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Cost and Security of Electricity Generated by High Altitude Winds

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Key Points

- In Australia and elsewhere, the winds at altitude are about eighty times more powerful and three times more persistent than the winds available to ground-based wind turbines.
- Harvesting this energy aloft gives the lowest cost of electricity in Australia and it addresses people's concerns about the ever-increasing price of electricity. The power availability can be considered as 'base-load' due to the persistence of these winds.
- Electricity generation by this method needs to be advanced through the construction and demonstration of an automated, tethered, generating rotorcraft. The relevant research and development has been completed, and commercialisation awaits.
- A derivative form of rotorcraft can be used for surveillance duties, both for military and civilian use.

Summary

This paper describes a new form of automated, tethered, quad-rotor craft, which can operate gyroplane-style, while simultaneously generating electricity. They can operate in the powerful, persistent and reliable winds over most of Australia at an altitude of 4 km. They are highly controllable and capable of being flown in arrays for the large-scale supply of power. The power produced has a base-load capability. A levelised cost of energy (LCOE) comparison with conventional systems, gives a LCOE of $24/MWh, post July 2012.

A derivative version of the technology can be used for military or civilian surveillance at any altitude; either ‘riding on the wind’, or operating as an elementary helicopter.

Analysis

The High Altitude Wind Resource

It is well known that extremely powerful and persistent winds, called jet streams, exist at altitude in both hemispheres. Over Australia, these winds are amongst the best in the world, if not the very best based on their strength, persistence and reliability. The winds occur in bands approximately 1,000 km wide; other bands, for example, run over the Mediterranean, Northern India, China, Southern Japan, North and South America and Africa. Furthermore, compared to the winds available to ground-based turbines, these streams offer annual energy outputs about two orders of magnitude greater than can be achieved by ground-based windmills of the same rotor area.

Extensive studies of wind probability statistics for Australia[1], using Bureau of Meteorology radiosonde data, gave annual average power densities of up to 19 kW/m2 in the 1,000 km band, along an axis extending from Perth to Brisbane. Figure 1 shows the isopleths of power density over Australia at a pressure altitude of 250 mb. The power distribution is spatially well organised because of the lack of high mountains, which tend to upset the orderly flow of air over a continent. These winds are about 80 times more powerful and about three times more persistent, than the winds generally available to ground-based wind turbines.

