AIRBORNE WIND TURBINE CONCEPTS

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INTRODUCTION

Imaginative concepts for flying wind machines have been introduced to take advantage of the larger magnitude and more constant wind speeds with low intermittence at higher elevations in the atmosphere. They also would avoid the near surface turbulence.

These new concepts revive the historical context between the heavier and lighter than air concepts in airplanes evolution.

KITE SHIP PROPULSION

Ships used sails to travel the seas for centuries. Over time, people have stopped using wind to power ships replacing it with steam engines, then internal combustion engines and even nuclear power.

Using a kite to propel a ship and saving on its fuel usage, using wind power has been reintroduced on a merchant ship in Germany.

Fig. 1: Kite attached to a 15 meters high mast helps propel a German ship for a trip across the Atlantic. Source: BBC.

In 2007, the 132 meters long ship underwent a test through a journey across the Atlantic Ocean and back to Europe.

The kite is guided by a computer and tied to a mast on the ship. The concept was introduced by Stephan Wrage, who got the idea since he was 16 years old when was flying kites and wondered if he could use their power to make a small sailboat go faster.

Fig. 2: Tethering of an air rotor system.

AIR ROTOR SYSTEM

An air rotor wind turbine concept based on the Magnus Effect has been proposed and is kept uplift by helium gas generating 4 kW of rated power, and costing about $10,000, with a payback period of about 6 years. It would be anchored by a tether that can extend up to 1,000 feet above ground. A height of 400 feet is enough to catch the minimum 3 m/s wind speed needed to sustain an adequate supply of electricity. The turbine spins in the air turning the generators. The rotation stabilizes the turbine while energy is transferred down to the ground through the tether.

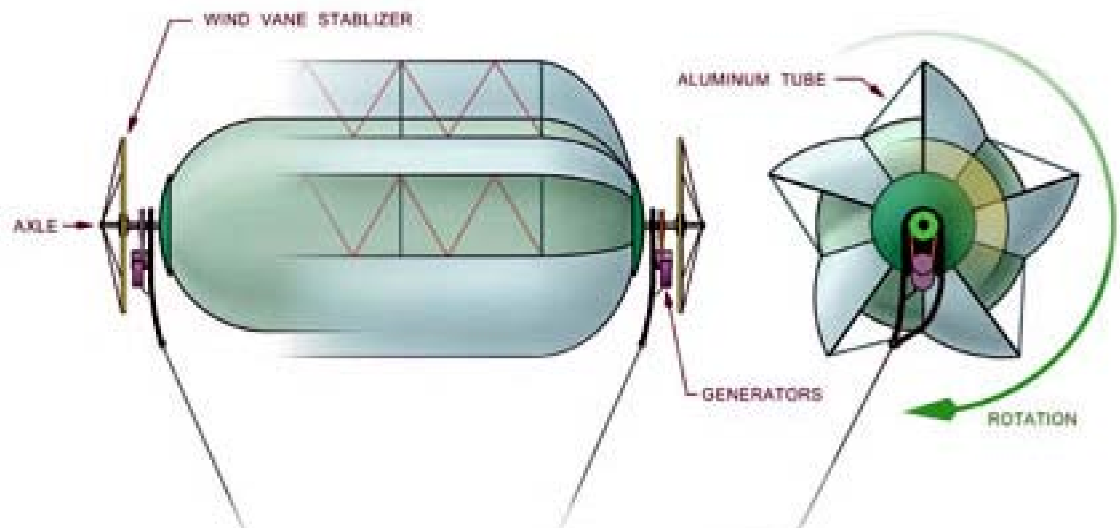

Fig. 3: Magenn air rotor concept.

The Magenn Air Rotor System (MARS) is a lighter than air tethered wind turbine that rotates about a horizontal axis in response to wind, generating electrical energy. This electrical energy is to be transferred down the 1,000 feet tether for immediate use, or to a set of batteries for later use, or to the power grid.

Helium gas sustains it and allows it to ascend to a higher altitude than traditional wind turbines. It captures the energy available at the 600-1000 feet low level and nocturnal jet streams that exist almost everywhere.

Its rotation also generates the Magnus effect which provides additional lift, keeps it stabilized, and positions it within a controlled and restricted location to adhere to Federal Aviation Administration (FAA) guidelines.

MAGNUS EFFECT

This is the effect, discovered in the mid 1800's, that creates lift when a spherical or cylindrical object is spun while moving in a fluid. A dimpled golf ball, hit properly, has a back spin that causes it to lift in flight. A baseball curve-ball pitch uses the Magnus effect. A back spin causes a low pressure region to form above the object and high pressure to form below, resulting in lift. A large object like the air rotor creates substantial lift, so much so that the device should actually work in a wind stream, without using a lifting gas like He.

