Altitude Energy

Reach For The Sky

SUBMISSION

on

MODERNISING AUSTRALIA'S ELECTRICITY GRID

from

ALTITUDE ENERGY PTY. LTD.

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# EXECUTIVE SUMMARY:

Altitude Energy’s objective in this submission is to show how harnessing the energy of the very powerful and persistent winds above Australia can dramatically improve the reliability and security of Australia’s electricity grid, while simultaneously reducing consumer costs and reducing greenhouse gas emissions.

The introduction to the submission describes the nature of the winds aloft and details how twin-rotor or quad-rotorcraft can be tethered at altitude to generate electricity, windmill-style, while simultaneously developing sufficient lift to maintain flight, gyroplane-style. The quad-rotor version is almost identical in form to the now-common, four-rotor ‘drone’ craft. University experiments, with an actual craft flying at low altitude, verifies beyond doubt that the technology is valid. Photographs are included and patents are held in Australia and the USA.

The submission highlights how the electricity grid can be supplied at capacity factors (CF) in the 70 to 80% range, because of the wind’s persistence at altitude. A theoretical justification of the aeronautical and electrical engineering in the above CF range is available upon request. These capacity factors are spectacular when compared to recently published capacity factors of 17.6% for solar PV systems and 33.6% for ground-based wind turbines. The latter two figures were derived using Australian 2015 Clean Energy Council data.

Three different scenarios are then examined in fine detail. Firstly grid-connected, solar PV units, supported by open cycle, rapid-response gas turbines driving generators, are examined. The supporting gas turbines are used to overcome the intermittency of the solar component. Generation by ground-based wind turbines is similarly treated, while generation by the third system uses grid-connected, quad-rotorcraft tethered in the persistent winds aloft. Storage support systems from pumped-hydro and/or batteries have been considered, but these are believed to be more expensive than gas turbine support. Therefore, it is important to realise that the subsequent analysis has been here examined using gas turbine support, but pumped-hydro or battery storage could be used and examined to produce the same result, namely the highly favourable outcome from electricity generated at altitude .

Power-Duration Curves (PDC) are shown in Figures 4, 5 and 6 for the three cases, each based on the Australian 2015 data for relevance. Capacity factors, system costs and greenhouse gas savings are all derived to indicate how Australia’s grid can be made more secure, reliable and cost effective. These 2015 figures are then linearly extrapolated assuming that each of the three above systems is used alone to generate 50% of the nation’s electrical energy (about 120 TWh/annum) at some time in the future.

The submission demonstrates the supreme position of Capacity Factor (CF) in determining answers to grid security, reliability and energy costs. For example, a CF of 80% for altitude energy generation compared to CFs of 17.6% and 33.6% for solar and ground-based wind turbines means that for equal installed power levels, at more or less identical installation costs of around $2,000/kW, the renewable energy produced per annum will be 4.5 and 2.4 times greater respectively for the system at altitude. This gives more saleable energy arising from similar capital cost expenditure on each.

This leads directly to lower and highly favourable LCOE electricity costs for the community. In addition, it is shown below that high capacity factor generation brings superior greenhouse gas savings and improved security through the need for much lower supporting generation from gas turbines, pumped-hydro or batteries.

The conclusion summarises the findings for each of the three cases. It shows beyond doubt that the altitude generating system, with its paramount capacity factor, is the way to the future giving superiority in reliability, cost with greenhouse gas savings. Altitude Energy has designs and a procedure ready to demonstrate the quad-rotorcraft capabilities. This technology needs to be urgently advanced through an appropriate Commonwealth agency to demonstrate that altitude generation produces a solution to current grid issues.

## 1. INTRODUCTION:

Altitude Energy Pty. Ltd. is an Australian owned company that promotes the use of quad-rotorcraft, or put more simply “generating drones”, tethered at known locations to generate electricity. These craft could harvest the energy of the extremely powerful and persistent winds above Australia. It will be shown that in Australia and elsewhere the wind’s annual average power density increases with altitude to a maximum of about 20kW/m2 at 10 km, with a corresponding increase in the wind’s persistence. Due to this persistence the electricity generated at altitude is potentially about three times greater than that obtained from a ground-based wind turbine of the same power rating. In addition, it has been shown in an Australian paper on electricity cost and security (1) that the resulting LCOE cost of electricity generation at altitude is equal to that of coal, prior to the application of any LREC credits. A similar result is given in a USA publication (9) for tethered quad-rotorcraft generating electricity at altitude. This resource aloft, described below in more detail, can be used in the future to significantly increase the security and reliability of Australia’s electricity network, because of the wind’s unmatched power and persistence.

