Harnessing High Altitude Wind Power

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***Abstract*--Flying electric generators (FEGs) are proposed to harness kinetic energy in the powerful, persistent high altitude winds. Average power density can be as high as 20 kW/m^2 in a approximately 1000 km wide band around latitude 30° in both Earth hemispheres. At 15,000 feet (4600 m) and above, tethered rotorcraft, with four or more rotors mounted on each unit, could give individual rated outputs of up to 40 MW. These aircraft would be highly controllable and could be flown in arrays, making them a large-scale source of reliable wind power. The aerodynamics, electrics, and control of these craft are described in detail, along with a description of the tether mechanics.**

A 240 kW craft has been designed to demonstrate the concept at altitude. It is anticipated that large-scale units would make low cost electricity available for grid supply, for hydrogen production, or for hydro-storage from large-scale generating facilities.

***Index Terms*--Wind power generation, Wind energy, Terrestrial atmosphere, Atmospheric measurements, Energy conversion, Power conversion**

I. Nomenclature

α_c	= Rotor's control axis angle
β	= Angle of cable to the horizontal
T, H, P	= Thrust, H-force and power output of a single rotor
C_p, μ	= Power coefficient and tip speed ratio, component of the wind normal to the rotor's control axis divided by the speed of the rotor blade's tip
R, Ω	= Tip radius and angular velocity of rotors
V, ρ	= Velocity and air density of the free stream
M, g	= Craft mass and acceleration due to gravity
X, Y, Z	= Wire fixed, orthogonal set of axes also forces in these directions. Alternatively wind axes are used.
x, y, z	= Displacements in X, Y, Z directions
ϕ, θ, ψ	= Angular displacements about X, Y, Z axes
θ_o	= Rotor's collective pitch angle
L_c	= Tether length from ground to craft
a_1	= Rotor's fore and aft flapping angle

II. Introduction

Two major jet streams, the Sub-Tropical Jet and the Polar Front Jet exist in both Earth hemispheres. These enormous energy streams are formed by the combination of tropical region sunlight falling and Earth rotation. This wind resource is invariably available wherever the sun shines and the Earth rotates. These jet stream winds offer an energy benefit between one and two orders of magnitude greater than equal-rotor-area, ground mounted wind turbines operating in the lowest regions of the Earth's boundary layer. In the USA, Caldeira [1] and O'Doherty and Roberts [2] have shown that average power densities of around 17 kW/m^2 are available. In Australia, Atkinson et al [3] show that 19 kW/m^2 is achievable. These winds are available in northern India, China, Japan, Africa, the Mediterranean, and elsewhere.

Various systems have been examined to capture this energy, and these include tethered balloons, tethered fixed-winged craft, tether climbing and descending kites, and rotorcraft.

Our preferred option is a tethered rotorcraft, a variant of the gyroplane, where conventional rotors generate power and simultaneously produce sufficient lift to keep the system aloft. This arrangement, using a twin-rotor configuration, has been described and flown at low altitude by Roberts and Blackler [4] (Fig. 1). More recent developments have produced a quadruple rotor arrangement [5] (Fig. 2). Commercialization of the quad-rotor technology could significantly contribute to greenhouse gas reductions.

Tethered rotorcraft, with four or more rotors in each unit, could harness the powerful, persistent jet streams, and should be able to compete effectively with all other energy production methods. Generators at altitude also avoid community concern associated with ground-based wind turbine appearance and noise. Bird strike problems are also less. However, tethered generators would need to be placed in dedicated airspace, which would restrict other aircraft. Arrays of tethered generators would not be flown near population centers unless and until operating experience assured the safety of such a configuration.

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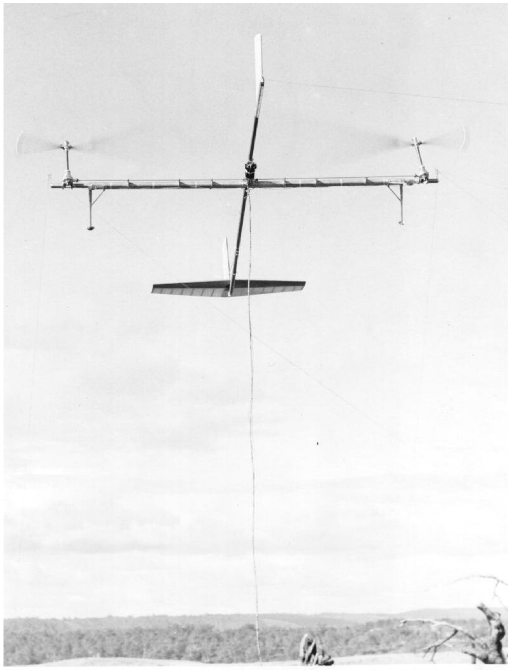

Fig. 1. Photograph of early two-rotor prototype in flight.

At this time, the best tether for the rotorcraft appears to be a single, composite electro-mechanical cable made of insulated aluminum conductors and high strength fiber. When operating as a power source, two, four, or more rotors are inclined at an adjustable angle to the on-coming wind, generally a 40° angle. The wind on the inclined rotors generates lift, gyroplane-style, and forces rotation, which generates electricity, windmill-style. Electricity is conducted down the tether to a ground station.