MAGNUS EFFECT AIRSHIP

Fred Ferguson proposed the Magnus Airship in the 1980s. This airship utilized the Magnus effect for the first time in lighter than air craft. This Magnus Airship was a large spherical envelope filled with helium to achieve static, buoyant lift. As the sphere rotated during forward motion, a Magnus lift was generated proportional to the airspeed flowing over the sphere; the faster the vehicle, the higher the Magnus lift.

The sphere rotated backwards as the craft flew forward. The resulting lift at cruise speed was greater than the total buoyant lift which could be up to 60 tons payload depending upon the final production size. As the wind speed increases, rotation increases, lift increases, drag will be minimized because of reduced leaning, and stability increases.

Fig. 4: Magnus Effect air-ship.

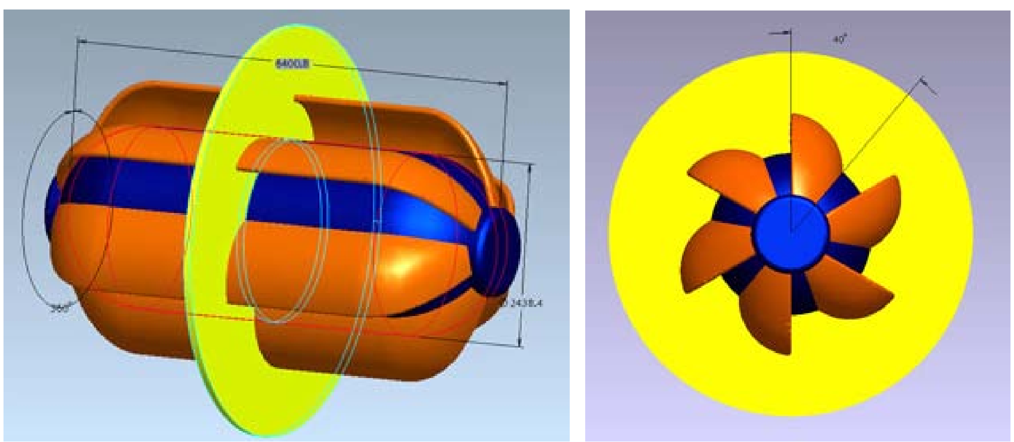

Fig. 5: Model of air rotor system.

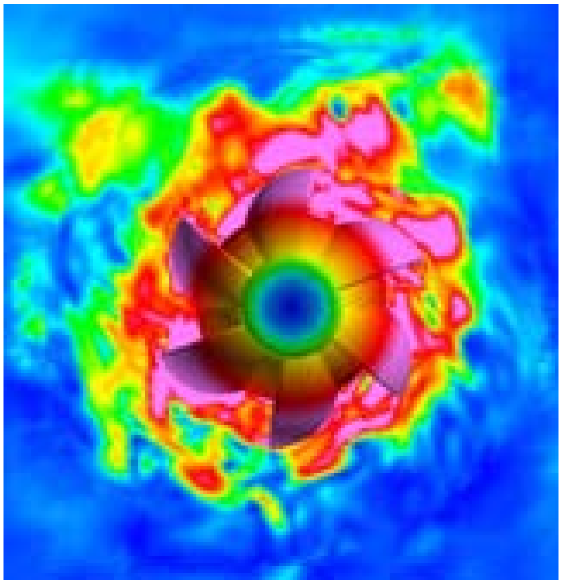

Fig. 6: Computational Fluid Dynamics (CFD) model of air rotor.

HELIUM GAS USE

The air rotor is filled with He gas, which is inert and non-flammable. The lifting gas creates a lift force that is in excess of the total weight of the system. The He gas provides at least twice the positive lift versus the overall weight of the unit. Additional lift is also created when the rotor is spinning in a wind. The aerodynamic effect that produces additional lift is the Magnus Effect.

Helium is a light inert gas and the second most abundant element in the universe. Helium was discovered in 1868 by J. Norman Lockyear. It provides extra lift and will keep an air rotor at altitude in very low winds or calm air. It is also plentiful, inexpensive and environmentally safe. Helium's inert quality over other lifting gases makes it very acceptable in North America. In other parts of the world other lifting gases such as H will probably suffice due to availability and low cost.

Hydrogen is a flammable gas that is lighter than air and the most abundant element in the universe. Henry Cavendish discovered that hydrogen was an element in 1766. In some applications, hydrogen is an attractive and inexpensive candidate for the lifting gas.

The combined lifting effect from the buoyant He lift and aerodynamic Magnus lift help stabilize the air rotor against leaning in the wind. In tests, an air rotor went straight up and held a near vertical position in various wind speeds, since the Magnus effect increases as the wind speed increases. Maximum lean is expected to be less than 45 degrees from the vertical.

One can buy wind rotor kites that demonstrate the Magnus effect. They are called Hawaiian kites and are interesting in that they go straight up in a wind; much straighter than a foil design or other kite designs.