### 1.1 High altitude wind resource:

It is well known that extremely powerful and persistent winds, called jet streams, exist at altitude in both Earth hemispheres. Over Australia these winds are amongst the best in the world, if not the very best. They also exist in bands running over the Mediterranean, Northern India, China, Southern Japan, North and South America, Africa and elsewhere. Extensive studies of wind probability statistics for Australia, using Bureau of Meteorology radiosonde data, gave annual average power densities of up to 19kW/m2 in a 1000 km band along an axis extending from Perth to Brisbane. Figure 1 shows the isopleths of power density over Australia at an altitude of 250mb.The power distribution therein is spatially well organized because of the lack of high mountains which tend to upset the orderly flow of air over a continent. These winds are about **eighty times more powerful and about three times more persistent** than the winds generally available to ground-based wind turbines. For example, the persistence of the winds at the abovementioned altitude have been measured at or above 10 m/s for 95% of the year, while for ground-based turbines the 10 m/s percentage is comparatively of much lower persistence, namely at or above 10 m/s for only about 30% of the year. This trend is quite striking and reported by Welch (2) for the Moree area in NSW.

Similar persistence trends can be found in (2) for all values of wind speed, for example speeds of 5, 15, 20….m/s.

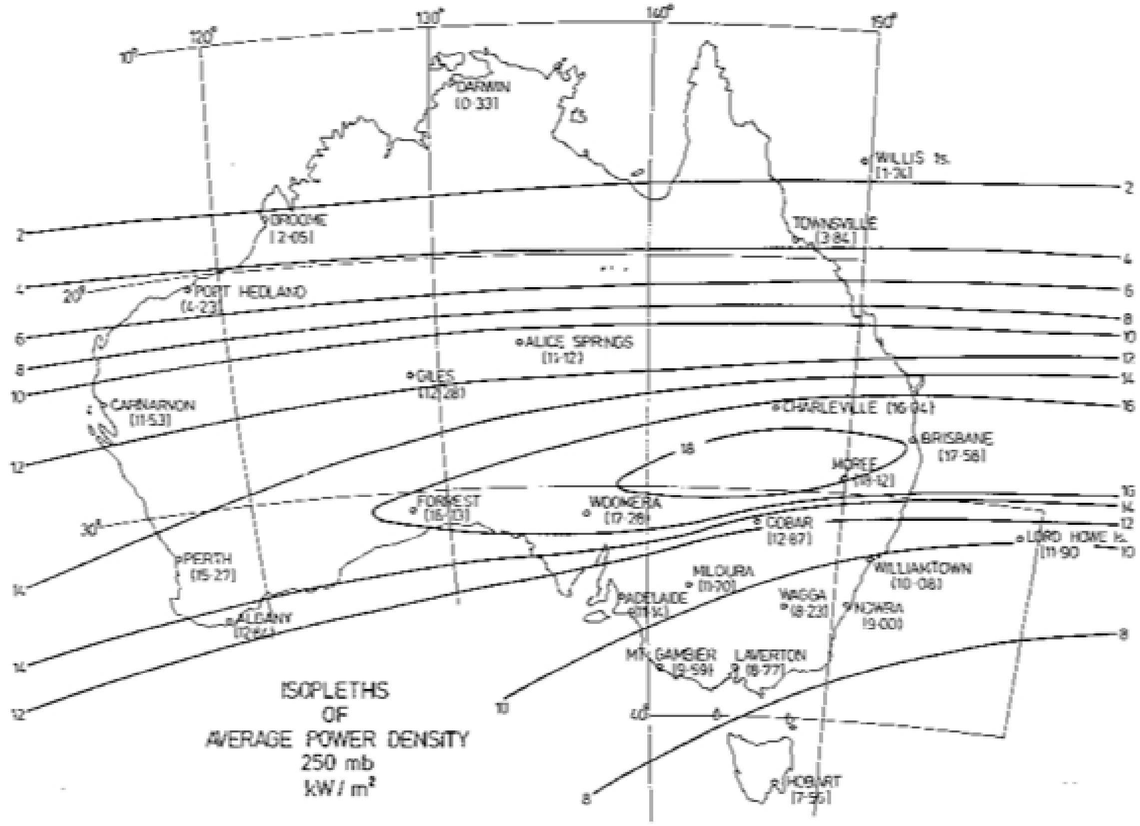


*Figure 1*

These average power densities are the highest found anywhere on Earth from any large scale renewable resource. They vastly exceed it from solar radiation. The latter's power density is generally only around 0.25 kW/m2 at the surface, depending on latitude. It also exceeds the power of near surface winds, ocean currents, tidal and the geothermal resources. This wind resource begins just 4km above ground level, where the energy is needed. Because of its vast power and persistence it would, if captured, be a very attractive and inexhaustible power supply.