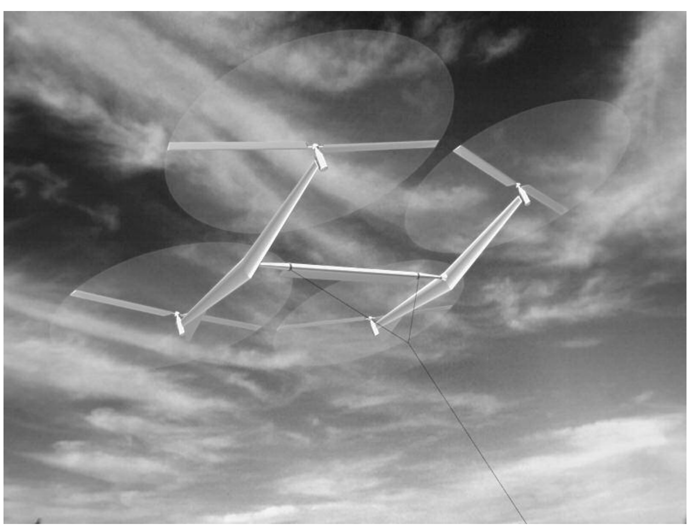

Fig. 2. Rendering of Sky WindPower Corp.'s planned 240 kW, four-rotor demonstration craft.

The craft simultaneously generates lift and electricity. However, it can also function as an elementary powered helicopter with ground-supplied electrical energy, and with the generators then functioning as motors. The craft can thus ascend or descend from altitude as an elementary, tethered helicopter. During any lull periods aloft, power may be supplied to maintain altitude, or to land on a small ground base. A ground winch to reel the tether, could be used to retrieve the craft in an emergency.

III. Upper Atmospheric Winds in US and Elsewhere

Based on the ERA-15 reanalysis of the European Centre for Medium-Range Weather Forecasts, we calculated the seasonal-mean, climate-zone wind power density from December 1978 to February 1994 [6]. Computed power densities in high altitude winds exceed a 10 kW/m^2 seasonal average at the jet stream's typical latitudes and altitudes. This is the highest power density for a large renewable energy resource anywhere on Earth. It exceeds the power densities of sunlight, near surface winds, ocean currents, hydropower, tides, geothermal, and other large-scale renewable resources [7]. For comparison, Earth surface solar energy is typically about 0.24 kW/m^2 [8], and photovoltaic cell conversion of energy into electricity has an efficiency several times less than that of wind power[7].

High power densities would be uninteresting if only a small amount of total power were available. However, wind power is roughly 100 times the power used by all human civilization. Total power dissipated in winds is about 10^{15} W [8]. Total human thermal power consumption is about 10^{13} W [9]. Removing 1% of high altitude winds' available energy is not expected to have adverse environmental consequences.

High altitude winds are a very attractive potential source of power, because this vast energy is high density and persistent. Furthermore, high altitude winds are typically just a few kilometers away from energy users. No other energy source combines potential resource size, density, and proximity so attractively.

IV. Description of the Preferred Energy Conversion System

The currently proposed new tethered craft consists of four identical rotors mounted in an airframe which flies in the powerful and persistent winds. The tether's insulated aluminum conductors bring power to ground, and are wound with strong Kevlar-family cords. The conductor weight is a critical compromise between power loss and heat generation. We propose employing aluminum conductors with tether transmission voltages of 15 kV and higher, because they are light weight for the energy transmitted. To minimize total per kWh system cost and reduce tether costs, the design allows higher per meter losses and higher conductor heating than does traditional utility power transmission. Depending on flight altitude, electrical losses between the tether and the converted power's insertion into the commercial grid are expected to be as much as 20%, and are included in energy cost estimates described in Section IX.

The flying electric generator units (FEGs) envisioned for commercial power production have a rated capacity in the 3 to 30 MW range. Generators arrays are contemplated for wind farms in airspace restricted from commercial and private aircraft use. To supply all U.S. energy needs, airspace for power generation is calculated to restrict far less airspace than is already restricted from civil aviation for other purposes. While similar in concept to current wind farms, in most cases flying generator arrays may be located much closer to demand load centers.

When operating as an electrical power source, four or more rotors are inclined at an adjustable, controllable angle to the on-coming wind. In general the rotors have their open faces at an angle of up to 50° to this wind. This disk incidence is reduced in various wind conditions to hold the power output at the rated value without exceeding the design tether load. Rotorcraft can also function as an elementary powered helicopter as described in section II.

Our capacity, or generating factor calculations account for wind lulls or storms during which the generators must be landed. However, the projected capacity for flying electric generators is far higher than for the best ground-based wind turbine sites because of the persistent winds at high altitudes.

High altitude wind speeds and other conditions are measured at 12 A.M. and P.M. at major airports worldwide by radiosonde weather balloons, and are reported on NOAA and other government websites. It is thus possible to calculate what the past capacity of flying generators at those locations would have been. Sky WindPower Corporation's detailed calculations for many worldwide sites from October 2000 to September 2001 may be accessed at skywindpower.com

The U.S. average capacity factor would have been about 80% for craft flying at 10,000 meters. At Detroit's latitude, the capacity factor was calculated at 90%, at San Diego's, 71%. This compares to capacity factors of about 35 percent for ground-based wind turbines operating at the best sites.

Fig. 2 above and Fig. 3 below show the four-rotor assembly with four identical rotors arranged, two forward, and two aft. The plan-form of the rotor centerlines is approximately square. Adjacent rotors rotate in opposite directions; diagonally opposite rotors rotate in the same direction.

