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ENERGY TRANSFER FROM AIRBORNE HIGH ALTITUDE WIND TURBINES: PART III. PERFORMANCE EVALUATION OF A SMALL, MASS-PRODUCED, FIXED WING GENERATOR

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ABSTRACT

High altitude, airborne, wind-energy extraction-systems are the only true alternative to carbon and nuclear produced energy. Airborne Wind Turbines are very efficient due to the possibility to search the altitude with the nominal wind velocity. Winds are very stable and fast at altitudes from 4,000m (13,000ft)-11,000m (36,000ft). It is possible have many airborne generators near consumers in restricted airspace regions. In the first two parts, autogiro solutions demonstrated to be fully feasible but not economically convenient. This third part of the paper deals with the design of a mass-produced fixed wing system for power generation. A fixed wing drone with a minimal airframe was conceptually designed for this purpose. The power generated is 220 kW at 13,600ft (4.15 km) as in the first parts of this paper. 13,600ft (4.15 km) is statistically the best altitude for high power availability and reasonable tether length. The drone is a simplified, unmanned ultralight aircraft. Therefore, it has all the advantages of ultralights: the simplified design rules, the vast knowledge and the mass-produced commercial parts and subsystems. Ballistic parachutes are also available for emergency. As in the first two parts of this paper, the airborne system is tethered to transfer the electric energy to the national grid. On ultralight-generator deployment, the reversible electric generator works as a motor and the airborne generator flies as an aircraft. This UAV (Unmanned Aerial vehicle) can take off from a very short grass field due to the low wing loading. The UAVs unfolds and holds the tether up the required altitude. In the climbing phase, the tether powers the aircraft using the national grid electric power. Once the airplane reaches the operating position, as the nose is turned into the wind, the wind provides the lift and the propeller is reversed to windmill. In this way, it is possible to convert the electric motor into a generator. The autopilot keeps the airplane in the desired position. In nominal attitude and altitude (100km/h@4,150m - 54kn@13,600ft), the rotor-generator outputs 0.22 MW. A preliminary design of a mass produced prototype is introduced in this paper with a cost per kWh competitive with fossil generated energy.

Keywords: airborne wind turbine, fixed wing, electric power generation, green energy, high altitude.

