, 10 m/s is a more accurate representation of wind speeds at 200 to 400 meters as opposed to the maximum.

Economic Analysis

With SkySails' AWE system power output modeled, it is now necessary to analyze how much this energy costs to produce. A basic LCOE formula from the National Renewable Energy Laboratory (NREL) was used, given by

$$LCOE = \frac{CRF * CapEx + OpEx}{AEP}, \quad (2)$$

where CRF is the capital recovery factor, $CapEx$ the capital expenditure, $OpEx$ the operational expenditure, and AEP the annual energy production (Weber). This function was evaluated over the system's lifetime, from construction to decommissioning, in MATLAB. Each of these input parameters were assumed to be rather low, especially when compared to traditional wind and other non-renewable energies: one year to construct, 10 years of useful life, and one year to decommission. Capital and operational expenditures, capacity factors, and discount rates were estimated based on the NREL report. All values and MATLAB code used may be found in the appendix. The results provided a levelized cost of electricity of about 70 dollars per megawatt-hour ($/MWh). For comparison, this is around double the price of utility scale solar power and triple the price of conventional wind (Lazard). Compared to conventional fossil fuel technologies, it falls within the upper and lower bounds of coal and gas (IEA). Overall, these numbers seem to be fairly accurate and agree with the NREL literature (Weber).

What the reviewed reports have not done is propose the following ways to reduce this cost, making the technology more competitive. The levelized cost was evaluated at various rated power outputs, capacity factors, and operational expenditures, each revealing potential key features that could give AWE systems a competitive edge.

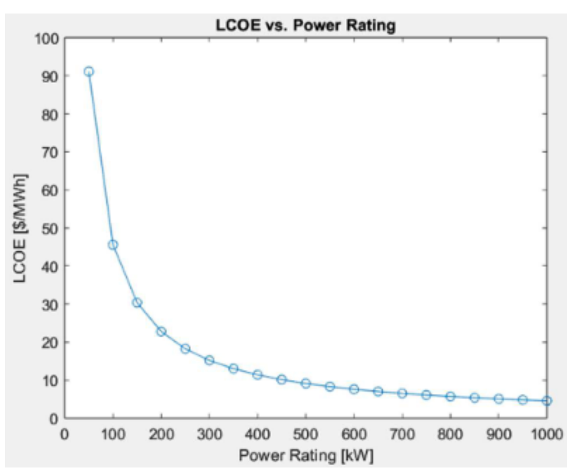

Figure 5: LCOE as a function of system power rating (MATLAB).

Firstly, shown in figure 5, as power production capabilities increase, the LCOE decreases towards a minimum value of less than 10 $/MWh. This inversely proportional relationship is obvious with a quick glance at equation 2. Though the $10 value it approaches is certainly optimistic, this drives motivation to research and develop AWE systems with power ratings of at least 500 kW instead of SkySails' goal of 100-200 kW.

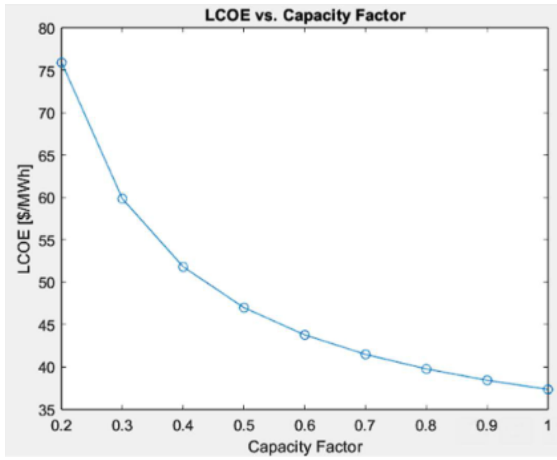

Figure 6: LCOE as a function of capacity factor (MATLAB).

Figure 6 illustrates a similar trend, highlighting that AWE systems, benefiting from more reliable high-altitude airflows, have the potential for significantly higher capacity factors than their grounded competition. Conversely, capacity factors could be negatively affected by the need to ground these systems during inclement weather. Nonetheless, the small footprint of AWE systems allows for deployment in a wider range of topographies than conventional wind.

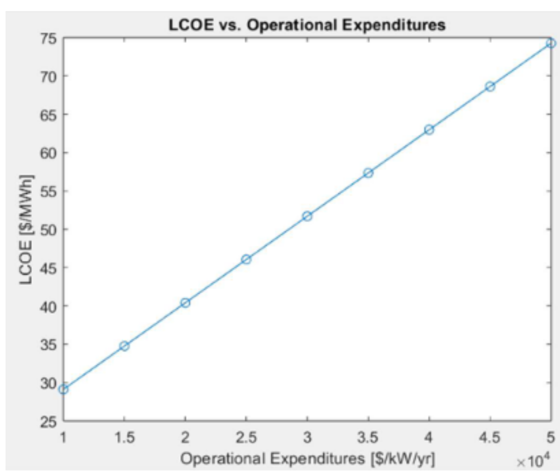

Figure 7: LCOE as a function of operational expenditures (MATLAB).

A steady increase in LCOE with operational expenditures is seen in figure 7, but what lies behind is another crux of AWE systems: maintenance only involves operations conducted on the ground, whereas traditional turbines require cranes or life-threatening climbs. Additionally, the components are cheaper, more common, and easier to transport than those for conventional wind – no more “oversized load” highway headaches. That being said, the drawback of AWE is that the high cyclic loading on the systems will likely require more servicing. The limited experimentation and operational history with AWE underscores the uncertainty surrounding which factors will emerge as strengths or weaknesses, emphasizing the need for continued research.