In this particular four rotor assembly, craft attitude in pitch, roll, and yaw can be controlled by collective rotor pitch change. No cyclic pitch control is needed to modify the blades' pitch as they rotate, as is needed in helicopter technology. This should help reduce maintenance costs. Rotor collective pitch variation then varies the thrust developed by each rotor in the format described below using GPS/Gyro supplied error signal data.

(1) Total craft thrust (and total power output) is controlled by simultaneously equal, collective pitch action on all rotors.
(2) Roll control is by differential, but equal, collective pitch action between the port and starboard pair of rotors.
(3) Pitch control is by differential, but equal, collective pitch action between the fore and aft pair of rotors.
(4) Yaw control, via differential torque reaction, is by differential, but equal, collective pitch changes on pairs of opposing rotors.

Ground-based wind turbines experience surface feature turbulence not present at high altitude. In addition, turbulence reaction is different for a FEG. Ground-based turbines are, more or less, rigidly mounted on support towers. Even when flexible units and procedures are used, direct and gust-induced moment loads are significant for these ground-based facilities. Considerable European and US research and development has been directed towards relieving load excursions from near-surface wind gusts.

Flying electric generators have a great, inherent advantage over equivalent ground-based facilities in their ability to reduce gust loads. This is due to tether cable flexibility, both as built-in elasticity and as changeable shape (drape) under gust conditions. This flexibility very significantly alleviates gust loads and torques applied to the rotors, gearboxes, etc. This means that gust loads in flying units are reduced by more than an order of magnitude compared to ground-based turbine gust loads. Sky WindPower Corp. has developed programs that demonstrate this gust alleviation process. Section V. details the flight performance of these flying generators.

V. Flying Generators Aerodynamic Performance

The flying generator's side view in Fig. 3 is for a typical flight configuration in a wind of velocity V. A single tether of length L_c is attached to the craft at a point A on the craft's plane of symmetry. The aircraft's center of mass is at C. The tether is assumed, herein for simplicity, to be mass-less and non-extendible.

For low altitude flight, around 1500 ft (< 500 m), the assumption of a straight, mass-less tether is reasonable. However, for higher altitudes, the analysis has been extended to included tether mass and tether air-loads. Roberts and Blackler [4] and Roberts and Shepard [5] have shown that higher altitudes are achievable using an aluminium-Kevlar composite [4] or an aluminum-Spectra composite [5] for the electro-mechanical tethering cable.

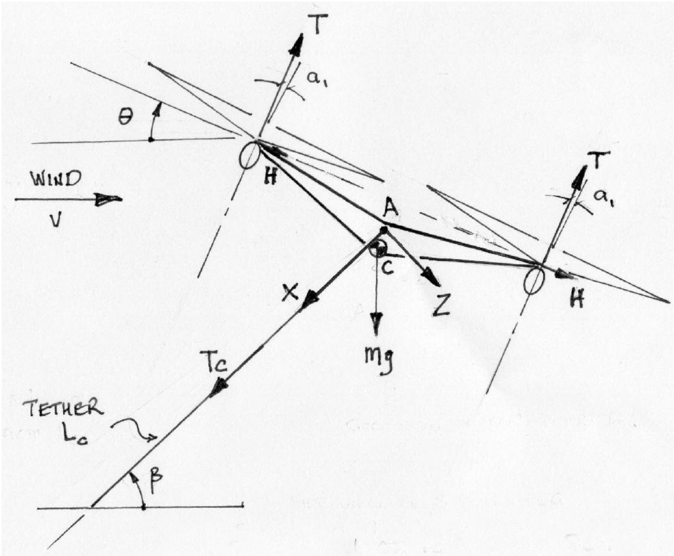

Fig. 3. Diagram of the FEG in flight, showing the craft's nose-up angle, θ, which is identical to the control axis angle, α_c, as no cyclic pitch use is planned. The rotor's fore and aft flapping angle, a_1, is shown as the angle between the normal to the tip-path plane and the control axis. The total rotor thrust component along the control axis is T, and normal to this axis is the component force H. If T and H forces are combined vectorally the total rotor force is almost normal to the tip-path plane.

A number of detailed equilibrium studies have been completed, such as those by Roberts [10], Ho [11] and Jabbarzadeh [12]. These were all based on the classic rotor theory of Gessow and Crim [13] applicable to rotors operating at high disk incidences with high in-flow conditions.

Fig. 4 shows the power output coefficient, C_p, for each rotor where

$$C_p = \frac{P}{\pi R^2 \cdot \frac{1}{2}\rho V^3} \tag{1}$$

The power output is plotted against the control axis angle, α_c, for values of constant tip speed ratio, μ.

By reference to Fig. 3 it can be seen that

$$\alpha_c = \theta \tag{2}$$

$$\text{and } \mu = \frac{V\cos\alpha_c}{\Omega R} \tag{3}$$

The dotted curve represents the maximum power output under conditions of zero profile drag on the rotor blades. Hence it follows that when $\alpha_c = 90°$ the value of C_p will equal the Betz Limit of 0.593. Using the methods of Gessow and Crim [13], the practical values of C_p have been calculated for a rotor solidity of 0.05. For a fixed value of μ the power coefficients adopt an inverted U-curve shape. On each of these curves, the power coefficient can be zero. These are the autorotation conditions where no power is being developed or supplied to the rotors. The favored autorotation condition, to be discussed below, is the left-hand side zero crossing of each inverted U-shaped curve. In these conditions the craft is self-sustaining in the prevailing wind, V, and rotor speed, Ω.