Current aerostats such as blimps and balloons are made of materials that have lasted over 20 years. The air rotor assumes a depreciable life span of at least 15 years before major refits are required.

The 4 kW rated power unit would require slightly over 6,000 cubic feet of He. The price of He varies from country to country. It could cost between 7-17 cents per cubic foot depending on location. Helium leaks at a rate of 0.5 percent per month or 6 percent per year, therefore the air rotor units will have to be topped up with He every 4-6 months.

COMPARISON WITH HORIZONTAL WIND MACHINES

Other things being equal, air rotors are 50 percent as efficient as the best propeller rotors, in terms of their wind intercepted area. For a standard propeller system, this is the circular swept area of the propeller, and for a wind rotor cylinder, it is the wind-facing area.

Thus a wind rotor must have an intercepted area twice as large to produce an equivalent output. However, there are other factors that will boost the wind rotor efficiency such as being able to deploy way above the ground's mechanical turbulence. The air rotor cylinders are basically strong, closed structures and therefore can be built in large sizes at low cost, resulting in a substantially reduced capital cost in comparison to the propeller units.

The wind turbine swept area efficiency is crucially important to a flat plate wind turbine. In the case of a wind rotor one can increase the size of the rotor at little cost and get equivalent or better economic efficiency per unit of swept area. Calculations use 40 - 50 percent of the total rotor frontal area to calculate the swept area efficiency. What is considered important is the overall cost and the rated output.

The air rotor can operate at speeds greater than 28 m/s. The unit uses torque loading as opposed to speed loading to transfer energy from the wind hence. It has very good low speed characteristics and broad speed latitude. The maximum wind speed is dictated by the structural integrity, and not by the tip rotation speed, therefore, the larger the air rotor, the higher the wind speed capability.

Over speed controls are built into the design of the air rotor. On the larger units, excessive speed is controlled by moderating the tether height.

A deflate system that is common on all blimps is an emergency system that would only be used if for some reason the rotor broke free or other extreme emergency.

The generators support the axle ends, but are off axis and slightly below the axle. They act as tether anchor points. In all cases the rotation speed is stepped up by a simple gear arrangement.

MATERIALS

The wind rotor is constructed with composite fabrics used in airships. The fabric will be either woven Dacron or Vectran with an inner laminated coating of Mylar to reduce porosity and an exterior coating of Tedlar which will provide ultra violet radiation protection, scuff resistance and color. Dacron is used for boat sails, Mylar in silver toy helium balloons, and Tedlar is the plastic coating found in all weather house siding.

HEIGHT RESTRICTIONS

The air rotor units may not operate in controlled airspace or within five miles of the boundary of an airport.

Units that are deployed over 150 feet on a permanent basis will require a Notice To Airmen (Notam). A Notam is issued by the FAA or its equivalent to inform pilots of new or changed aeronautical facilities, services, procedures, or hazards, temporary or permanent. Notams are not difficult to obtain, but will be necessary in most deployment cases in the USA, Canada and Europe.

The units that operate over 150 feet will have a lighting system including individual lights that are placed every 50 feet on its tether. The lights will flash once per second.

The deployed units will have a Rapid Deflation Device installed that will automatically and rapidly deflate the balloon if it escapes from its moorings. The device will be equipped with at least two deflate systems that will bring the units slowly and safely to the ground. If a unit cut down system does not function properly, it will immediately notify the nearest ATC facility of the location and time of the escape and the estimated flight path of the balloon.

The unit's balloon envelope is equipped with a radar reflective material that will present an echo to surface radar operating in the 200 - 2,700 MHz frequency range.

The USA military uses inflated He filled aerostats that are 400 ft in length and are tethered at up to 15,000 ft in altitude. These aerostats are illuminated, including the tethers, and indicated on all general aviation charts and Notams. The aerostats carry many tons of radar equipment and are powered through the tether which is connected to ground winches which raise and lower the aerostat for servicing. Lightning is not a problem since the aerostats have lightning arrestor equipment.

KITE FLYING GENERATOR

INTRODUCTION

Giant sized kites floating at a height of 1 mile attached to a generator as they fly around in a carousel are proposed as a power plant potentially generating 1,000 MW of rated power.

Fig. 7: Carousel kite generator power producing plant.

The concept was suggested by Massimo Ippolito who envisions such multiple kite generator machines that could produce power at the level of existing power plants.

The energy source for the project is the high altitude wind of the troposphere. The method of channeling this source makes use of arrays of large tethered kites whose movements are controlled electronically by sophisticated sensors and computer control software.

PLANT CONFIGURATION

The kites would be anchored to a revolving structure on a vertical axis, analogous to a gigantic carrousel, which conveys the mechanical energy thus generated to the alternators and turbines of a classical power plant, incorporated within the structure itself.