### 1.2 Development of a twin-rotor airborne generator:

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

The best option, for a variety of reasons, is a tethered rotorcraft, a variant of the gyroplane principle. Here, conventional rotors operating at significant incidences generate power in the on-coming wind, windmill-style, while **simultaneously** producing sufficient lift to keep the entire system aloft, gyroplane-style. A single electromechanical tether is used to secure the craft to a ground point, while electrical energy is conducted at high voltage down the tether into the grid. These generating craft would be located in restricted airspace, anywhere in the above mentioned 1000km band, close to already existing transmission lines to save transmission infrastructure costs. They would also avoid on-going community protests about the location and noise emissions from ground-based windmills.

The electrical generating twin-rotor craft concept was extensively investigated by academic staff and 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 this rotorcraft generating system when placed at Australia's Davis Base in Antarctica [3]. 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 in May 1986 at the University of Sydney's Mt. Pleasant farm near Marulan in the windy southern highlands of NSW. This craft had twin 3.66m diameter rotors, an all-up weight of 29.0 kg and incorporated a tail empennage for pitch control and stability. A full description of this craft's design and its preliminary performance can be found in an Australian Government NERDDC report [4]. This 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 below. Therein it should be noted that the twin rotors are synchronized 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 rotated 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 feature of the concept and it can be identified in Figure 2, and also in Figure 3 below.

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

In addition, these units 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, these craft can remain airborne in the winds aloft for extended periods without the need for battery power, or liquid fuel as in a regular helicopter. It therefore raises the prospect of having platforms aloft 'riding on persistent winds' giving a near-infinite endurance to perform military or civilian surveillance duties. A typical example is their use as elevated mobile phone/internet towers located at altitudes of about 6km. Each of these would cover a direct line-of-sight area of 560km in diameter and would be an alternative to numerous short-range 'black spot', ground based towers. They would be particularly suitable for use in regional and remote regions of Australia, subject to CASA approval.

The next section of this introduction describes a very significant improvement to the electrical generating concept described above. This advance has been made over the past few years.