Conclusion

Comparing AWE directly to conventional horizontal-axis wind turbines seems to be the most logical approach, considering their shared reliance on wind. Although an in-depth lifecycle analysis that analyzes the carbon footprints of these technologies and their fossil fuel counterparts could be done, the assumption that AWE demands significantly fewer resources renders such a lengthy endeavor unnecessary.

Numerous studies have been conducted on the topic of AWE and how it stacks up against other technologies, a lot of which were thoroughly reviewed and referenced throughout this paper. All reached a similar general conclusion: the technology just isn’t ready yet. The absence of megawatt-scale AWE systems prove that widespread adoption is not yet feasible. On the other hand, numerous applications do exist, offering alternatives to conventional wind, whether it be helping energize the Republic of Mauritius or hybridizing existing technologies. History attests to the value of investing in smaller-scale, emerging renewable energy technologies – though initial investments always pose risks, the long-term gains outweigh the uncertainties.

References

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Images

Figure 1: https://www.laborelec.com/airborne-wind-energy-pv-battery-storage-maximize-self-consumption/

Figure 2: https://www.tudelft.nl/en/2020/lr/13-years-of-makani-airborne-wind-energy-knowledge-available-open-source

Appendix

EES Code

```
//energy analysis

P_wind = (2/27) * rho_air * A * (v_w^3) * C_L * (C_L/C_D^2) * 0.65          //eqn 2

rho_air = 1.2 [kg/m^3]          //air density
v_w = 25 [m/s]          //wind speed
A = 180 [m^2]          //kite area
C_L = 1          //study showed it range from 1 to 0.5
C_D = .25          //study showed it range from .06 to .25
C_ratio = C_L / C_D          //lift and drag coefficient ratio
v_reel = (1/3) * v_w          //reel velocity (ideal is 1/3 wind velocity)


P_wind_eq1 = F_L * v_reel * (4/9) * (0.866)     //eqn 1
F_L = (1/2) * (rho_air) * (v_w^2) * A * (C_ratio)^2 * 0.75          //lift force
```

SOLUTION

Unit Settings: SI C kPa kJ mass deg

$A = 180$ [m^2] $C_D = 0.25$ $C_L = 1$

$C_{ratio} = 4$ $F_L = 810000$ [N] $P_{wind} = 2.600E+06$ [W]

$P_{wind,eq1} = 2.598E+06$ [W] $\rho_{air} = 1.2$ [kg/m^3] $v_{reel} = 8.333$ [m/s]

$v_w = 25$ [m/s]

No unit problems were detected.

KEY VARIABLES

$A = 180$ [m^2]

$C_D = 0.25$

$C_L = 1$

$C_{ratio} = 4$

$\rho_{air} = 1.2$ [kg/m^3]

$v_w = 25$ [m/s]

$P_{wind} = 2.600E+06$ [W]

MATLAB Code

```
%% final proj - airborne wind energy levelized cost of electricity (AWE LCOE)
close all
clear all
clc

fcr = 0.08; % fixed charge rate (%/year)
cpx = 107412; % capital expenditure [usd/kW]
opx = 24570; % operational expenditure [usd/kW/yr]
cf = 0.54; % capacity factor
r = 0.05; % discount rate
```

```matlab
%% cost w.r.t. power capabilities
power_ratings = 50:50:1000; % [kW]
lcoe_power = zeros(size(power_ratings));
for i = 1:length(power_ratings)
	lcoe_power(i) = LCOE_AirborneWind(fcr, cpx, opx, cf, r, power_ratings(i));
end
figure;
plot(power_ratings, lcoe_power, '-o');
xlabel('Power Rating [kW]');
ylabel('LCOE [$/MWh]');
title('LCOE vs. Power Rating');

%% cost w.r.t. capacity factor
capacity_factors = 0.2:0.1:1.0;
lcoe_capacity = zeros(size(capacity_factors));
for i = 1:length(capacity_factors)
	lcoe_capacity(i) = LCOE_AirborneWind(fcr, cpx, opx, capacity_factors(i), r,100);
end
figure;
plot(capacity_factors, lcoe_capacity, '-o');
xlabel('Capacity Factor');
ylabel('LCOE [$/MWh]');
title('LCOE vs. Capacity Factor');

%% cost w.r.t. operational expenditures
op_expenditures = 10000:5000:50000;
lcoe_opex = zeros(size(op_expenditures));
for i = 1:length(op_expenditures)
lcoe_opex(i) = LCOE_AirborneWind(fcr, cpx, op_expenditures(i), cf, r, 100);
end
figure;
plot(op_expenditures, lcoe_opex, '-o');
xlabel('Operational Expenditures [$/kW/yr]');
ylabel('LCOE [$/MWh]');
title('LCOE vs. Operational Expenditures');


%% cost function
function cost = LCOE_AirborneWind(fcr, cpx, opx, cf, r, power_rating)
	electrical_power_rating = power_rating;
	t_life = 10; % [years]
	t_build = 1; % [years]
	t_decom = 1; % [years]
	%initialize
	t_total = t_life + t_build + t_decom;
	cap_ex = zeros(1, length(t_total));
	op_ex = zeros(1, length(t_total));
	power = zeros(1, length(t_total));
	o_m = zeros(1, length(t_total));
	% capital recovery factor
	crf = (r*(1+r)^t_total) / ((1+r)^t_total - 1);
	% construction
	capital_cost(1:t_build) = cpx * (1 + r).^(t_build-1:-1:0);
	% useful life
```

```
    for t = t_build+1:t_total-1
        o_m(t) = opx * (1 + r)^(t - t_build) * cf;
        power(t) = electrical_power_rating * cf * (1 + r)^(t - t_build);
    end
    % decommissioning
    decommissioning_cost = 0.05 * cpx;
    total_cost = sum(capital_cost) + sum(o_m) + decommissioning_cost;
    cost = total_cost * crf / sum(power);
end
```