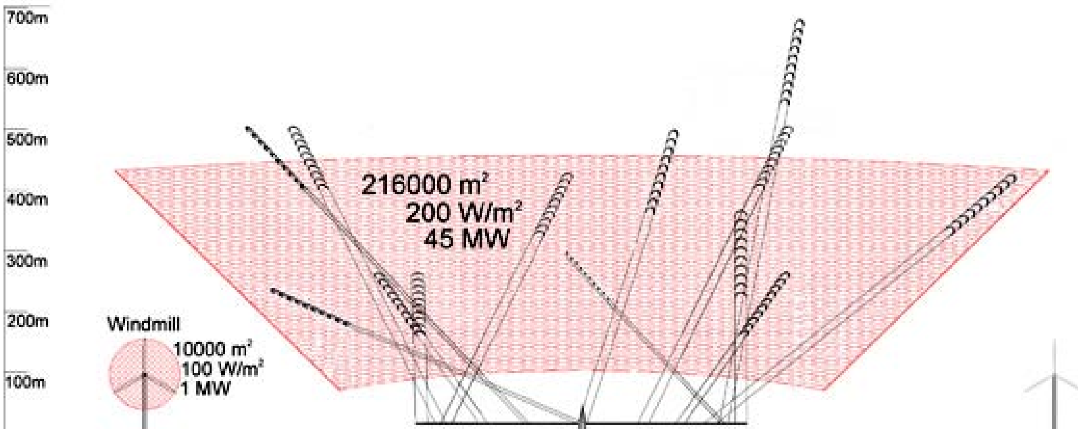

Fig. 8: Carousel power generator driven by tandem kite arrays.

Fig. 9: Three flexifoils and single arc kites.

At the heart of the project are Triaxial Acceleration Computers as the basis for a three dimensional control system for the kites. These would monitor the location of the kites in the sky and provide the information to modify their position, speed, angle and tension, enabling them to engulf the greatest wind force.

Calculations suggest that the production cost of electrical energy would be approximately 18 times lower than that of conventional generation plants.

The power kites are constructed so as to take off in a light breeze. They are giant airfoils whose individual surfaces are several dozen of square meters. They are maneuvered from the ground via a pair of high strength lines that control their direction and their angle with respect to the wind.

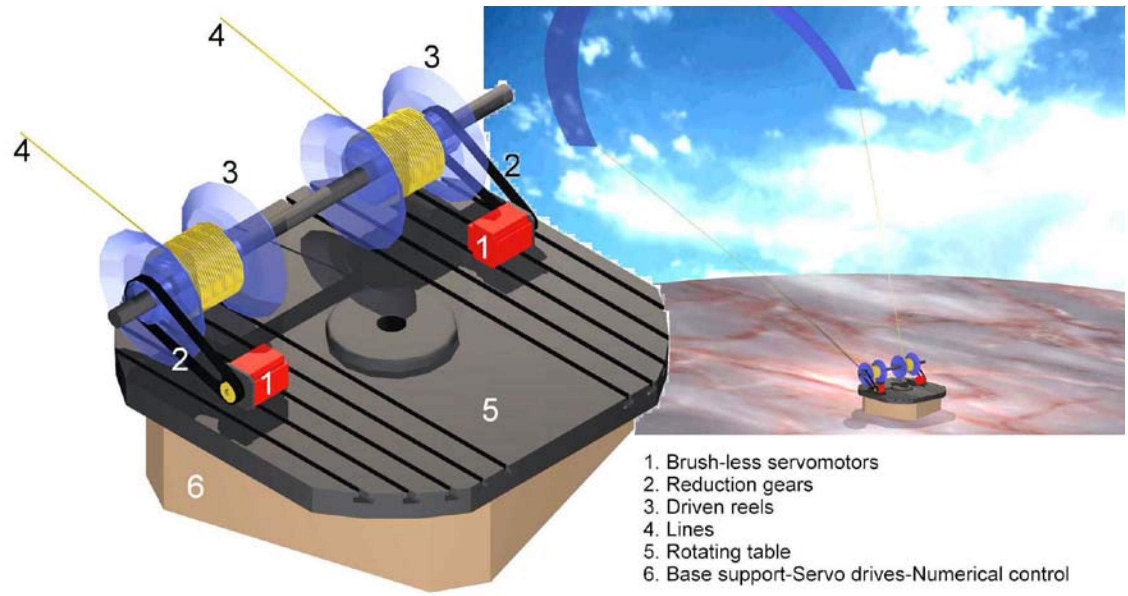

Fig. 10: Power kite control base station.

POWER GENERATION

In the presence of high winds, a single kite is capable of exerting a traction force equivalent to several hundred kilo Newtons, moving at speeds that can exceed 80 m/s. The product of the force multiplied by the speed provides to the order of magnitude of the potential power generated by the kite:

$$P = F.V\,[\text{Newton}.\frac{\text{m}}{\text{sec}}],[\frac{\text{Joule}}{\text{sec}}],[\text{Watt}] \qquad (1)$$

A single kite has the theoretical potential at a speed of 80 m/s and a force of 100,000 Newtons of generating a power of:

$$P \approx 100x10^3.80 \approx 8x10^6[\text{Watt}] = 8[MW]$$

which exceeds the rated power of existing horizontal axis wind turbines at 7 MW.