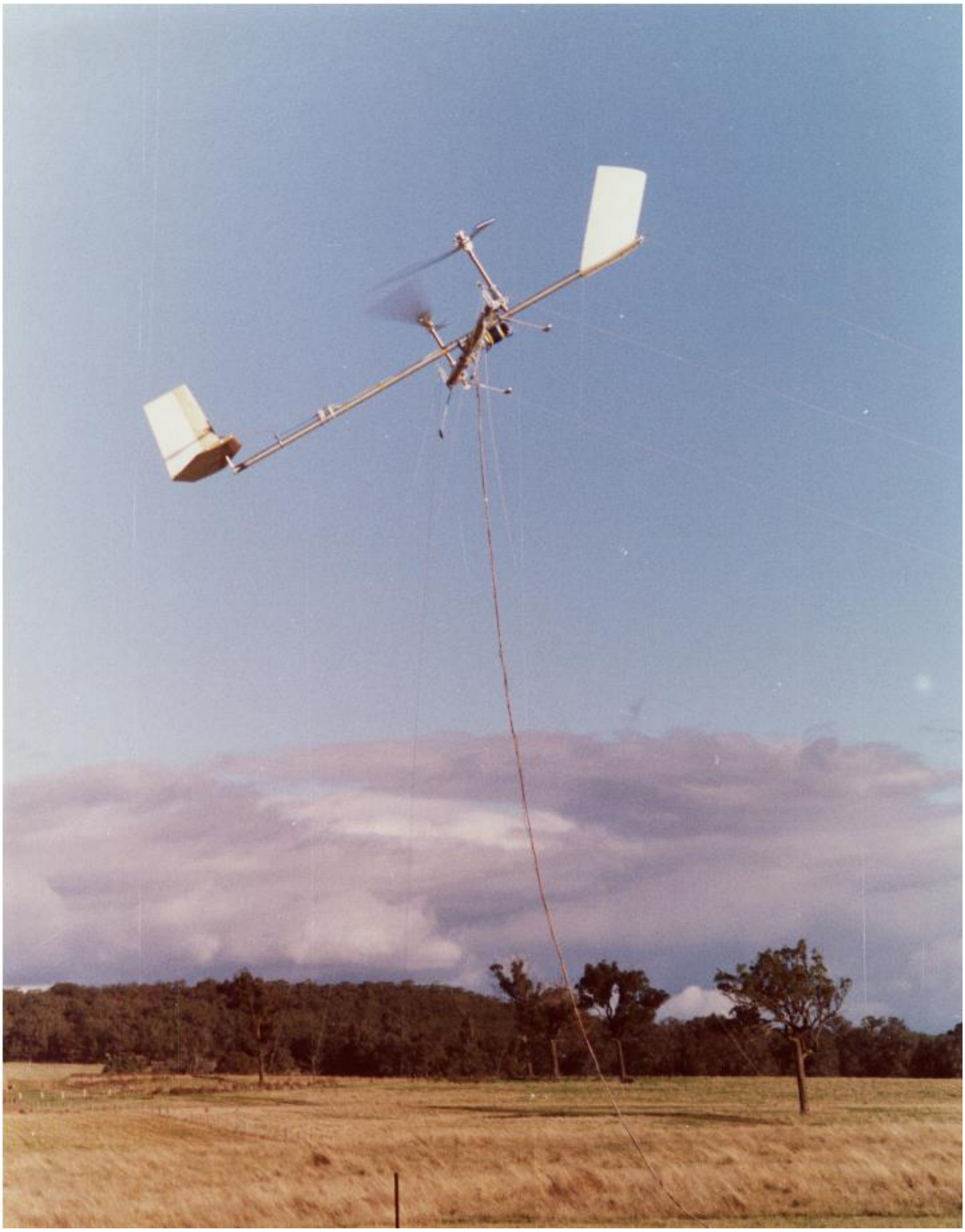

*Figure 2*

### 1.3 Recent Evolution of the Quad-Rotorcraft:

In 2004 a quad-rotor assembly was proposed that gives superior flight controls and reduced fatigue loads on the rotor assemblies compared to the twin-rotor assembly described in Section 1.2 above. The latest version of the quad-rotor arrangement is shown in Figure 3. An engineering review of the quad-rotorcraft system is given in a 2011 paper presented to the Royal Aeronautical Society's London conference on “Future Rotorcraft” [5].