Fig. 4 shows that the preferred generating conditions are at a power coefficient of around 0.4 with a control axis of about 50° at a tip speed ratio of 0.075. The tip speed ratio, in the current context, is defined by equation (3) above. The best autorotation condition will now be discussed.

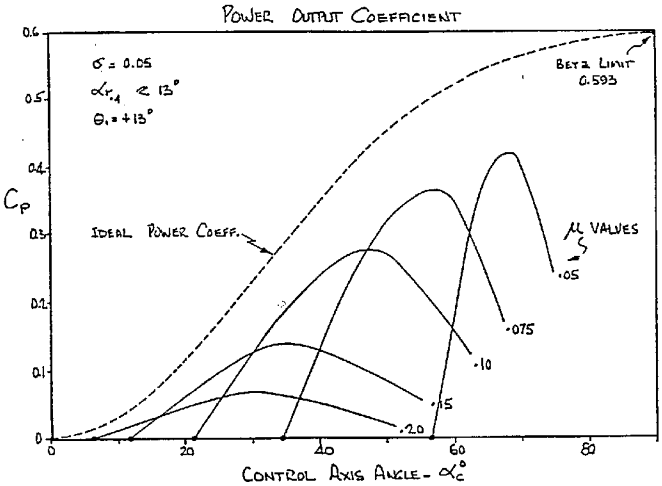

Fig. 4. The power coefficient, C_p, plotted as a function of the control axis angle, α_c. α_c is equal to the craft's nose-up angle, θ, as no cyclic pitch use is planned and is used in the strict rotorcraft sense. The power coefficient, C_p, is the actual shaft power divided by the power contained in the on-coming wind stream with an area equal to the swept area of the rotor. The tip speed ratio, μ, is the component of the wind normal to the rotor's control axis divided by the speed of the rotor blade's tip.

The autorotation conditions physically relate to conditions when wind speed is insufficient to support the craft and its tether, and the system is on the point of collapse. The left-hand side cutting of the inverted U-shape curves in Fig. 4 with the ordinate axis, implies that all the wind's kinetic energy is being used to generate lift and that no power is being developed. The left-hand cutting with the ordinate is preferred because in this condition it favors the tether cable more than does the companion right-hand crossing of the ordinate. This implies that the craft's lesser nose-up attitude allows a more near vertical application of force at the top of the tether.

The question now arises as to which of the left-hand crossings is most favorable for our purposes. Jabbarzadeh [12], and Roberts and Shepard [5] have found that the minimum wind speed to stay aloft occurs when the craft nose-up attitude is around 24° with a corresponding tip speed ratio of 0.10. These values will vary somewhat with different rotor and tether parameters, but it is important to realize that autorotation at a minimal wind speed is fundamental to the system's performance. A typical minimum wind speed for autorotation is around 10 m/s at an operating altitude of 15,000 feet (4600 m).

VI. Electrical System Details

Flying electric generators need to ascend and remain aloft for short periods on grid-sourced energy. In low-wind conditions, only a small proportion of output rating as grid-sourced energy is required to raise or maintain the craft aloft. Voltages at the terminals of both the generator/motor and at the grid interface need to be kept within designed tolerances and/or be adjusted by timely voltage regulation.

In a national regulated electricity market, such as that found in Europe and elsewhere, a System Impact Study (SIS) is required to connect a new generator to the grid [14] if the generator's capacity is above a minimum level, e.g. 5 MW. Even non-dispatchable "embedded generators" require Grid System Impact Assessments. The generator proponent usually pays for the generator-to-grid network connection. Land and sea locations for generation from renewable energy sources, especially wind energy, are often remote from the existing grid, hence, connection costs are often 50% of the total investment for new generating capacity. Also where a renewable energy source generator is not n-1 reliable for availability, the Network Connection Contracts usually include the costs of back-up supply contingencies. These relate to network charges when the renewable generator is not supplying.

Flying electric generators at altitude will have a relatively high availability, around 80%. Reliability and peak premium sales could be enhanced by a link to a pumped storage facility for off-peak filling/storage and peak-release energy sales and delivery. Energy could be stored as hydrogen gas produced from electrolysis, or as water pumped-back and re-released for hydroelectric generation.

Conventional ground-based wind energy systems harvest only about 30% availability. Flying electric generators, in single units of 20 MW or more, can achieve about 80% availability with suitable siting at land or sea locations. These generators at altitude involve power transmission over lengths of between 4 and 8 km. Flying generator/tether voltages between 11 kV and 25 kV ac could be used on units of 30 MW at the most extreme altitudes. Also there are recent modern innovations, which use powerformers/motorformers™ [15, 16]. The latter, being developed by equipment suppliers such as ABB, Siemens, Mitsubishi, etc., would allow polymeric cable stators and tether voltages at say 33 kVac or more. Grid interfacing would then be easier at bulk energy levels.

The jet-stream location can drift north and south, so seasonal mobility from one prepared site to another could be a feature of flying generators' grid utilization and optimization. This could be advantageous in seasonal summer/winter demand-side management through peak-matching generator placement or relocations. This would include matching seasonal peaks for rural industries, such as grape processing, cotton harvesting, and irrigation to urban air-conditioning etc.