The kite wind generator can be envisioned as a giant carousel, solidly anchored to the ground. Its nucleus consists of a central structure, tall enough to support the arms by means of a tenso structure. This carousel is put into motion by the wind itself that drags the kites out from their funnels within the arms, and into the sky. The rotating central structure contains the automatic winches that control the pairs of cables of thousands of meters in length which guide the kites.

Cables made of high strength materials such as Dyneema have a tensile strength that is capable of holding 30 tons/cm^2, and these cables weigh just 100 kg/km.

WIND POWER AND KITE POWER FACTOR

The gross available wind power can be expressed as;

$$P = \frac{1}{2}\rho A C_{kite} V^3 \tag{2}$$

The kite power factor depends from the kite to wind speed ratio:

$$\begin{aligned} C_{kite} &= \frac{V_k}{V_w}(C_L - C_D.\frac{V_k}{V_w})\sqrt{1+\left(\frac{V_k}{V_w}\right)^3} \\ &= \frac{V_k}{V_w}C_D(\frac{C_L}{C_D} - \frac{V_k}{V_w})\sqrt{1+\left(\frac{V_k}{V_w}\right)^3} \end{aligned} \tag{3}$$

where:

ρ is the air density [kg/m^3]

A is the projected kite area [m^2]

C_{kite} is the kite power coefficient

V_w is the wind speed [m/s]

V_k is the kite speed [m/s]

C_L is the kite lift coefficient

C_D is the kite drag coefficient

KITE OPERATIONAL MODES

The kite operational modes can cover four different situations:

1. Buoying kite:

This is a steady flying kite whose lines are connected to a fixed ground vinculum. The power factor is zero since $V_k = 0$. Some wind energy is converted into turbulence and if the lift to drag ratio is more than one the kite reaches an equilibrium position close to the azimuth.

2. Dragging kite:

This is a kite dragging the ground vinculum with some force and speed in the wind direction. The power factor is very low; typically the highest power is obtained at the ratio of kite speed to wind speed of 2/3, according to Betz' Law.

3. Lifting and dragging kite:

This is like the dragging kite case, but in addition, the kite's position can oscillate by sweeping arbitrarily the wind front surface. The kite is free to sweep the wind front surface and the projected kite area increases consequently. The power factor reaches a value of more than 10 with a lift to drag ratio of 10 and can achieve a power factor of 60 with a lift to drag ratio of 20.

4. Cruising kite:

This is like in the previous case, but in addition the vinculum follows the kite in different directions, rotating in a ground circular path. This can offer an additional advantage because it is possible to obtain a speed of the dragged vinculum that is intermediate between the kite axial speed and the kite thrust speed, by multiplying by a coefficient corresponding to the high power of the thrusting and dragging situation.

NET POWER PRODUCTION

$$P_e = \frac{1}{2}\rho A C_{kite} V^3 C_{\substack{thrust \\ to\,axial \\ speed}} \eta_{gear\,box}\eta_{generator}\cos\alpha \qquad (4)$$

The net obtainable wind power that can be converted into electrical power is obtained multiplying the kite power by the average of the cosine of the angle α between the direction vector of the ground vinculum and the kite line's vector and all the chain of the efficiency factors $\eta_{generator}$ $\eta_{gear\ box}$

EXAMPLE

An example of obtainable peak power for the cruising kite situation is considered. Let:

The ground wind speed = 9 m/s
The altitude wind speed V_w = 15 m/s
The kite speed V_k = 80 m/s
The mean air density $\rho = 1\ kg/m^3$
The kite area $A = 40\ m^2$
Product of generator efficiency and gearbox efficiency $\eta_{gear\ box}\eta_{generator}$ = 0.70
The mean cos α = 0.45
Lift to drag ratio C_L / C_D= 18
Drag coefficient C_D = 0.06

Thrust to axial speed coefficient $C_{\substack{thrust \\ to\,axial \\ speed}} = 2$

The available power flux would be:

$$P_a / A = \frac{1}{2}\rho V^3 = \frac{1}{2}.1.15^3 = 1687.5[\frac{Watt}{m^2}]$$

The available kite power would be:

$$P_a = \frac{1}{2}\rho A V^3 = 1687.5x40 = 6.75x10^4[Watt]$$

The kite power factor can be estimated as:

$$C_{kite} = \frac{V_k}{V_w} C_D (\frac{C_L}{C_D} - \frac{V_k}{V_w}) \sqrt{1 + \left(\frac{V_k}{V_w}\right)^3}$$

$$= \frac{80}{15} 0.06(18 - \frac{80}{15}) \sqrt{1 + \left(\frac{80}{15}\right)^3}$$
$$= 50.09$$