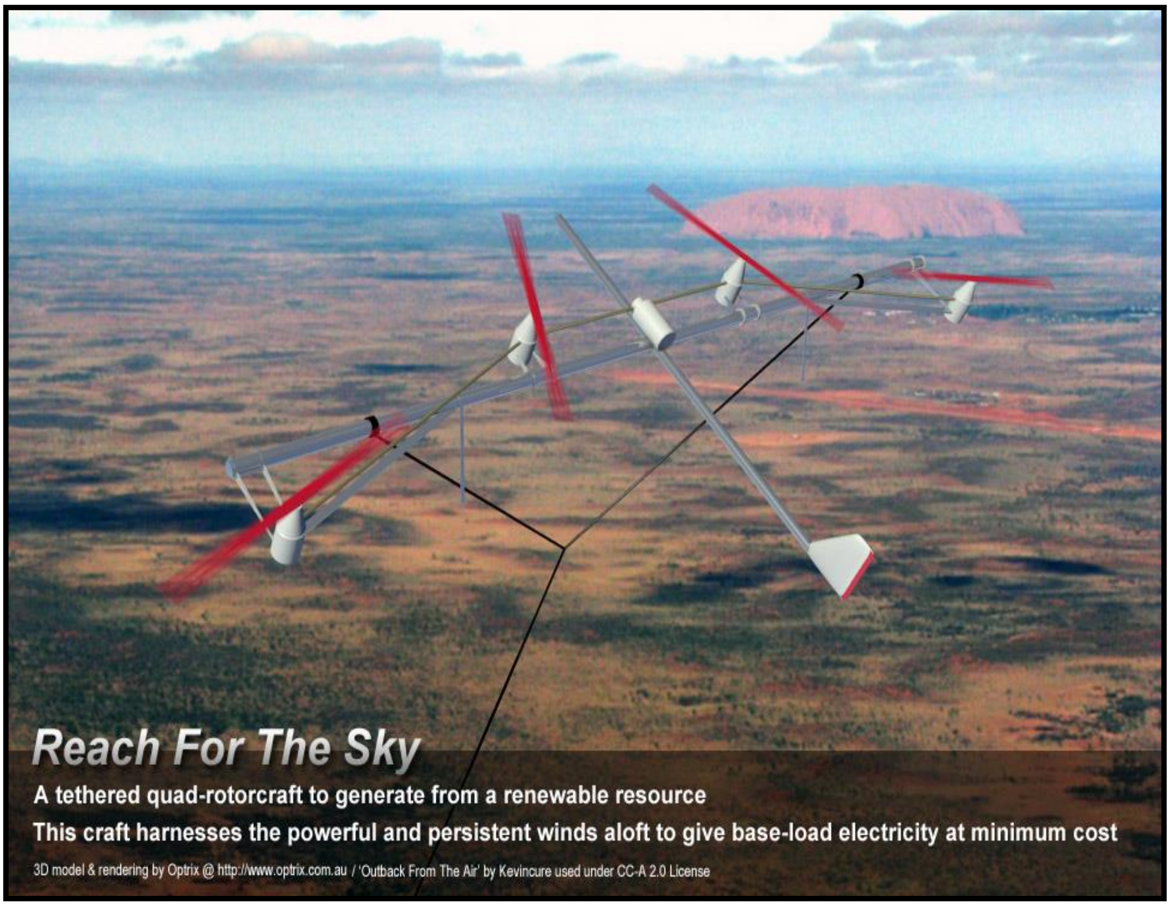


*Figure 3*

Simply described, the four rotors in Figure 3 are again synchronized with cross-shafting that was previously proven to be entirely satisfactory on the twin-rotor prototype, Gyromill Mk2, described above. In Figure 3 the central cross-shaft is identical to that in Figure 2. The significant improvement is the cross-shafts linking the two outmost rotors in Figure 3. These cross-shafts are supported by bearings mounted on the lateral bracing tubes which link these outermost rotors to the main fuselage tube.

In this quad-rotor 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 control the craft's four basic functions, namely power output, pitch, roll and yaw. Two Australian owned patents cover this development and both have been granted.

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 on conventional windmills for power control. No cyclic blade pitch action is necessary. This reduces construction costs and maintenance expenses, while avoiding community concerns about the noise and visual impacts associated with conventional ground-based wind turbines.

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

Altitude Energy's business plan for Australian commercialization of the quad-rotorcraft, shown in Figure 3, is in four steps. The initial step involves the detailed design, construction and demonstration of a small quad-rotor craft. It would produce electrical power in a wind of 12.9 m/s or more. It is planned to demonstrate this system at an altitude of 0.5km.

Step 2 of the business plan is to operate with higher voltages with grid-connection at an altitude of about 4km, after a successful outcome in Step 1. Different arrangements for the four rotors are being investigated. Subsequent steps would be to increase the scale of the units to give a single unit electrical output of around 10 to 20 MW, when flown in the powerful winds aloft. A wind farm with ten of these units would need airspace of about 10km by 10km in extent and be equivalent in output more or less to a modern electrical power station. Documents held from CASA give approval for demonstration flights at altitude at a location yet to be nominated

Calculations, using Australian wind statistics and a suitable craft weight to rotor area ratio, show that electricity can be generated for grid connection. The reliability of the supply would be in the 70 to 80% range, meaning that power would be available for this percentage of time. In strict electrical terms, this percentage is called the capacity or generating factor of the system.

Through a variety of approaches, our upper atmospheric technology has been established within the Australian Government. The system has already been demonstrated in concept in university experiments and elsewhere and the necessary research and development has been finalized to the commercialization stage. Numerous peer-reviewed papers have been published. 'Time' magazine in Nov. 10 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 Dec. 2009.

The rotorcraft technology described above has important implications in connection with the recent Finkel report on the "Future Security of the National Electrical Market" (NEM). A submission to the Finkel report has been made along similar lines to this submission. This current submission will strongly advance the use of quad-rotorcraft at altitude as a significant new technology, both nationally and globally, to address the **concerns of security, reliability and costs associated with Australia's current grid system**.