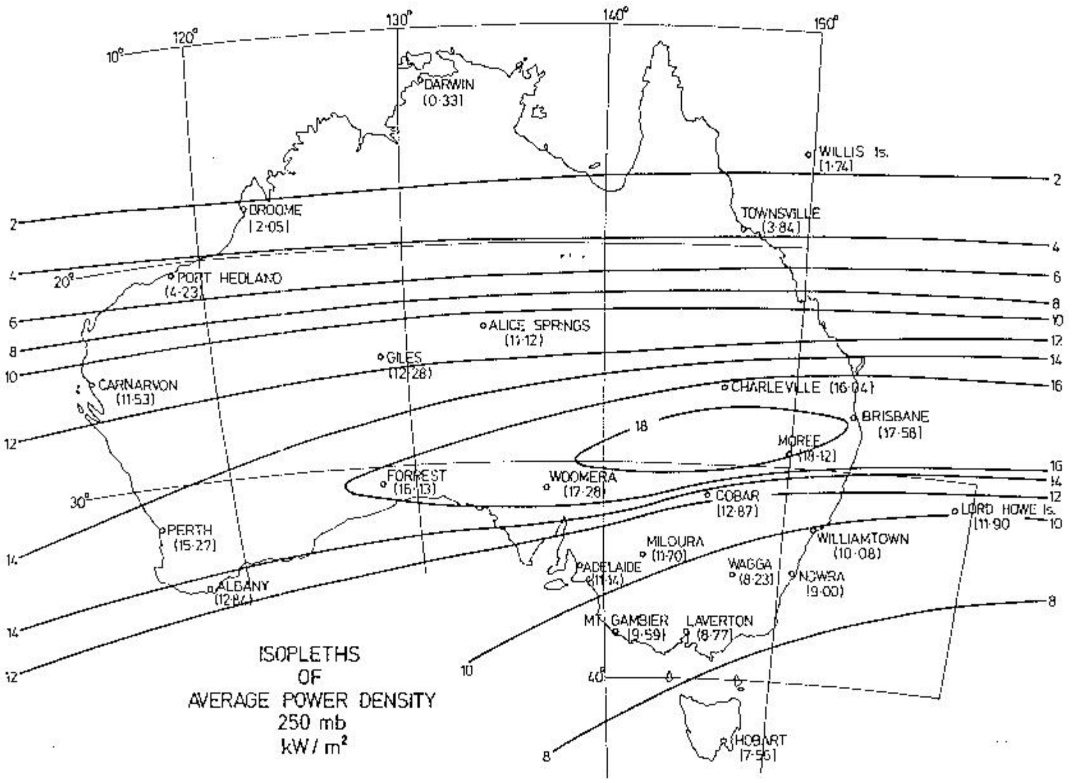

Figure 1: ***Isopleths of Power Density over Australia***

[1] Atkinson, J.D. et al, “The Use of Australian Upper Wind Data in the Design of an Electrical Generating Platform” Chas. Kolling Res. Lab. TN D-17 University of Sydney June 1979, pp. 1-19.

These average power densities are the highest found anywhere on Earth for any large scale renewable resource and vastly exceed those for solar radiation. The latter's power density is generally around 0.25 kW/m2 at the surface, depending on latitude. The power of the jet stream also exceeds the power of near-surface winds, ocean currents, tidal and geothermal resources. This wind resource occurs just 4km above ground level and because of its vast power and persistence, potentially offers a very attractive and inexhaustible power supply. It also raises the prospect of other important civil and military applications. These will be discussed below.

Early Development of a Twin-Rotor, Airborne Generator

Various systems have been examined to capture the kinetic energy of the high-altitude winds. These studies have covered tethered balloons, tethered fixed winged craft, tethered kites in simple or cross-wind flight, climbing and descending devices, and rotorcraft. The general object of the work was to develop a pollution-free, renewable energy system, for the generation of grid electricity.

Our preferred option, for a variety of reasons, is a tethered rotorcraft; a variant of the gyroplane principle. Here, conventional twin or quad-rotors, operating at significant incidences, generate power from the on-coming wind, windmill-style, while simultaneously producing sufficient lift to keep the entire system aloft, gyroplane-style. An electro-mechanical tether is used to secure the craft to a ground point, while electrical energy is conducted at high voltage down the tether to the ground station. These generating craft would be located in restricted airspace, anywhere in the 1,000km band, preferably close to already existing transmission lines, to save transmission infrastructure costs. They would also avoid the current community protests about the location of ground-based windmills.

The twin-rotor electrical generating rotorcraft (EGR) concept was extensively investigated by the author, academic colleagues and his students, both postgraduate and undergraduate, at the University of Sydney over many years prior to 1994. One student was awarded a Sydney University Graduation prize for his study of the cost benefits of EGRs placed at Australia's Davis Base in Antarctica.[2] Subsequent work was continued at the University of Western Sydney. All of this early work was funded through grants from the Australian Government's Dept. of Resources and Energy, the NSW Energy Authority, the Solar Energy Research Institute in the USA and Transfield Ltd. Wind tunnel models were constructed and tested, along with a number of atmospheric prototype vehicles.

A twin-rotor craft, known as Gyromill Mk2, generated power successfully during low-level flight at the University of Sydney's Mt. Pleasant farm near Marulan, in the windy southern highlands of NSW. This craft had twin 3.66 m rotors, an all-up weight of 29.0 kg and incorporated a tail empennage for pitch control and stability. It was controlled manually, while being flown on multiple tethers. A full description of the craft's design and its preliminary performance can be found in an Australian Government National Research Development and Demonstration Council report.[3]

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[2] Slee, R. "Cost Benefit Analysis of a Tethered Gyromill Wind Energy System for Davis Base on the Antarctic Continent", BE Thesis, Dept. of Mech. Engg., Univ.of Sydney, 1986, pp. 1-68.
[3] Roberts, B. W. "Design and Preliminary Performance of the Gyromill Mk2". National Energy Research, Development and Demonstration Council, Australia, End of Grant Rep. 380, Oct. 1984, pp. 1-109.

The craft was operated successfully, without any component failure, for a total of about 50 hours. It is shown in low-level flight in Figure 2. The twin rotors are synchronised and phased in their rotation by a linking cross-shaft, mounted in bearings attached to the main boom. The cross-shaft assembly is in turn coupled, via a centrally located gearbox, to a central generator/motor unit. This electrical unit rotates at about 25,000 rpm, to give a highly favourable power to weight ratio for the overall assembly. The weight saving, cross-shaft principle is a particular feature and the shafting can be identified in an enlarged version of Figure 2.