The kite rated power is:

$$P_{kite} = \frac{1}{2}\rho A C_{kite} V^3$$
$$= 6.75x10^4 x 50.09$$
$$= 3.381x10^6[Watts]$$

The electrical power production would be:

$$P_e = \frac{1}{2}\rho A C_{kite} V^3 C_{\substack{thrust \\ to\,axial \\ speed}} \eta_{gear\,box} \eta_{generator} \cos\alpha$$
$$= 6.75x10^4 x 50.09x2x0.70x0.45$$
$$= 2.13x10^6[Watts]$$
$$= 2.13[MWe]$$

For each relatively small kite it is possible to generate up to 2 MWe of deliverable electrical power. The number, the dimensions and the altitude of kites could grow arbitrarily to construct bigger plants.

HIGH ALTITUDE GENERATORS

DESCRIPTION

The high energy winds are at altitudes miles above us, not just a few hundred feet where they can be tapped by rotors on towers. This was demonstrated in the form of detailed charts calculated by Ken Caldeira, from the Lawrence Livermore National Laboratory (LLNL) and the Carnegie Department of Global Ecology at Stanford University. These charts show at what latitudes and altitudes this energy source can be tapped

Bryan Roberts from Australia set out to demonstrate how Flying Electric Generators (FEGs) technology would work at high altitudes.

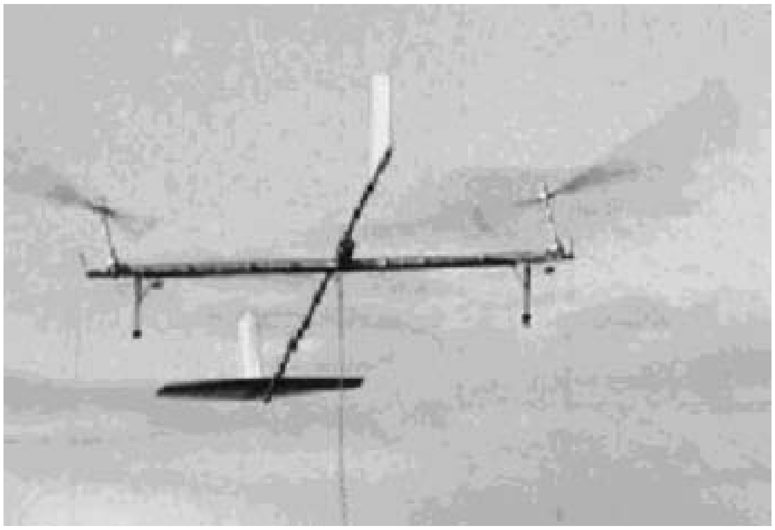

Fig. 11: Tethered rotor craft with two 15 feet in diameter rotors.

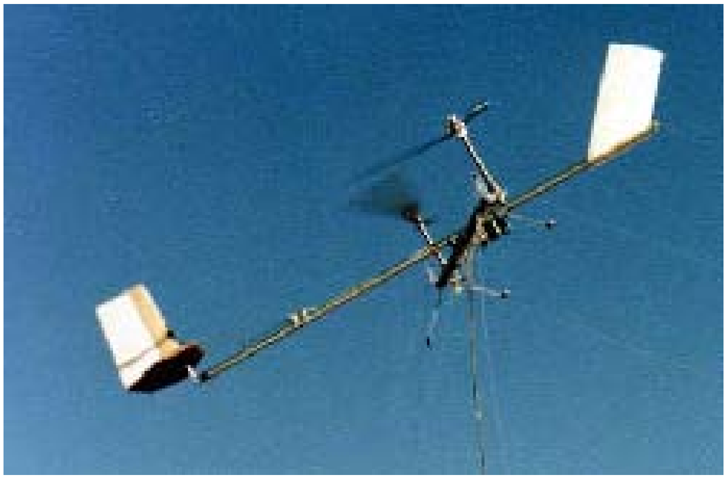

Fig. 12: Flying Electric Generator (FEG) with two contra rotating rotors.

In an experimental device, the rotor craft was kept almost horizontal, with two contra rotating rotors having been powered by electricity from the ground to have the craft reach its operational altitude. The craft is then tilted by command, and the wind on a windy day is turning the rotors, thus both holding up the craft and generating power which is transmitted back to the ground.

The fact that an FEG rotor is rotating does not stop its surfaces from also having a kite like lifting action. Depending on the angle of the rotor plane to the horizontal, there is an energy division between the wind energy going into lift and the wind energy going into generating power. Since this angle can be controlled, it is continuously set automatically to keep the FEG at the desired altitude and generate a rated power if possible, but not more. While lift would appear to be important, in most situations the rotor craft design uses relatively little of the wind's energy to provide the lift to stay aloft compared to that used in generating power.