Because arrays of flying generators could move north or south to follow seasonal shifts in wind patterns or power demand, it could be advantageous to have "plug-in" flying generators at pre-arranged sites along an existing grid 33 kV, or more, overhead feeder with minimal interfacing. This would use, for example, a HV Live Line HV Bypass cable, sometimes called Temporary cable, with a mobile or transportable High Voltage Generator switchyard circuit breaker/metering unit.

If the tether arrangement were to contain three conductors - two could form the single-phase circuit, while the third could be the ground wire and control cabling function. Three-phase balance is then achieved by adding other nearby generator outputs to form single-phase combinations for grid connection. Alternatively, if necessary, a transformer with OLTC could be used, similar to that used for monoplex or 50 kVac duplex rail electric traction supply. This would be similar to a rail traction supply transformer of 50 MVA and 132 kV three phase to 25 kV ac positive and 25 kV ac negative to centre tap earth.

When using a shipboard site, fixed ocean site, or a site adjacent to a water-reservoir which is remote from the desired FEG ground-surface connection location, then the use of HVDC on tethers, with surface/submarine cabling, should be considered in combination with a HVDC voltage motorformer/powerformer™ design. In addition, a unit's DC motor/generator commutation by conventional brushes might be facilitated by more modern electronic switching or by triggered Vacuum Gaps (TVG).

Where an AC interfacing transformer, or a HV AC /DC Converter Station (usually with an included transformer) is required for grid interfacing connectivity, the economics of scale would encourage more multiple-unit connections.

A 60 MW to 150 MW grid connection composed of three 20 to 50 MW airborne units with a powerformer™, or HVDC AC/DC connection, can perform as a synchronous condenser, thereby adding AC grid stability advantages in the SIS. This will depend on grid siting.

Starting and retrieval characteristics of flying units at specific grid connections could be an important SIS review item. A higher fault level at the connection site is desirable for a large motor start up. Generator and tether performance depend on a good lightning storm detection system. Surge protection schemes and hardening of the control systems are also under examination.

VII. Flight Control Using GPS and Gyro Data

Very accurate control is needed to precisely maintain a desired position in the sky. GPS with gyroscopes is an ideal way to provide the reference data necessary to provide this control.

The Global Positioning System (GPS) consists of a constellation of 24 satellites that provide a continuous navigation capability to users at any location on (or near) Earth in all weather conditions. With this system, currently operating with 29 satellites, real-time, three dimensional position information with accuracies on the order of 5-10 m can be achieved [17].

Main error sources for the system include signal propagation effects through the atmosphere, satellite orbit and timing errors, and GPS receiver noise and signal reflection (multipath). When used in differential mode, where measurement corrections are computed at a GPS reference station sited on a known location, accuracies can be improved quite easily to within a few meters (DGPS).

Although generally used for positioning and navigation, GPS can also be used for platform attitude determination and control. If three or more GPS receivers and antennas are mounted on a platform, such as an FEG, the GPS carrier phase data can be used to directly estimate the roll, pitch, and heading of the platform in real-time at a rate of 1-20 Hz [18].

The attitude parameter accuracy is primarily a function of the signal multipath, and antenna separation (wider spacing yields higher attitude accuracies – Fig. 5). For the FEG, multipath could occur through the reflection of the signals off the structure itself. However, when antennas are separated by over 5 m on the FEG, attitude accuracy should be better than 0.25° with multipath present, which is well within the required attitude control specifications.

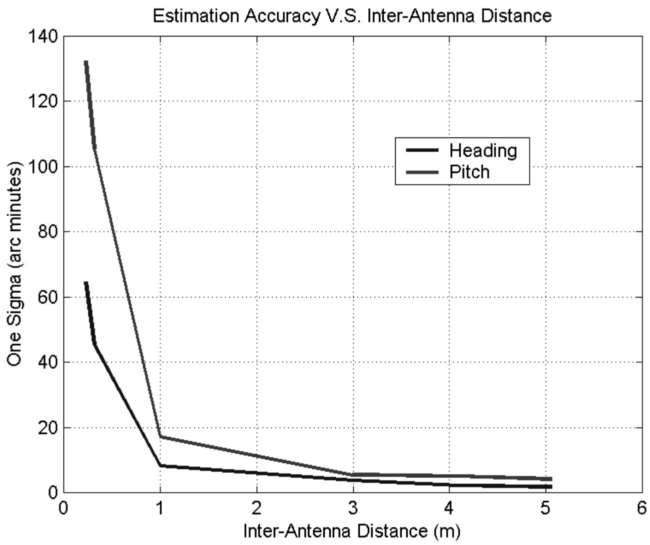

Fig. 5. Relationship between the achievable GPS-derived heading and pitch accuracy and antenna separation

Two other factors must be considered when using GPS for attitude determination and control on the FEG. One is the rigidity of the structure itself. Antennas with maximum separation increase the achievable accuracy, but function best with antennas located on a rigid frame. A second factor is system performance during significant FEG nose-up angles. These angles range from 0° when hovering up to 45° when generating. While hovering, some GPS satellites may be obscured since the FEG may block reception signals along the line-of-sight. Tests show that attitude parameters can still be estimated up to at least a 45° tilt, however, a gyroscope used as an auxiliary attitude sensor, augments GPS availability and reduces noise. This has been implemented for many applications, and overall accuracy is a function of the gyro sensor characteristics [19].

VIII. Details of a 240 kW Demonstration Craft

Sky WindPower Corp. has completed the design for a 240 kW demonstration craft. Fig. 2 is an isometric view of this craft.