INTRODUCTION

On a world scale, the actual and future global energy request represent a very serious problems. Actually, fossil fuels supply more than 80% of the TPED (Total Primary Energy Demand). Even with fracking, a restricted number of countries has a primary oil and natural gas production. At the same time, China, India and other emerging countries, are quickly increasing their production of primary energy. Only for this reason, a projection of the TPED in the next 20 years, foresees an increase by 50% in the next 20 years. In addition, fully electric transportation will require a two orders of magnitude increase in the installed power of national electric grids. Therefore, governments have adopted plans and regulations for the availability of energy sources at acceptable cost. In addition, the limitation of emissions of greenhouse gases has become a primary concern. The main strategies to reach these goals are to increase the power efficiency and to use higher shares of renewables. Hydro is the most convenient renewable source with 2% of the TPED and about 16% of the world electricity production. Unfortunately, most hydropower sites are already being exploited. Solar energy contribution is limited by the low energy density and the very low efficiency of energy production plants. Therefore, wind power is the only renewable energy source for the world's fast growing energy market. Following European EU 20/20/20 renewable energies will supply 20% of the total European primary energy and California wanted to reach 33% by 2020. Many studies based on available data showed that wind power alone would be sufficient to supply the whole future TPED by using AWE (Airborne Wind Energy). Land based wind turbines have limitations in terms of energy production costs, required land occupation, capacity and environmental impact. The capability of harnessing wind energy at high altitude is the only possibility to reach these objectives. Therefore, many countries are investing in the research and development of airborne wind farms and AWT (Airborne Wind Turbines). Ground based and low altitude windmills are already used to generate substantial amounts of electricity. However, winds tend to be stronger and steadier at altitudes much higher than the ones that today's wind turbines can reach. In this way, these winds can be an even larger source of energy. The amount of energy that is available from high-altitude winds is enormous. Therefore, various research and startup companies have demonstrated the possibility to capture energy from these high-altitude winds by using aerial vehicles and devices tethered to the ground. To scale up, these aircraft must be able to compete in the electricity market by producing electricity cheaply and reliably. Several research groups at companies, universities, and government labs have been studying "airborne wind energy" devices. These airplanes, autogiros, kites, wings, parachutes, airships, blimp and balloons, harness the wind energy. In every case, the aircraft-generator is tethered to a ground station that transmits and converts the energy from high-altitudes down to the ground electric network. However, the airborne wind energy is still in its infancy. In fact, it is still necessary to work out the most promising technologies to make them develop from prototype stage to commercial stage. "Inflatable" structures like balloons, blimps and airships proved to be too difficult to control and maintain, while mechanical air-to-ground transmission is too fragile and too flexible to be really usable for power generation. Fixed wings and autogiros with electrical cable systems are the most promising technologies. Offshore-systems may be more convenient than land-based systems due to easier solutions to regulatory. Lawrence Livermore National Lab and the Carnegie Institution of Washington have published estimations that just the jet streams embed 100 times as much power as actual world demand. High-altitude winds are stronger, depend on location and blow more consistently than low-altitude winds. Therefore, airborne wind energy is potentially able to provide enough electricity, in more locations around the world to replace completely fossil fuels. Research follows three different approaches to harness wind energy differentiated by the type of airborne device. The first group is based on wings, fixed in unmanned airplanes and rotating in unmanned autogiros. Another group is based on individual or a series of kites. The third type uses a lighter-than-air technology of airships, balloons and blimps. In addition, the transformation of energy into electricity differs in the various approaches. The simpler method uses on-board wind turbines driving electric generators. The US-Company Makani-Power uses an airplane at altitudes up to 600 meters with several mini-wind turbines Google has invested 15 million USD in the Makani project and also the ARPA-E has put 3 million USD in it. The US-Company Altaeros uses donut-shaped blimps to hold a wind turbine installed the hole. In Makani's and Altaeros's turbine generators, the electric power is transmitted down to the ground by the tether. Another much less practical approach transmits the wind energy mechanically trough the tether to a ground-based generator. The most popular approach of this kind uses yo-yo operating kite. The operating cycle of this device is divided into two phases. In the first one, the kite is pushed higher by the wind pulling out a length of tether, which turns the shaft of an electric generator through a spindle. In the second phase, the kite attitude in changed to eliminate the lift and the kite falls down. In this phase, the tether is winched back. The German-company SkySails Power tested such kite on cargo ship to evaluate the fuel savings. In this way the ships can be pulled partly by wind and save on fuel. The Italian companies KiteGen and KITEnrg are developing similar devices, but land-based. Wind depends on location, for example, NYC, Tokyo, Sydney and Seul are extremely windy cities. Wind intensity increases up to an altitude of 500m above sea level, and then it remains approximately constant from 500m to 2km. Then the winds increases again up to a maximum intensity just below commercial jets normal cruising altitude (8km - 26,000ft). Therefore, two different groups of airborne devices can be developed for altitudes within 500m and from 2km up to 8km. In general, greater heights means more expensive devices, because the aircraft should provide the lift to balance the heavier weight of the tether as it grows longer. Now most systems are designed to fly within 500-600 meters. In the previous two parts of this paper, systems that fly at a compromise altitude of 4,150m proved to be feasible but not economically convenient. The new airborne device introduced in this third part of the paper can operate in both the altitude regions (500-600m and 2,000-8,000m). This flexibility is one of the advantages of this solution. Another problem is the scale of the system. In fact, even enormous airships are small in the sky. Small-scale systems are easiest to test in the near term, and are best suited for location without access to a national grid, such as remote locations and developing countries. If the system is not too small, it is also possible to use it to form large airborne wind farms. Small system are in the range up to 200kW, while large system should exceed 1 MW, the most significant psychological barrier. In this paper, a 220kW system was developed starting from the idea to upgrade and simplify an ultralight, designed to be mass-produced. This choice would simplify tests, certification and serial production. In addition, maintenance and repair are cheaper. In the U.S. and in Europe, for example, the FAA and EASA have strict rules for different classes of aircraft, limiting where they can fly, at what altitudes, and asking for compulsory safety devices, such as flags and lights on the aerial device and its tethering system. In December 2011, the FAA started discussion with interested industries on rules for airborne wind energy systems. Control systems are also crucial: in fact airborne wind energy system should stay aloft for long time with shifts in wind direction and in most weather conditions, even with icing, lightning storms and hail. At the same time, they should control the tether and produce significant electricity most of the time. For this reason, an inherently stable, simple, small airplane is far easier to control that a large, multiple propeller aircraft. Operating costs are the most significant issue found in the two previous parts of this paper. Simplified maintenance, inherently robust design and redundancy are used to reduce costs in this third airborne wind energy system.