The body of this submission will now discuss the security, reliability, costs and emissions involved in the current national solar PV system and the current national ground-based wind turbine system.

These systems will be evaluated and compared to demonstrate how necessary improvements can be achieved by operating a quad-rotorcraft generating system in the very powerful and persistent winds aloft at a convenient altitude.

## 2. THE FUTURE USE AND COST OF SOLAR PV SYSTEMS IN AUSTRALIA:

The use of grid-connected, solar PV systems in Australia is significant on an international basis. Federal and state governments offered generous subsidies to encourage folk to install PV panels on the roof-tops of their houses and elsewhere. The uptake, along with the offer of over generous feed-in tariffs (now discontinued in some cases), has resulted in the current installation of around 1.5 million variable renewable electricity (VRE) solar generators. The average installed power of these units is about 5kW and the Clean Energy Council publishes annually collective data for units having installed powers at less than 100 kW. For this class of generators we can extract and develop the following information.

Of **utmost importance** is the capacity factor (CF) of the generating units within Australia's extensive grid network. This CF is sometimes referred to as the generating factor. For an electrical generating facility the capacity factor is defined as the ratio of the actual average power developed over a period of time, usually one year, compared to the potential power the facility could generate if it were operating at its rated or nameplate power over the same period of time. This measure of reliability, through a calculation of the generator's capacity factor, is an important and fundamental concept. This point will be considered later in this submission, but in principle the higher the capacity factor the more reliable will be the generating facility. In addition, there is the implication that if a generator is more reliable then it is more secure, therefore not normally requiring interconnection of power from another of the network's generators. These aspects will now be discussed below in more detail.

Capacity factors are not specifically published in Australia's premier data resource on renewable energy, namely the Clean Energy Australia Report (7), published by the Clean Energy Council. However, as an alternative approach for the determination of the capacity factor, the published figures can be used by reading from report (7) the annual average of the total installed power of the generating facility along with the annual energy output from these units. For example, the solar PV figures (for less than 100kW units) published in the 2015 Clean Energy Report give the annual average of the total installed power at 3,665 MW which gave an annual energy output of 5,655 GWh. This leads directly to a capacity factor for solar PV at 17.6%. This in effect means that the national PV system is overall unreliable and intermittent in its availability, compared to CFs of around 90%, or more, for coal-fired facilities. Thus solar PV systems need, in general, supporting generators, or supporting storage systems, in order to guarantee a continuous supply. Sections of the power industry refer to the supporting generators as "dancing partners" used to guarantee supply on the occasions that solar PV is either unavailable in a grid network, or when the electrical demand exceeds the solar supply. The capacity factor and its relationship to reliability also has security implications. For example, if a generating facility had a high CF and thus a high reliability, then there would be a lesser need for the interconnection of a generator from elsewhere. In other words the security of supply is greater the higher the facility's capacity factor.