Figure 2: Gyromill Mk2 during low-level flight at the University of Sydney's Mt. Pleasant farm

Another feature is the contra-rotation of the twin rotors, through the linking cross-shaft, which means that no conventional tail rotor is necessary.
These craft can also operate as elementary helicopters. In this mode, the electrical generators described above can function as electric motors by the use of suitable switching. With power supplied from the ground it is then possible to have the craft stay aloft during short wind lulls, or land on a small ground base during excessive wind lulls or during extreme storms.

In addition, they can 'ride' on the wind as a basic gyroplane, without power being supplied to, or extracted from, the system. This mode of operation is called autorotation. In other words, the craft can remain airborne in the wind stream without the need for battery power or liquid fuel, as required by a regular helicopter. It therefore raises the prospect of having platforms aloft 'riding on persistent winds' with near-infinite endurance, to perform military or civilian surveillance duties. On-board sensors could be powered by the unit's generators to eliminate the need for conventional batteries. This aspect will be discussed in more detail below.

The next section of this paper describes a very significant improvement to the twin-rotor system described above; which has been achieved over the past few years.

The Recent Evolution of the Quad-Rotorcraft

In 2004, the author proposed a quad-rotor assembly that gives superior flight control and reduced fatigue loads on the rotor assemblies, compared to the twin-rotor assembly described in section 2 above. The latest version of the quad-rotor arrangement is shown in plan view in Figure 3. An engineering review of the quad-rotorcraft system was released in

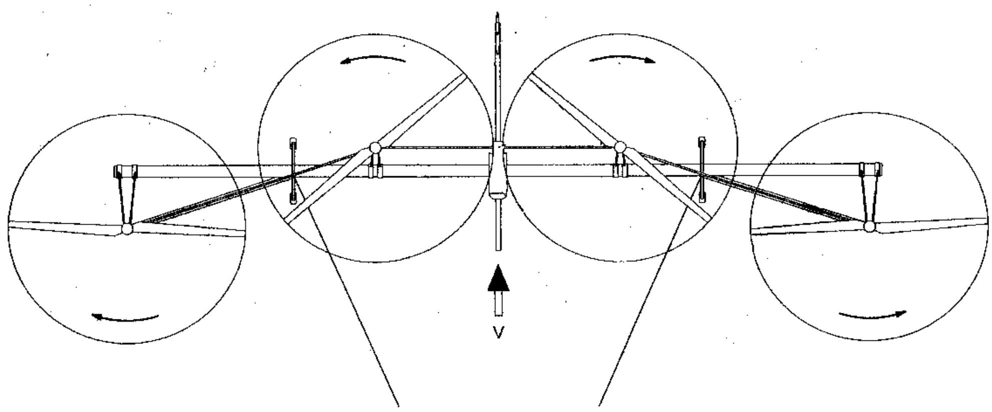

Figure 3: The Latest Version of the Quad-Rotor Arrangement

2011, in a paper presented to the Royal Aeronautical Society's London conference on "Future Rotorcraft".[4]

Simply described, the four rotors are again synchronised, using the cross-shafting previously proven to be entirely satisfactory on the twin-rotor prototype, Gyromill Mk2. In the quad-rotorcraft of Figure 3, the central cross-shaft is identical to that in Figure 2. The significant improvement is in the cross-shafts linking the two outermost rotors in Figure 3. These cross-shafts are supported by bearings mounted on the lateral bracing tubes, which link the outermost rotors to the main fuselage tube. Two auxiliary tethers join below the craft to form one tether thereafter.

In this craft, differential collective pitch action is applied to the blades on each of the four rotors. This action allows rotor thrust variations on each of the rotors, to automatically control the craft's four basic functions, power output, pitch, roll and yaw. Australian owned patents currently in process in Australia and elsewhere cover these developments. An earlier quad-rotor version is currently being developed under licence in the USA.

With this particular control strategy, the craft's attitude and power output can be controlled by the application of collective pitch changes to the rotors; exactly the same as the method used for power control on conventional windmills. No cyclic blade pitch action is necessary. This reduces construction costs and maintenance expenses.

Tethered rotor craft have a further advantage over ground-based wind turbines in their ability to significantly alleviate the effects of wind gusts, which can introduce excessive loads and torques on rotors, shafts and gearboxes. This force reduction is due to the flexibility of the tether cable, which does not exist in rigid tower-mounted, ground-based turbines. The flexibility arises from cable elasticity and changes in cable shape under gust conditions.