FARMS FOR AIRBORNE GENERATION

Wind farms or parks are a group of AWTs in the same restricted area used to produce electricity. Actually, ground based wind farms reach several hundred wind-turbines and cover hundreds of square miles. The Roscoe Wind Farm in Texas has 634 wind turbines with an installed capacity of 781.5 MW on a 400 km^2 area. Onshore ground-based wind farms have a visual impact and need to be built in wild and rural areas, with habitat loss, and drop in tourism. Onshore airborne-based wind farms also need to be built on wild and rural areas, while their visual impact is small. Ground-based wind farms also interfere with radar, radio communication and television. Airborne-based wind farms have a limited impact on communication while radars may be affected by the presence of many AWTs. Beside the higher availability of wind power, another advantage is the arrangement of the AWTs in 3D matrixes. In fact, ground based wind farms have to be installed on the 2D surface topography of terrain. A third dimension can be added for AWT farms: vertical wind farms are possible. Several AWTs can be installed on the same tether to improve power production and to share tether loads. In this case, the AWTs should operate in formation flight. These 3D wind farms should be flexible enough to change altitude to search for the best wind velocity pattern and to deploy and land safely in case of problems. This is an unavoidable technology challenge to harness the huge amount of energy necessary to modern industrialized countries. In fact, no other renewable energy has the potential of AWE to replace completely fossil fuels. In addition, vertical fuel farms may reach very high altitudes 10,000-11,000m where winds are most fast and persistent.

ELECTRIC POWER COMPONENTS: TETHER

Conductor and voltage V are the central elements of the power transmission system. The electric energy transfer to the storage system and to the electric motors/generators, actuators, avionics is a crucial issue. “Electric power distribution” is “state of the art” with voltages up to 24,000V in Formula 1 racing cars. On the contrary, the tether is a new research field in aviation. DC power transmission provides advantages in terms of conductor weight and Electromagnetic Compatibility (EMC). However, AC power transmission is more common and commercial cables are available. Copper and aluminum are today’s most common conductors in electric grids onboard aircraft. With $\sigma=5.96\times10^7$ S/m, copper offers the best conductivity, while its specific conductivity $\sigma/\rho=6{,}881$ Sm^2/kg is far less than aluminum ($\sigma/\rho=12{,}635$ Sm^2/kg). However, due to its better ductility, corrosion resistance and smaller conductor volume, copper cables are more common. However, aluminum cables are gaining importance in today’s aircrafts, where the number of electrical connections is increasing, due to weight reduction. The product of the voltage, the current and the phase difference as given by equation (1) can express the electric power transmitted in a AC conductor.

$$P = VI\cos(\varphi) \tag{1}$$

The required conductor cross section area of a DC cable depends on the current intensity I, being cos(φ) unitary. Resistance losses and the generated heat of the conductor material follow the ohmic resistance and the square of the current intensity as given by equation (2).

$$P = RI^2 \tag{2}$$

The operating temperature is reached when the heat dissipation to the environment equals the loss heat into the conductor. The isolation materials limit this temperature. For circular cross section, the heat dissipation depends on surface, while the heat buildup depends on the inverse of the volume, leading to lower current densities (A/mm²) for larger cross sections. Unfortunately, alternating current is forced away toward its outer surface by the acceleration of an electric charge in the waves of electromagnetic radiation that reduce the propagation of electricity toward the center of high conductivity materials. For this reason, AC resistance is higher than the DC resistance, causing a higher energy loss due to ohmic heating (2). For ground-based power-installation low-to medium-frequencies cables, DIN 0276603 defines nominal current densities for aluminum and copper. These current densities apply for Litz wires that partially mitigate the skin effect. Regression equations (3) and (4) give the resulting maximum current density depending on the conductor area for aluminum and copper.

$$A_{alu} = 0.02098 \times \mathrm{I}^{\,1.46349} \tag{3}$$

$$A_{copper} = 0.0144 \times \mathrm{I}^{\,1.4642} \tag{4}$$

Equations (5) and (6) give the length-specific weight of the conductor material:

$$w_{alu} = 5.6646 \times 10^{-8}\ \mathrm{I}^{\,1.46349} \tag{5}$$

$$w_{copper} = 1.28448 \times 10^{-7}\ \mathrm{I}^{\,1.4642} \tag{6}$$

An isolation material, whose thickness depends almost linearly on the nominal voltage, covers conductors. An outer sheath provides damage protection of the isolation material. In the case of the tether, the sheath may also provide the necessary tensile strength to the cable. High altitude cables for power transmission also suffer of the reduction in heat dissipation. This is due the decrease in air density with altitude. The allowable cable current will be therefore reduced following equation (7) valid up to 11,000m.

$$I_{allowed} = 100 - \frac{2h}{1375}\ [\%] \tag{7}$$

The theoretical advantage of superconducting DC energy transmission is due to the extremely limited ohmic resistance when cooled down below its critical temperature. Unfortunately today’s superconductive materials applications like bismuth strontium calcium copper oxide (BSCCO) and yttrium barium copper oxide (YBCO) need cryogenic cooling to keep temperatures below 90 K.