CHARACTERISTICS

An FEG is free to fly at the best altitude at any time, taking into account both wind velocity and expected turbulence which existing towers do not have the freedom to do.

The use of more than two rotors permits the avoidance of the biggest component maintenance problems of two rotor helicopters, caused by the cyclic pitch effect, in which the blades are forced to change pitch back and forth by swash plates during every rotation.

Avoiding these problems is accomplished by the use of collective pitch , in which the blade pitch remains constant through complete revolutions, using temporary change in the constant pitch of pairs of rotors when direction change to the left, right, up, down, is desired; with the pairs selected depending on the direction of change desired.

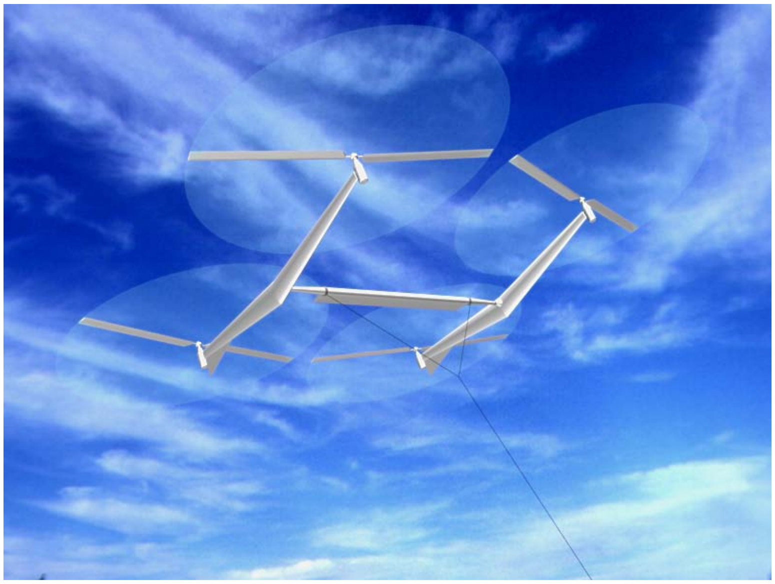

Fig. 13: Conceptual design of a four rotors FEG.

An FEG is a tethered device, and tethers going up to high altitudes pose a problem to aircraft. But, while it is not well advertised, balloons tethered at up to 15,000 feet already exist along the southern border of the USA carrying radar equipment to monitor drug flights and illegal immigrants traffic.

An FEG rated at 240 kW was planned with rotor diameters of 35 feet. The total swept area for a 1.5 MW FEG with rotor diameters of 88 feet is 24,329 square feet, as compared with a ground base wind turbine 1.5 MW turbine such as the GE Model 1.5 sl, with a single rotor diameter of 252.6 feet and total area of 50,115 square feet. The FEG would produce over twice as much electricity per year at typical locations due to the much higher high altitude wind speeds and their constancy.

The fact that the wind velocity is typically 2 to 3 times as large at 30,000 feet, in some cases even at 15,000 feet, as it is at 100 feet above ground means a factor of $2^3 = 8$ to $3^3 = 27$ as great for power production from these high altitude winds, reduced only by the lesser air density factors at those altitudes.

Air density, which is a linear factor, does decrease with altitude. At 15,000 feet it is typically 57 percent of its density at sea level and at 30,000 feet it is typically about 31 percent of its density at sea level.

CAPACITY FACTOR CONSIDERATIONS

In the year 1999 the average capacity factor for the wind turbines in California was 19.2 percent. Since then wind turbine efficiencies have improved, but ground based sites at which capacity factors are as high as 35 percent are difficult to find.

By contrast, capacity factor calculations for FEGs operating at high altitude typically range from 70 percent in the south of the USA up to in some cases over 90 percent at the latitude of Detroit, then starting to taper off going further north.

In addition, at high altitude ground topology has almost no bearing on the capacity factor.

LADDER MILL CONCEPT

DESCRIPTION

The ladder mill concept consists of a series of airfoils or kites connected to a cable that forms a large loop. Like the wings of an airplane the wind generates an upward lift force on the upper surface of the wings. By changing the attitude of the wing or angle of attack with respect to the wind, the lift force be made larger or smaller.