Two units will demonstrate the commercial viability, or otherwise, of the flying generator concept. These craft have four, two-bladed rotors turning in paired counter-rotation as described above. The rotors are 10.7 m in diameter with solidity of 5%, and the un-twisted blades are of conventional construction. Collective pitch control on the rotors will be via electric actuators. The craft is designed for operations up to 15,000 feet (4600 m).

The rotors are connected to four separate gearboxes, which drive four motor/generator units supplied by AC Propulsion. These electrical machines are of high armature speed to ensure a satisfactory power-to-weight ratio. They are also electrically linked to ensure that rotor speeds do not vary with one another. Typical armature speeds are 24,000 rpm. The four power units are mounted in an elementary, low-drag fuselage of fiber composite construction. The all-up weight of each craft is estimated at around 1140 lbs (520 kg).

The electro-mechanical tether is designed to transmit 240kW at a voltage of 15kV. The electrical transmission efficiency is 90%. The tether has two insulated aluminum conductors embedded in a Vectran fiber composite. The tether's specific weight is around 115 kg/km at a diameter of 10mm. A sample has been constructed. The electrical ground facility is configured for a DC supply to and from the platform. The motor/generators are series connected.

The craft's rated output is developed at an 18.4 m/s wind speed at an altitude of 15,000 feet (4600 m). The 11.5 m/s autorotation speed is at the same altitude. The power consumption in no wind (hover) at 15,000 feet (4600 m) is estimated to be around 75 kW. Rotor speeds are in the range of 130 to 300 rpm. The craft in this demonstrator is designed to withstand a wind of 35 m/s at 15,000 feet (4600 m). Throughout the operating envelope the craft's nose-up attitude varies in the range 10 and 45°. At no time during these operations does the blade incidence on the retreating blade exceed acceptable values at the conventional reference station, while tip Mach numbers never exceed about 0.6.

Finally, there is some merit in the view that the best return on investment of these craft will be dependent on an optimal, operating altitude. At low altitudes the average wind velocity wanes, while at higher altitudes, adjacent to the jet stream core, the costs produce a less than beneficial return, because of the need for a higher transmission voltage as the altitude increases. Thus it will be necessary to find the best return from an investment as a function of the maximum operating altitude. This aspect will be developed and confirmed over 12 months of flights planned during the demonstration program.

IX. Cost and Performance Projections at the Large Scale

A. Scalability Considerations

As discussed in section IV. , the tethered rotorcraft is inherently scalable in size and output, from small prototype configurations of below 240 kW, through commercially viable systems with competitive costs of energy, in the range of 3 MW to 30 MW per craft. Larger sizes are more economical and may utilize more than four rotors to maintain economy and manageability of materials.

In this section we analyze cost and performance of a four-rotor, 3.4 MW (platform-rated) configuration as might be deployed in an array over various sites in the U.S. Because of losses described earlier, the actual output after conditioning would be about 20% lower. The 3.4 MW size was chosen because it is large enough to provide competitive economics in a four-rotor configuration, and a rotor design that is within the scope of currently available methods and materials.

B. Weights and Costs

For cost illustration purposes, we use a 100 MW array, comprised of 3.4 MW FEGs. The cost estimates are based on 250 FEGs/year production rate assuming prior production of 150 FEGs, in accordance with NREL guidelines [20].

A 3.4 MW platform-rated craft is estimated to weigh 21,000 lbs (9500 kg) and cost $1,360,000. Adding ground systems and production profits brings the total to $2,260,000 per 3.4 MW. The balance of station costs for the 100 MW array, including site preparation, facilities and equipment, spare parts and construction is $4,210,000. Taken together these initial capital costs come to $71,200,000 per 100 MW.

C. Performance and Net Annual Energy Production

Three design sites were chosen for analyzing the output of the 100 MW array, Topeka, Kansas, Detroit, Michigan and San Diego, California. Topeka is a "Great Plains" site, Detroit is a site where a great deal of energy is used, and San Diego is a site where capturing power from the wind is not normally thought to be practical.

Net Annual Energy Production kWh/yr is determined by multiplying rated power by a site capacity factor. Capacity factors for FEGs of the proposed design are based on wind statistics provided by NOAA radiosonde readings for major airports near the design sites, normally taken daily at noon and midnight. FEGs are to be flown at the most efficient altitude for prevailing wind conditions, and capacity factor is calculated in the normal manner.

In making these calculations we have taken into account the projected operating characteristics of the 3.4 MW design through the range of altitudes up to 9,000 meters. Over the current range of interest the rated wind speed has been approximated to the linear variation (4), while the air density varies according to NACA Standard Atmosphere values.

Capacity factors have been computed for the three design sites using software we developed, from data downloaded from NOAA. The data is for the year starting September 20, 2000 and ending September 21, 2001.

$$V = 14\,m/\sec + 5.7\,m/\sec \times \frac{H}{10{,}000\,m} \qquad (4)$$

$V \equiv$ Required wind speed in meters per second to operate at rated capacity, and

$H \equiv$ Altitude in meters.

Capacity factors for Topeka, Detroit, and San Diego are 91%, 90% and 70%, respectively. As a reserve against storms, maintenance and mechanical problems, we assume 10% downtime. This gives Net Annual Energy Production figures of 581 GWh/yr, 575 GWh/yr and 447 GWh/yr, respectively for a 100 MW array at each of the three sites.