ELECTRIC POWER COMPONENTS: MOTOR/GENERATOR

Current-generation motors/generators for electric ground vehicles and aircraft up to a few hundred kW

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provide a maximum specific continuous power in the range of 2-6 kW/kg, excluding the cooling system. Motor/generator efficiency in this class depend on the operating point, usually from 70% up to 90% in the design optimum. The critical constraint is usually the thermal management at high power rating. In fact, best today's brushless electric motors/generators achieve a specific power density of 10 kW/kg at peak power that is reduced to 5.5 kw/kg for continuous power. A conventional electric motor/generator cannot be scaled up to the required power of an aircraft gas turbine. In fact, the heat losses of the electric motor/generator goes with the volume (or the third power of a reference size) of the machine, while the heat dissipation depends on the surface (or the square of the same size). For this reason, large motors/generators have significantly larger cooling problems than small ones. For the same reason their efficiency is usually larger than usual hundreds-of-kW ones and hydrogen or cryogenic cooling is used. In any case, in ground based applications this problem is solved by cutting the current density in the windings and decreasing power to mass rating. A possible weight relationship based on the interpolation of existing air and liquid-cooled design is shown in equation (8).

$$Mass = 0.0079\,\mathrm{P}^{1.586} \tag{8}$$

As it can be seen, it is very convenient to use several small motors/generators instead of a single large motor/generator. This is evident in solar airplanes that use several motors operating several propellers. Large motors/generators become convenient if you use cryogenic cooling systems and superconductors. Unfortunately, the mass and power absorption of the cryogenic cooling system increases as the size of the motor is decreased. In an optimized design, propeller, motor/generator and cooling system are optimized together. In fact, they are installed on the airplane with a cooling Meredith effect system for best-combined weight and performance. A good design makes a compromise between operating temperatures and cryogenic cooling system mass. In fact, at lower temperatures, the current density can be increased, with a reduction of motor/generator size and mass. In contrast, the cryogenic cooling system mass and size increase. Even if the Meredith duct converts the heat into thrust, large cooling systems complicate the overall design of the aircraft. Operating temperatures between 50 and 60 K are often the best compromise. Equation (9) shows that large cryogenic motors/generators are convenient.

$$PowerDensity = 4.2388\,\mathrm{P}^{0.277} \tag{9}$$

In general, gearboxes are to be avoided. Unfortunately, this is not always possible. Gearbox loss depends on the applied input power rating. For turboshaft gearboxes, reasonable results follow equation (10).

$$\eta_{gearbox} = 99.5\left(\frac{P_{rating}}{100}\right)^{0.0135} \tag{10}$$

Equation 11 holds for the gearbox mass

$$M_{gearbox} = 34\,\frac{\mathrm{rpm}_{\mathrm{motor}}^{0.13}P}{\mathrm{rpm}_{\mathrm{propeller}}^{0.89}}. \tag{11}$$

The motor/generator controller provides alternating current to the motor in the required frequency and voltage level to obtain the desired shaft speed and torque. When the propeller works as a wind turbine, the system converts the electric energy to the tether voltage and frequency and keep a small battery pack at the required charge level. The controllers are typically build up using solid-state thyristors, MOSFETs, IGBTs and/or switches and filters. DC-AC and DC-DC converters are also used. During operation, extremely low losses occur due to resistance in the semiconducting materials and switching. Typical efficiencies of motor controllers are in the range of 98% with specific power around 10 kW/kg.

FLIGHT CONTROL AND SAFETY

Aircraft generator control should maximize the power output while maintaining the assigned position and minimizing the tether loads. For vertical wind farms, with several airplane-generators linked at the same tether, formation flight should take place. Formation flight of UAV (Unmanned Aerial Vehicle) maximizes the energy generation, improves efficiency in air traffic control and cooperative airspace allocation. The lead aircraft is the highest one. The formation flight begins at take-off and ends when the last airplane has landed. Several vertical farms form the 3D matrix of an airborne wind farm. In this way, it is possible to occupy the reserved airspace efficiently. The control system is relatively easy to implement by relying on GPS receivers with gyroscopes backup. In fact, extensive research have been funded for military UAVs and autopilots are currently installed on most airplanes. In differential mode, D-GPS can achieve 1m accuracy with frequencies of 10Hz. It can also be used for aircraft attitude detection. Emergency systems that control AWT in case of tether accidental damage should be implemented. In addition, a last crash site for the aircraft is usually inputted into the system.