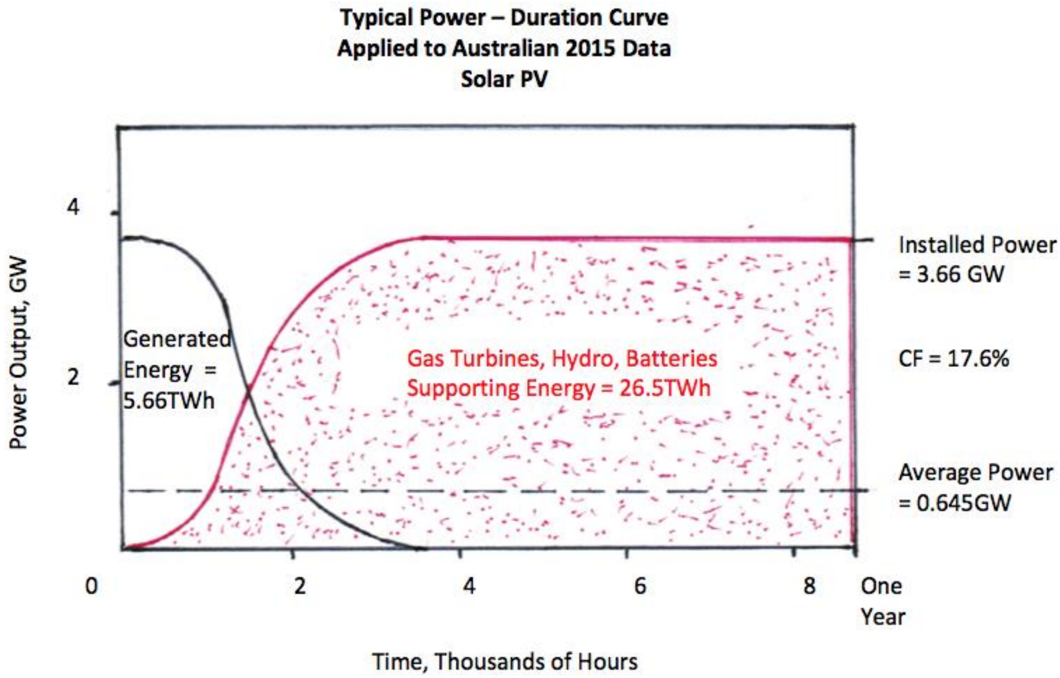


*Figure 4*

For the above class of solar PV units the annual average of the total installed power in 2015 was 3,665 MW. In total these generators produced an energy output of 5,655 GWh, to give a calculated capacity factor of 17.6% for the year. Thus it is possible to construct the typical Power-Duration Curve (PDC) from these values. It is well-known that the shape of the PDC derived from solar radiation follows an approximate cosine-shape, shown in Figure 4. In other words a typical plot of power output against a yearly duration, measured in hours, is the black left-hand curve given in Figure 4. This black portion of the figure can be interpreted as follows: any point on the black curve represents the total number of hours in the year that the generated power was **at or above** a certain value. For example reading from the black curve, the generated power was at or above 3,000 MW for about 1,600 hours during 2015. In addition, power was only generated for about 3,500 hours in that year. It is important to note that this black curve has been carefully drawn to give a capacity factor of 17.6% using the typical known shape associated with solar radiation. Furthermore, the area under the black curve of Figure 4 represents the total energy generated in the year, namely 5.665 TWh as given in reference (7), while the average power generated over the year was 645 MW. This latter figure is shown on the right side of figure 4.

Now turn to the red curve and captions shown in Figure 4. The red curve is the form of the power output from a supporting electric generator which would ensure that the combined power supply was constant throughout the year at 3.665 GW. Within a national network devoid of any unplanned influences from other parts of the network, this combination may be considered to be a stand-alone arrangement, giving important guidelines to the requirements for the grid's generator components.

On the above basis, consider that the objective of this combined solar facility is to deliver a constant power output at a rated power of 3.665 GW for the whole year. This implies that the network demand can at all times accept the 3.665 GW supply. In this situation it will be necessary to connect the solar facility, in a tandem arrangement, to a supporting energy supplier, or a so called 'dancing partner'. This connection will thereby ensure the 3.665 GW supply can be maintained throughout the year. The Power-Duration Curve (PDC) of the supporting generator is the red curve in Figure 4. Note that this red PDC has its origin at the 1 year mark and its hours are read in the opposite direction to hours of the black PDC. The addition of the black curve to the red curve gives a uniform supply of 3.665 GW at all times. The area under the red curve is the energy supplied over the year by the supporting generator. For 2015 the magnitude of this latter energy was 26.5 TWh, namely 4.7 times larger than the energy generated by the solar (black) portion in the first place.

Up until now it has generally been standard practice to use the coal-fired generators acting as the supporting generators for the country's solar PV units. This practice has been more or less satisfactory provided the solar portion is only around 5% to 10% of the national energy output. The reason for these percentages is that it is possible to slightly vary the coal-fired output when the solar output suddenly drops due to cloudy or unfavourable weather. But it is essential during larger, sharp output surges that the supporting generator must be capable of **rapidly** increasing or decreasing its energy supply to fully maintain the total power output. However, if the solar proportion is too large compared to the coal-fire's dynamic capability, then the overall system will fail. Therefore, in the future, when the renewable energy's share of the energy market is increased to significantly offset global warming, our national grid will be in a fragile state. To avoid this undesirable situation the supporting generators will be hydro driven electric generators, gas turbine driven electric generators, electric batteries or some other form of generator, all of which can be started or closed down in a matter of seconds, to meet any surge or slackening of the solar supply. Currently the favoured form seems to be gas turbines using an open cycle. A combined cycle gas turbine facility uses steam in its combined cycle, but this gives poor dynamics from the steam-raising portion of the cycle. This makes the combined cycle unattractive.