D. Projected Cost of Energy

Annual Operating Expenses (AOE) include Land Lease Costs (LLC), Operations & Maintenance (O&M) and Levelized Replacement/Overhaul Costs (LRC). AOE projections are necessarily subjective, since no plant like this currently exists. O&M costs are derived from an $82,000/yr estimate for a 3.4 MW FEG, multiplied by 29.4 FEGs/100 MW plant. Life-limited components are anticipated to require replacement at 10 years and 20 years. Tether longevity is a risk. Replacement cost is estimated at 80% of the initial capital cost for the whole system. Expressed in per kWh terms, the AOE for the Topeka, Detroit, and San Diego sites are estimated at $0.0102/kWh, $0.0103/kWh, and $0.0129/kWh, respectively.

We have assumed a Fixed Charge Rate (FCR) of 0.0750/yr. The cost of energy was computed using the formula (5). For the Topeka, Detroit, and San Diego sites the costs of energy (COE) are $0.0194/kWh, $0.0196/kWh, and $0.0249/kWh, respectively.

$$COE = \frac{(FCR \times ICC)}{AEPnet} + AOE \qquad (5)$$

X. Energy Storage Issues

Electric utilities want constantly available “dispatchable” power, which cannot be provided economically if capacity factors are low, such as the thirty percent that is typical of ground based wind turbine sites. However, with the high capacity factors, such as 85 percent, that are expected at average FEG sites in the United States and many other places in the world (especially in the mid-latitudes), this dispatchable electricity becomes economical. This is because the expected storage requirement in connection with FEG derived electrical energy is storage for only the shorter periods when FEGs are grounded due to inadequate winds or bad storms.

Pumped water storage, where available, is a very economical means used now for such temporary storage. A well known example is used by the utility PG&E in California to pump water up to a high lake during low electrical-use hours and then have that water generate electricity at high demand times on the way back to a lower lake.

Existing hydroelectric power at dams may be considered to be the equivalent of pumped water storage facilities by deliberately phasing in and out generation in complementary fashion to wind availability at a nearby FEG array. In that combination the combined output could be dispatchable power with as much as four times the capacity of the existing hydroelectric site.

Compressed Air Energy Storage (CAES) is another energy storage means presently coming into use. In special circumstances, where pumping compressed air into existing large caves or porous rock strata is feasible, it may well be especially economic. Commercial tanks built for the purpose may be the most economic storage means where very short-term energy storage is needed.

Hydrogen, not currently a means of economic storage as are some of the methods mentioned above, has the advantage that it can be stored in one season and used in another. Hydrogen can be produced from low cost FEG electricity supplied by water electrolysis, stored in typically good wind winter months, and then used to generate electricity in typically low wind summer months. For example, the capacity factor at Patiala, India for an FEG flying at 35,000 feet (10700 m) is calculated at only about 37 percent for the summer months, but approximately 90 percent for the remaining months. Therefore, north India's hydrogen generation using FEGs in the good months should sufficiently supply all its energy needs. Summer electricity would be generated from stored hydrogen fueling turbines in the south, not directly from FEG arrays.

Furthermore, high altitude winds are often described by the planetary scale thermal wind equations. These thermal winds, including the jet stream, tend to shift latitudinally but rarely stop blowing. Thus, a latitudinally spaced configuration of flying electric generator arrays, coupled with long-distance electricity transmission, could potentially smooth out much of the local variability in high altitude wind power generation.

Thus, the economics of supplying the dispatchable electricity, which electric utilities want, should be favorable in connection with energy storage when that electricity is generated by FEGs with their high capacity factors. This is an important factor in determining the relative worth of FEG generated electricity compared with that of fossil fuels such as natural gas, and, therefore, also the financing costs of FEG facilities.

XI. Conclusions

It has been shown that flying electric generators can harness the powerful and persistent winds aloft to supply electricity for grid connection, for hydrogen production or for hydro-storage. Globally, upper atmospheric winds provide an enormous resource for this application. The environmental impacts at altitude are minimal with virtually no visual, or noise intrusion and no bird strikes. The proposed systems lead logically to rural/remote area installations in regions of restricted airspace.

Sky WindPower is well advanced in the design, and in vendor-supplied qualified components for the demonstration of a small 240 kW craft for operation in the southern US and/or out-back Australia. Full-scale facilities, using individual FEG units of rated power around 30 MW, could easily form wind-farms equivalent in output to regular coal, gas and nuclear facilities. These wind-farms would give capacity (generating) factors around three times greater than that from conventional wind-farms. The estimated bulk electricity cost for the power so produced is estimated to be of the order of $20/MWh.

High altitude wind power is not science fiction. It depends on currently available technologies and engineering know-how, building on decades of experience with wind turbine and gyroplane technologies. Harnessing high altitude wind energy, using a combination of essentially existing technologies, appears to be thoroughly practical and suggests that this energy source can play an important part in addressing the world's energy and global warming problems.

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XIII. Biographies

Bryan W. Roberts graduated BE, with honors and university medal, from the University of New South Wales in 1959 after serving an engineering apprenticeship with the Colonial Sugar Refining Company, Australia. He received a Ph.D. from the University of Cambridge, UK in 1962 in the field of aeronautics. He has held positions in the engineering faculties of the University of Sydney and the University of Western Sydney. He is now retired from the latter where he held the position of Foundation Professor of Mechanical Automation Engineering.

His research has involved theoretical and practical studies of the stability and control of tethered rotorcraft. He has some 80 publications and is a Senior Member of the AIAA, a Member of the American Helicopter Society and a Fellow of the Institution of Engineers, Australia.