AWT FEASIBLE APPROACHES

AWTs will require huge investments in the next few years to achieve cost-effectiveness and safety levels competitive with fossil fuel power stations. The first two parts of this paper demonstrated that the autogiro solution is not cost-effective. Blimps and airships are not sufficiently reliable and controllable to be used for AWTs. Ground based generators moved by aerial vehicle(s) are not practically feasible. Fixed wing is the only remaining practical approach. Two very different approaches can be used for AWT design: a small, mass produced airplane-generator or a very large one. The very large one should produce quite a large amount of energy and will necessitate of a very accurate design and certification process. A feasible solution will be introduced in the IV part of this paper. The small AWT should be mass-produced in millions per year like cars and when disposed should be completely recycled. An example of this AWT is described in this paper. Mass production is the design and implementation of assembly lines to produce large amounts of standardized products. During WWII, airplanes were mass-produced with high quality standards. The Messerschmitt Bf 109 Fighter is the most-produced ever single-seat aircraft. It was produced in 34,852 items in Germany from 1936–1945. Unfortunately, its quality standards were poor, especially during the latest years of the war. It is also not a good example of assembly line production, since it was produced in sub-assemblies in several different sites. Several final assembly sites took together the various parts and deliver the aircraft. Proper assembly lines were the ones for the Liberator and B17 bombers and the most advanced assembly line of the period was the one of the North American P-51 Mustang. These people are also the inventors of the modern quality system that was successfully introduced by Toyota in automotive assembly lines. Automotive assembly lines produce and enormous number of cars per day in several different configurations. The US Ford-Kansas City Assembly Plant built 321,322 examples of the Ford Escape in 2011 or approximately 1,000 cars per day. This number is high but not exceptional: 927,910 Volkswagen Golfs were produced in 2016 in 6 different production sites. Mass production makes it possible to reduce costs massively with cars that are sold to the costumer for less than 10,000 USD. Likewise, it is possible to mass-produce AWTs. To obtain a quality product you should have a suitable number of subcontractors capable to supply sub-assemblies and parts at a sufficient rate. For this reason, it is necessary to use technologies and part assembly lines that are available today's or in the near future. In practical terms, you should design an AWT with part that can be shared with the automotive industry production chain.

COMPONENTS AND PARTS AVAILABILITY

The design of the mass produced AWTs should take into account of several factors. The parts availability in numbers, the recycling of disposed AWTs and the feasibility and sustainability of the flow production. Flow production is currently available for small leisure airplanes with MTOW (Maximum Take Off Weight) up to 750kg (ANAC National Civil Aviation Agency - Brazil) and engines with power up to 141HP (Rotax 915 IS). Ultralight aviation airplanes, commonly called "ultralight aircraft" or "microlights", account for a very important fraction of the global civilian-owned aircraft. In February 2018, the Canadian ultralight aircraft fleet was the 20.4% of the total civilian aircraft registered. For this reason, subcontractors for parts and components are widely available. The significance of supplier availability for the mass flow manufacturers is that it requires the assemblers to secure an adequate and stable supply of parts and sub-assemblies. In the classical automotive approach, subsidiaries are controlled through stock investments, executive dispatch and in-site quality control. In a more modern approach, the suppliers are recruited suppliers from existing firms, in most cases small, local industries. The suppliers are subdivided into quality groups depending on the amount of controls to be performed on components before final assembly. The latter development has the advantage to require less capital, and it is the fastest way to build up the assembly line. It also has the advantage of the cheap labor cost in smaller firms and of reducing the risks in case of slump in sales. However, the limited control on subcontractors limits the possibility of an effective control on products design and quality control. In any case, the subcontracting system is strictly necessary to reduce investments and to provide a buffer for the manufacturer against business cycles. In 1992, Kia, the Korean automotive company, had 288 subcontractors and 49.7 per cent of its cars was purchased from subcontractors. In the same period Fiat, the Italian Company, had even larger shares with a few model with more than 85% of the car in value build by subcontractors. In the US and in Japan, about 70% of a car's value comes from commercial parts. Therefore, the design of a new product to be mass-produced should start from subcontractors and commercial parts availability. In modern flow-production, Toyota's lean approach is used. It implements the just-in-time pull system in global supply chain to minimize stocks, synchronize and change strategy of production. The cut down in stocks reduce investments and market risks. However, the safety-related recall issue demonstrated that this approach should use as much as tested components as possible. For this reason, it is convenient to maximize the use of parts from the ultralight and the automotive market for the proposed AWT.