Altitude Energy's business plan for Australian commercialisation of the EGR, shown in Figure 3, covers four steps. The initial step involves the detailed design, construction and demonstration of a quad-rotor craft, with rotors of about 2 m in diameter. It would produce about 4 kW of electrical power in a wind of 12.9 m/s or more. The unit will weigh around 20kg and its single electromechanical tether around 25 kg per km of linear length. It is planned to demonstrate this system at an altitude of 0.5 km.

Step 2 of the business plan is to operate with higher voltages at an altitude of about 4 km, after a successful outcome in Step 1. Subsequent steps will increase the scale of the units to

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[4] Roberts, B. W. "Rotorcraft to Capture High Altitude Energy", 'Future Rotorcraft' conf., Royal Aeronautical Society, London, June 15-16, 2011, pp. 1- 13.

give a single unit electrical output of around 20 MW, when flown in the powerful winds at that height. A wind farm with ten of these units would need airspace of about 10 km by 10 km and have a power output roughly equivalent to a modern electrical power station.

Calculations using Australian wind statistics and a suitable weight to rotor area ratio, show that sufficient electricity can be generated for grid connection.
The capacity or availability factor for the system would be in the 70 to 80% range; sufficient to class the quad-rotorcraft as a base-load generator.

Through a variety of approaches, recognition of our upper atmospheric technology has been established within the Australian Government. A review by Australia's Chief Scientist has also been undertaken. The concept has already been demonstrated in university experiments and elsewhere, and the necessary research and development has been carried to the commercialisation stage. Numerous peer-reviewed papers have been published. Time magazine on 10 November 2008, rated the system as one of "The 50 Best Inventions of the Year", while Scientific American magazine rated it as one among twenty "World Changing Ideas" in December 2009.

Cost Item	Coal	Ground Wind	Altitude Wind
Installed power, MW	100	100	100
Unit's installation cost, $/MW	1,800,000	1,560,000	1,590,000
Facility install cost, $ million	180.0	156.5	159.0
Capacity factor, %	90	28	70
Energy output, MWh/annum	789,000	245,450	613,500
Interest rate on borrowing, %	6.0	8.0	10.0
Coal consumed, tonne/annum	320,000	0	0
Cost of coal, $/MWh	12.6	0	0
Cost of borrowing, $/annum	10,800,000	12,520,000	15,900,000
Return of capital, $/annum	9,000,000	7,825,000	7,950,000
Operating to capital cost ratio, %	6.50	2.00	4.63
Total operating costs, $/annum	11,700,000	3,130,000	7,365,000
Operating costs, $/MWh	14.6	12.8	12.0
Depreciation allowance, $/MWh	11.4	31.9	13.0
Basic cost of energy, $/MWh	63.7	127.6	63.8
plus carbon tax, $/MWh	23.0	0	0
less LREC credit (LGC), $/MWh	0	40.0	40.0
Net LCOE, $/MWh	**86.7**	**87.6**	**23.8**

Figure 4: The Potential Financial Superiority of Electricity Generated at High Altitude

Cost of Electricity

The potential financial superiority of electricity generated at high altitude is demonstrated in Figure 4, using the well-known method of levelised cost of energy (LCOE). The computations are applied to three different generating systems, with the results applicable to the eastern states of Australia. South Australian and Western Australian calculations would, we believe, give similar results.

Figure 4 considers three 100 MW electrical power stations powered by three different generating methods: coal, ground-based wind and altitude wind. The installation costs for each have been taken from published figures, from operator's websites or from a paper published by the well-respected Institute of Electrical and Electronic Engineers.[5] In these calculations, money is borrowed at rates appropriate to the type of venture involved. Capital is returned over a period of twenty years, while coal is supplied at a subsidised price of $31/tonne. All facilities are depreciated linearly at a rate of 5%/annum.

The operating costs are reasonable estimates. These include cost of wages, insurance, maintenance, repair/overhaul and land rental. The operating cost to capital cost ratio used in each of the three cases, reflects the complexity of high temperature/high pressure coal-fired stations, the relative simplicity of ground-based wind systems and the additional complexity of airborne wind systems compared to ground-based wind systems. Estimates indicate that the airborne wind system's operating costs would be about two and a half times greater than those for ground-based wind turbines.