David H. Shepard (M’1954) started in electrical engineering at Cornell in 1941 but was called up by the Army in 1943 and sent to Michigan to learn Japanese. From there he was sent to Washington, where he worked successfully on Japanese codes. After the war he obtained his M.S. at Michigan. Subsequently he founded Intelligent Machines Research Corporation (IMR), which delivered the world’s first dozen commercial OCR systems.

Mr. Shepard later founded Cognitronics Corporation, which developed Interactive Voice Response (IVR) technology. Retiring as CEO at the age of 65, he moved to California, where he decided that the world should be tapping the energy in high altitude winds. In 1985 he came across the work of Professor Roberts, decided his approach made the most sense, and contacted him. In 2002 he contacted Prof. Roberts again and they decided the world should now be more interested in capturing high altitude wind energy. Mr. Shepard has 27 U.S. patents, including in the fields of OCR, IVR and high altitude wind energy capture.

Ken Caldeira is a staff scientist at the Carnegie Institution’s Department of Global Ecology at Stanford University. Prior to that, Caldeira spent 12 years at Lawrence Livermore National Laboratory, most recently in its Energy and Environment Directorate. Caldeira was a post-doc in the Geosciences Department at Penn State. He earned his Ph.D. in Atmospheric Sciences from New York University in 1991.

Caldeira is a lead author of the “State of the Carbon Cycle Report”, an interagency report of the US Government requested by the US Congress. Caldeira was part of the US delegation in climate change negotiations leading up to the 2005 G8 summit in Gleneagles, Scotland. Caldeira was a member of the US Carbon Cycle Steering Group, and a Coordinating Lead Author of an IPCC report on carbon storage in the ocean. He was a member of the UNESCO International Oceanography Commission CO2 Panel of Experts. While at Lawrence Livermore National Laboratory, Caldeira was awarded the Edward Teller Fellowship, the highest award given by the laboratory.

M. Elizabeth Cannon is Dean of the Schulich School of Engineering at the University of Calgary where she conducts research in the area of satellite navigation for land, air and marine applications. Elizabeth has been involved with GPS since 1984 in both industrial and academic environments and has published over 90 journal and 150 conference papers. Her research has encompassed the development of new satellite navigation methods, algorithms and integrated systems that have been applied to such area as vehicular navigation, precision farming, and aircraft flight inspection. The results of her research have been commercialized through the licensing of software to over 200 agencies world-wide.

Elizabeth is a Fellow of the Canadian Academy of Engineering, the Royal Society of Canada, and was an NSERC Steacie Fellow during 2002-2004.

David G. Eccles (M’2001) is a Senior Electrical Engineer with a NSW Energy Utility, having 30 years professional power distribution/subtransmission engineering experience in distribution utilities including Prospect County Council, urbanising Western Sydney, Shortland Electricity, and Hunter Valley NSW Coalfields supply and rural systems. He was Design Engineer at PCCC Electricity in rural/industrial Tamworth, an 1888 pioneer Power Innovation Team. Eccles was amalgamation/merger Network Policy Engineer for NorthPower, NSW/Queensland and involved in the State Electricity Market/National Electricity Market startup, including feasibility assessments for several power stations up to 50 MW, and actively involved in the world's first fast-track underground HVDC Network Interconnector.

More recently, he has worked on mining boom supply projects, rural bushfire resistant steel poles trials, field trial of an NKE wave/GPS accurate fault location system, High Voltage Live Line Safety and Innovation Product Championing. Eccles was an IEEE CCWG participant in carbon gas measurement & auditability, for ISO14064.

Albert J. Grenier obtained his engineering degree from Clarkson University in 1965. He was first employed as an Industrial Engineer for Eastman Kodak Co., specializing in the study and improvement of engineering model shops, helped by the fact that his father was an expert in the field, and had a professional model shop in the family basement. After two years at Kodak, Grenier joined General Dynamics Corp. and became Manager of Manufacturing for the Datagraphics Division. Subsequently Mr. Grenier joined Cypher Data Corp where he became Vice President of Operations.

Grenier founded and became president of Cykic Software Corporation, where he still serves on its Board. Becoming intrigued with the promise of capturing high altitude wind energy, in 2004 Grenier joined Sky Wind Power Corporation as Executive Vice President, where he has contributed to Flying Electric Generator (FEG) design and taken the lead in qualifying components to be supplied by vendors for the planned 240kW FEG high altitude wind energy capture demonstration.

Jonathan F. Freidin is Vice President and Engineering Director at Sky WindPower. Prior to joining Sky WindPower, he was a cofounder of Connected Corp., where he developed the hierarchical storage manager for its DataProtector server. Freidin was allowed a patent for his work on Connected systems. Prior to that, Freidin was ECAD Manager at Concurrent Computer Corp., and Design Methodology Manager at Kendall Square Research, where he developed proprietary IC CAD tools. Freidin was Associate Director of AI Technology at Palladian Software, where he developed the Financial Advisor and Operations Advisor, expert systems for business decision support.

Freidin worked first for General Electric at M.I.T. Lincoln Laboratory. He later joined the staff at Lincoln Lab to help develop the MacPitts Silicon Compiler for DARPA. He was a cofounder of MetaLogic, where he developed a commercial product based on MacPitts.

Freidin has a B.S. in Applied and Engineering Physics from Cornell University.