ULTRALIGHT VS. AWT WEIGHT BREAKDOWN

The MTOW (Maximum Take Off Weight) of the aircraft is the most difficult issue in preliminary design. In the case, of an ultralight MTOW is given by Law. It depends on the local Laws reaching 750kg in Brazil. In Italy, the MTOW for ultralights is 450+ the mass of the ballistic parachute. Usually, the designer makes the calculations with 500kg. Table-1 shows the weight breakdown of an Italian, mostly aluminum alloy, UltraLight (UL) The aluminum alloy construction is important for several reasons. The most important one is low manufacturing and maintenance costs due to the worldwide diffusion of this technology. A second reason is the corrosion resistance that makes this aircraft last for more than 50 years. The third reason is the high recycling possibility and the ease of disposal.

Table-1. UL mass breakdown.

Item	Mass[kg]	Percent of MTOW
Maximum Take-off Weight (MTOW)	450	100
Crew weight (total)	172	38.22
Baggage	10	2.22
Fuel	28.1	6.24
Engine (installed)	95	21.11
Propeller	5	1.11
Wing	47	10.44
Horizontal tail	12.2	2.71
Vertical tail	12.5	2.77
Fuselage	28	6.22
Landing gear	13	2.88
Fuel system	5.3	1.77
Control system	8.9	1.97
Instruments	3	0.66
Furnishing	10	2.22

Table-2 shows the mass breakdown obtained by replacing all the “human related parts”, the engine, with generator, controller, high voltage transformer, tether, control system and communication suite.

Table-2. UL mass breakdown of the AWT version.

Item	Mass [kg]	Percent of MTOW
Take off Weight (MTOW)	298.6	100
Motors+Controller+ wiring+battery	25	8.4
Propeller (variable pitch)	10	3.4
Wing	47	16
Horizontal tail	12.2	4
Vertical tail	12.5	4
Fuselage	28	10
Landing gear	18	6
Communication suite	7	2.3
Control system	38.9	13
Tether	100	33

The total weight of the AWT is far less than the ultralight; therefore, it is possible to install a larger propeller and generator to increase the output power.

PROPELLER SIZING

The curve of the power coefficient C_p coefficients as a function of the specific speed λ_0 of a 2-blade wind turbine were tested at the Eiffel laboratories. The maximum power coefficient C_p was found to be $\lambda_0=7$ (12)

$$\lambda_0 = \frac{\pi D n}{60 V_1} = 7 \tag{12}$$

With a power coefficient Cp=0.4 (13).

$$C_p = \frac{8P}{\pi \rho D^2 V_1^3} = 0.4 \tag{13}$$

That corresponds to an angular velocity n given by equation (14):

$$n = \frac{135 V_1}{D} \tag{14}$$

A typical problem of AWTs is the diameter D of the propeller. A 220 kW AWT at 4,150m with a nominal wind velocity V_1=100 km/h would therefore need a propeller with D=9m. The ideal propeller calculated with the Betz equation (15) would have a diameter of 7.4m.

$$P = \frac{16}{27} \frac{\rho \pi D^2}{8} V_1^3 \tag{15}$$

The propeller efficiency obtained by the tests in the Eiffel wind tunnel is 0.67. A propeller with a diameter of 9 m (29.5 ft) requires a very large and heavy undercarriage. Two contra-rotating propellers can be used. Theoretically, to have the same disk area the contra-rotating propeller needs a diameter of the square root of 2. Unfortunately, a more realistic number is 1.36 [2]-[18]. Therefore, the diameter D_2 of the contra-rotating propeller will be D_2=6.62 m (21.7 ft) (16).

$$D_2 = \frac{D}{1.36} = 6.62 \tag{16}$$

This huge propeller will not only require a large undercarriage, but it will also add weight to the airplane. Equation (17) makes it possible to evaluate the weight of the new propeller.

$$W_1 = K_w \left[\left(\frac{D_{feet}}{1.0} \right)^2 \left(\frac{B}{4} \right)^{0.7} \left(\frac{AF}{100} \right)^{0.7} \left(\frac{n\ D_{feet}}{20000} \right)^{0.3} \left(\frac{P_{HP}}{10 D_{feet}^2} \right)^2 \right] \tag{17}$$

Equation (17) has been adapted to very low Activity Factor CFRP (Carbon Fiber Reinforced Plastic) untwisted propellers with lightweight hydraulic variable pitch hub. In this case the mass W_1 is about 156 lb (71 kg).