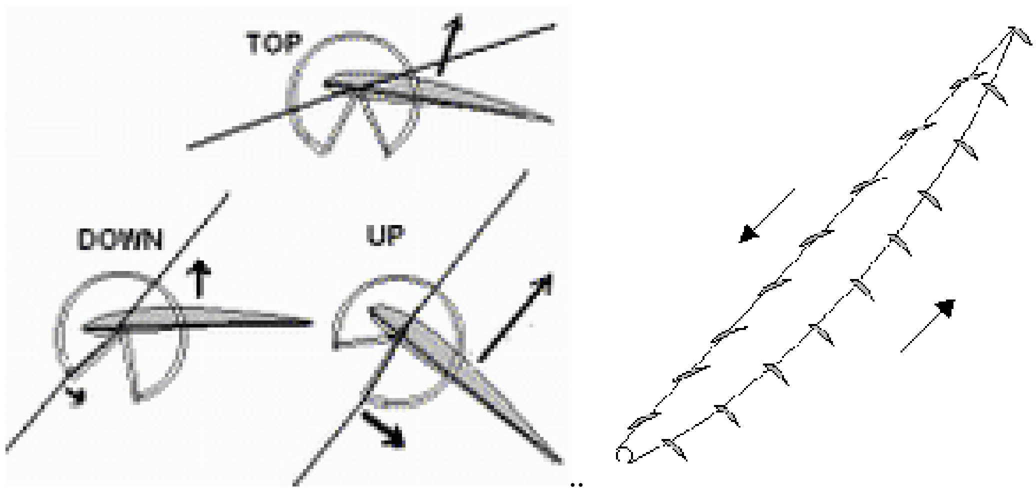

Fig. 14: Ladder mill concept.

The airfoils on one side of the cable loop are all placed such that they produce the maximum lift force, while the wings on the other side of the loop will generate a much smaller lift that in fact is just sufficient to support their own weight and the weight of the cable.

The result is a large difference in force between the two ends at the ground. When the cable loop is guided around a wheel on the ground the force difference will drive the wheel. By connecting the wheel to a generator electricity would be produced.

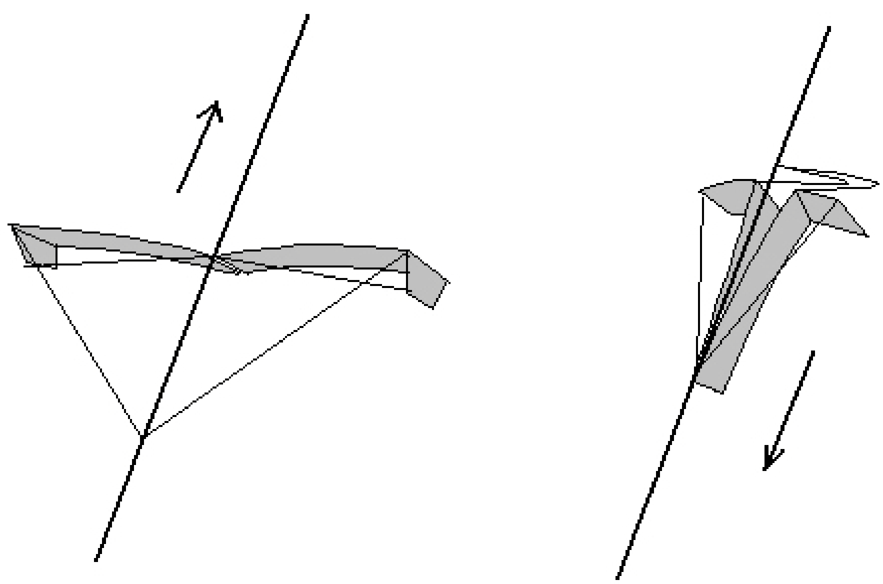

Fig. 15: Foldable kite for the ladder mill concept.

KITE PROPERTIES

It is desirable that the kites have the following properties:

1. The possibility to stack the kites by attaching several kites behind each other to a line.
2. Changing the pulling forces of the kite by changing the angle of attack.
3. A high lift to drag ratio (L/D) for the kite.
4. Stability, it is preferred that the kites stay in the air without active steering.

A row of kites is needed to build a loop. The climbing kites have to generate more lift then the diving ones to make the loop rotate. This can be done by decreasing the angle of attack, or by decreasing the surface of the kite when it reaches the top. Stability becomes important when wanting to avoid active steering.

In the lower layers of the atmosphere up to 100 m the wind velocity is usually not as uniform as on greater heights. Stacking the kites can result in dynamic stability problems. The movement of one kite affects the others. This can result in a growing oscillation of the stack. A high lift to drag ratio L/D is required to be able to fly the kite and reach a reasonable height with as less line as possible.

The kites that have been considered are the Flexifoils, Arcs, and the sled kites. Flexifoils are inflatable wings with one front spar. They can be stacked, have a high L/D, and are rather stable in steady winds. They have to be improved however to change the angle of attack. Another possibility would be to deflate the kite, to make the kite come down.

The Arc kite is an inflatable wing without a spar. It has four lines which makes it possible to change the angle of attack. The Arc is stable in steady winds. The effect of stacking this kite has not been tested, although it is suggested that this is no problem. Even the smallest version of this kite generates forces that require a kind of ground anchor.

Sled kites are stable and can be stacked, however, the low Lift/Drag (L/D) of these kites make it difficult to construct a loop.