The table does not include LCOE calculations for solar and other more expensive renewable systems. It can be clearly seen that the increased cost of generating coal-fired electricity is due to the recent introduction of a carbon tax at the equivalent of $23/MWh. In addition, the inclusion of credits for Large Renewable Energy Certificates (LREC), or Large Generation Certificates (LGC), enhances the renewable energy position.

There is a tendency to dismiss this table on the grounds that the LCOE for altitude wind is unrealistically low. The net LCOE of $23.8/MWh for altitude wind is primarily due to the large capacity or availability factor of 70% (see row 4 of the table). This 70% factor, compared to 28% for ground-level wind, means that the altitude wind system produces two and a half times more energy per annum. In other words, the airborne system is more expensive to install and operate, but it gives an outstanding increase in energy output per annum; this produces the superior cost per MWh quoted in the table. Fundamentally, this is due to the greater persistence of the winds at altitude. The capacity factors involved in Figure 4 dominate the LCOE calculations.

It is also useful to note that because of their greater relative size and the nature of ground-based wind turbines, the weight of construction materials for them is more than twelve times greater than for the altitude wind system. This advantage arises due to the vastly higher average wind power density at altitude. This is confirmed by Figure 1.

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5 Roberts, B. W., Sheppard, D. H., Caldeira, K., Cannon, M. E., Eccles, D.G. et al "Harnessing High Altitude Wind Power", Special Issue on Wind Power - Trans. of Energy Conversion, Vol. 22, No.1, Institute of Electrical and Electronic Engineers, March 2007, pp. 136-144.

The Australian population is increasingly concerned about the apparently never-ending increases in their electricity bills. Consequently, it is important to note that altitude wind energy systems, when commercialised, will help address this pressing political issue.

Other Applications – Military and Civil

Section 1 above, referred to a range of additional uses for tethered rotorcraft. They offer the prospect of having platforms 'riding on persistent winds' to give near-infinite endurance, for military and civilian surveillance or for power generation.

A proposal to the Department of Border Protection and Customs, suggested that a quad-rotor platform, with rotors around 2 m diameter could be launched, towed and retrieved by our Armidale class patrol boats or similar Navy ships, to detect illegal boat arrivals or other incidents. The platforms, if towed at an altitude of 3,000 feet, would give a direct line-of-sight for good return signals from radar or other sensors, to a range of 115 km. When the vessel is underway the platform would be self-elevating, as well as generating on-board power for the sensors. If the vessel is stationary, the platform could operate in its helicopter mode using power provided by the vessel. Subsequent correspondence discussed the use of land-tethered platforms at Christmas Island, to enhance the island's radar facility and avoid any further boat accidents. Radar short-comings have been found to be important in the recent accident at the island.

In summary, 'border security with quad-rotorcraft' can be applied to the protection of vessels, landmass, troop emplacements, crops, oil rigs and many other facilities.

Proposals were also made to Defence in the context of unmanned platforms at various altitudes, for surveillance, security and detection of the planting of improvised unexploded devices (IUD) in combat zones. In military operations, airborne electrical generators could be useful in alleviating the demands for liquid-fuel and the difficulties of fuel transport and storage. Similarly, expensive wax-free diesel fuel could be conserved in Antarctica using EGRs. These units could be tethered in the clear air above the snow-drifts, at an altitude of 1 km. This would avoid rotor blade erosion by ice particles, which often occurs on ground-based windmills in Antarctica.

In northern Australia, mobile surveillance platforms could very easily be placed and then relocated as necessary, in the event of a security threat along our northern coastline. The system could also be useful for low- and high-level bushfire surveillance and command, particularly in gorges and similar terrain.

In civil applications, long-endurance surveillance platforms could be placed adjacent to expensive, off-shore oil rigs, for protection against terrorist or other intrusions.The ease of transporting these quad-rotor units could also be very useful, when communities are relocated or when new population centres are rapidly established, as for example during the current Australian mining boom. The same situation could apply in a national emergency or during a terrorist threat, when electricity generating facilities may need to be built or moved to new and/or more secure locations. A whole range of further applications can be envisaged.

Conclusion

Altitude Energy Pty. Ltd. is an Australian-owned company with extensive experience in the design, construction and use of airborne wind-driven electric generators and similar devices. With the recent establishment of the Australian Renewable Energy Agency (ARENA) by the Australian Government, Altitude Energy intends to apply for funding when the call for proposals is announced.

The company believes that the electrical generating technology described here is well founded, achievable and important to Australia's future.

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About the Author:

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