WEIGHT ESTIMATION

The original ultralight wing was designed for very low altitudes (<1,000 ft); the AWT will flight much higher, from 4,000 up to 11,000m (13,000-36,000ft) depending on weather and winds. Therefore, the wing loading has to be reduced. The new wing should be sturdy, easy to maintain and should operate in icing conditions (with de-icing).The NASA-LANGLEY-LS(1)-1-12-17-GA(W) airfoil is an acceptable choice due to the low Reynolds number (<3,000,000). The wing can be calculated with a maximum takeoff weight of 750kg (Brazil ultralight rules). The ballistic parachute (≈50kg) and the Tether weight (≈100kg) should be added, for a total of 900kg. A trapezoidal untwisted wing can be designed according to Naca report TR-572. The Svoboda [1] method can be used for a weight estimation of wing W_9 and empennage W_7 (18) (19). Wing data are summarized in Table-3.

$$W_9 = S_w(0.10625\frac{W_{T0}}{S_w} + 1) \tag{18}$$

$$W_7 = S_w(0.0625\frac{W_{T0}}{S_w} + 0.6) \tag{19}$$

Table-3. Wing data.

Description/Symbol	Value	Unit
Wingspan	54	ft
Wing area	200	ft^2
Mean Aerodynamic Chord	3.7	ft
Aspect Ratio	14.7	-

For the fuselage, the weight from Svoboda's equation can be halved, due to simplified constructions and no internal payload (20).

$$W_8 = \frac{1}{2}S_w(0.8 + 0.0375\frac{W_{T0}}{S_w} + 0.8) \tag{20}$$

Mass of motor generator with controller W_2, landing gear W_{10} and actuators+control W_{11} can be evaluated from equations (21), (22) and (23).

$$W_2 = 0.0079\,\mathrm{P}^{1.586} + \frac{1}{10}P \tag{21}$$

$$W_{10} = 0.026\left(\frac{D_2}{1.8}\right)^{\frac{2}{3}} W_{TO} \tag{22}$$

$$W_{11} = \frac{W_{TO}}{12.85} \tag{23}$$

$$W_{TO} = \sum_{i=1}^{11} W_i \tag{24}$$

It is possible to have the "final" take off mass of the 220kW@4,150m AWT by iterating W_{TO} in equation (24). The convergence result is 890 kg (1,963lb) that is slightly higher than the WTO of a Brazilian ultralight (800kg). Figures 1and 2 show a possible design of this AWT.

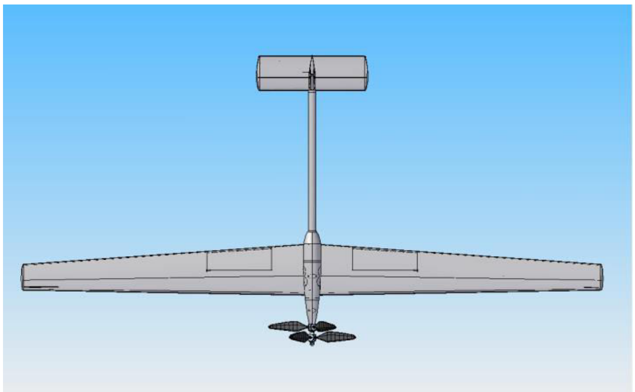

Figure-1. The proposed solution (aerial generator - "ultralight")

AIRBORNE SYSTEM DESIGN CONSIDERATION

The construction of the AWT can be simplified to reduce costs. The fuselage can be designed in very few parts to be manufactured with aluminum alloy and FSW (Friction Stir Welding), GFRP (Glass Fiber Reinforced Plastic) or CFRP (Carbon Fiber Reinforced Plastic), depending on the costs of manufacturing, maintenance and disposal. The aluminum alloy is to be preferred due to the higher recyclability and the environmental friendliness. Figure-2 shows a lateral view of the AWT with the large landing gear that is used also to anchor the tether [2-29].

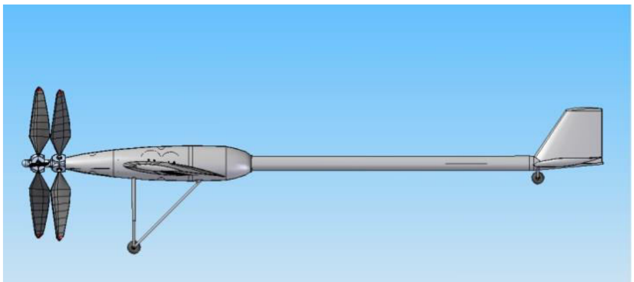

Figure-2. The proposed solution (aerial generator - "ultralight"). Lateral view.

COST ESTIMATION

The mass produced airplane will cost less than 10,000 USD. The life is more than 30,000h (airframe life of a Cessna 172). The costs per hour for airframe maintenance for a Cessna 172 is about 5 US. The pure costs of the single kWh will be 0.037 USD per kWh (25). Operating costs are very low, since the same team can operate several AWTs.

$$Cost_{kWh} = \frac{10,000}{30,000 \times 220} + \frac{5}{220} = 0.037\,USD/kWh \tag{25}$$

Therefore, the solution is competitive with carbon-generated energy.

CONCLUSIONS

This paper showed that airborne airplanes could supply electricity for grid connection by harnessing the powerful and persistent winds at altitudes up to 36,000ft (11 km) by arranging several aircraft connected to the same tether. Two radically different solutions are possible: very large Airborne Wing Turbines (AWT) or smaller, mass produced units. This second way is analyzed in this paper. The main problem is the propeller diameter that is 6.62m (25.7ft) for 220kW@4,150m (13,600m) with a wind of 100km/h (54 knots). This diameter is due to efficiency requirements and the propeller is a contra-rotating one, otherwise the diameter would be 9 m (29.5 ft). It is also necessary to reduce the wing loading for high altitude flight. This paper proposes a very simple aluminum alloy aerial vehicle, with quite a large landing gear that is also connected to the tether. The takeoff weight is in the range of an ultralight (Brazilian Law). This make it possible to find off-the-shelf parts and to reduce costs. The choice of an aluminum alloy structure makes it possible to reduce manufacturing and maintenance costs. Two 110kW motor/generators with controllers and transformers to 36 kV complete the hardware. The 36kV tether is commercial, even if an additional reinforcement will be necessary for tensile load. Mass production makes it possible to reduce unitary costs under 10,000 USD, with a possible life of 30,000h (5 years). In this period, it will produce 6.6 MWh of energy. The unitary cost is therefore due mainly to maintenance and operational costs that are in any case very low. The solution is competitive with carbon generated electric energy. The only shortcoming it the high number of the AWTs that should be used to obtain consistent amounts of energy. On the other hand, the small AWT will enjoy the huge cost reduction of mass production.

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SYMBOLS

Symbol	Description	Unit	Value
P	Motor Generator Power	kW	220
V	Tension	V	-
I	Current intensity	A	-
A_{alu}	Aluminum Alloy cable section	mm^2	-
A_{copper}	Copper cable section	mm^2	-
W_{alu}	Aluminum Alloy cable specific mass	kg/m	-
W_{copper}	Copper cable specific mass	kg/m	-
$I_{allowed}$	Current intesity at altitude	A	-
Mass	Motor generator mass	kg	-
Power Density	Motor generator power density	$kW\ kg^{-1}$	-
$\eta_{gearbox}$	Gearbox efficiency	-	-
P_{rating}	Gearbox nominal power	kW	-
$M_{gearbox}$	Gearbox mass	kg	-
rpm_{motor}	Angular velocity motor generator	rpm	
$rpm_{propeller}$	Angular velocity propeller	rpm	-
λ_0	Specific propeller velocity	-	7
D	Propeller diameter	m	-
V_1	Nominal wind velocity	m/s	27.78
n	Nominal propeller angular velocity	rpm	593
ρ	Air density	$kg\ m^{-3}$	0.806242
C_p	Propeller Power Coefficient	-	0.4
D_2	Contra-rotating propeller diameter	m	6.62
W_1	Contra-rotating propeller mass	lb	156
K_w	Weight factor	lb	60
D_{feet}	Contra-rotating propeller diameter	feet	21.72
B	Total number of blades of propeller	-	3+3
AF	Propeller activity factor	-	20
P_{HP}	Nominal propeller power	HP	295
W_2	Mass, electric motor generator + control	lb	138
W_3	Mass, transformer	lb	110
W_4	Mass, battery	lb	110
W_5	Mass,tether	lb	220
W_6	Mass, communication kit	lb	37
S_w	Wing area	ft^2	200
W_7	Mass, empennage	lb	242
W_8	Mass, fuselage	lb	197
W_9	Mass, wing	lb	409
W_{10}	Mass,landing gear	lb	121
W_{11}	Mass, actuators	lb	152
W_{TO}	Mass, maximum take off	lb	1,963