If we use the current price of gas at around $3.65/MBTU along with an open-cycle gas turbine efficiency of power conversion at 39%, then the cost of the provision of the supporting energy shown in Figure 4 will be $ 0.85 billion per annum. This figure does not cover the cost of the purchase and installation of the gas turbine machinery. This latter cost per annum is estimated to be in the order of $6.6 billion amortised over the life of the turbines.

The above figures can now be linearly extrapolated to a future condition where say 50% of the national grid's energy comes from the above renewable source, namely from the above PV solar/ gas turbine supporting system. Such a scenario is not unreasonable, as a number of Australian states have already gazetted a policy of 50% renewables by 2030. If figure 4 were to be extended to cover this 50% situation, then the annual generation from the combined solar/gas supporting system would be about 120 TWh/annum, leading to all energy values in Figure 4 being increased by a factor of 120/(5.66 + 26.5) = 3.73. In this situation the total greenhouse emissions from such an arrangement would be zero from the solar component plus 61.3 million tonnes of carbon dioxide per annum from the gas turbine component, using the standard pollution figures per MWh given in reference (6). However, if we assume that all the energy replaced in this 50% example came from black coal-fired power stations (herein assumed to be now shut-down), then the carbon emissions would have been 112.8 million tonnes per annum. Therefore in summary, the carbon savings through the introduction of this solar/gas supporting system would be (112.8-61.3) = 51.5 million tonnes per annum, while the cost of the natural gas consumed in the process would be $3.2 billion per annum. In addition, the cost per annum for the purchase and installation of the supporting gas-turbines is estimated to be $24.6 billion amortised over the life of the turbines. Also the magnitude of the solar PV generation would need to be increased by a (3.73 - 1) factor, namely 10.0 GW, to meet the above chosen overall target of 50%. The purchase and installation of this PV hardware increase is estimated to be around $18 billion amortised over the life of the PV collectors.

If hydro or battery facilities were to be used in place of the chosen supporting gas turbines, then the associated calculations can be straight-forwardly computed in a manner similar to that described above.

In conclusion the following parameter list summarises the improvements in using a combined solar PV/gas turbine system to replace 50% of the country’s current electricity usage.

**Security and Reliability of Supply:**

Capacity factor of solar PV system acting alone = 17.6%

Percent of national network’s energy from genuine renewable resource = 8.8%

Installed power of supporting gas turbines = 13.7 GW **‡**

**Relevant Energy Costs:**

Prime cost to expand the solar PV facility = $18 billion **‡**

Prime cost of the supporting gas turbines = $24.6 billion **‡**

Cost of the supply of gas fuel = $3.2 billion/annum

**Carbon Savings to Achieve Greenhouse Abatement:**

Total coal-fired emissions prior to the 50% installation = 112.8 million tonnes/annum

Total emissions after the 50% installation = 61.3 million tonnes/annum

Emission savings from the 50% installation = 51.5 million tonnes/annum

**‡** It is important to note that all the figures given above have been derived from the **average conditions** in the Australian network for 2015. The information so derived, and highlighted above with an **‡**, would need to be modified by a suitable percentage to cover the peak demand over and above the annual average used herein. The need for this increased supply would occur, for example on a hot afternoon in summer to meet the above average demand for air-conditioning. Thus in a practical application of the above scheme it would be necessary to expand the **‡** marked items by a further 30 or 40% thereabouts. The CF of the combined solar/gas turbine system would then be reduced from 100%. But the quoted total cost of the gas fuel needed and the resulting emissions would remain unchanged, as given above, because the surges and slacks in supply would annually average-out to the above values. Nevertheless, the above figures do give stand-alone, guiding principles to be applied if a solar/gas turbine generating system is adopted.

## 3. THE FUTURE USE AND COST OF GROUND-BASED WIND TURBINES IN AUSTRALIA:

The use of grid-connected, ground-based wind turbines in Australia will now be examined in detail following the same format as that given for the solar PV system above. These wind turbines are the largest contributor to Australia's renewable electricity generation at this time. Some 2,062 turbine units were in operation at the end of 2015, with an average rated output of 2.03 MW per unit. The generated energy in 2015 was 11,802 GWh from an annual average of the total installed power of 4,000 MW (7). Knowing the total hours in a year, the capacity factor (CF) of this wind turbine system is 33.6%. This CF figure is comparable to the CF in the USA, where for 2015 their wind turbine systems' CF was 32.2% (8).

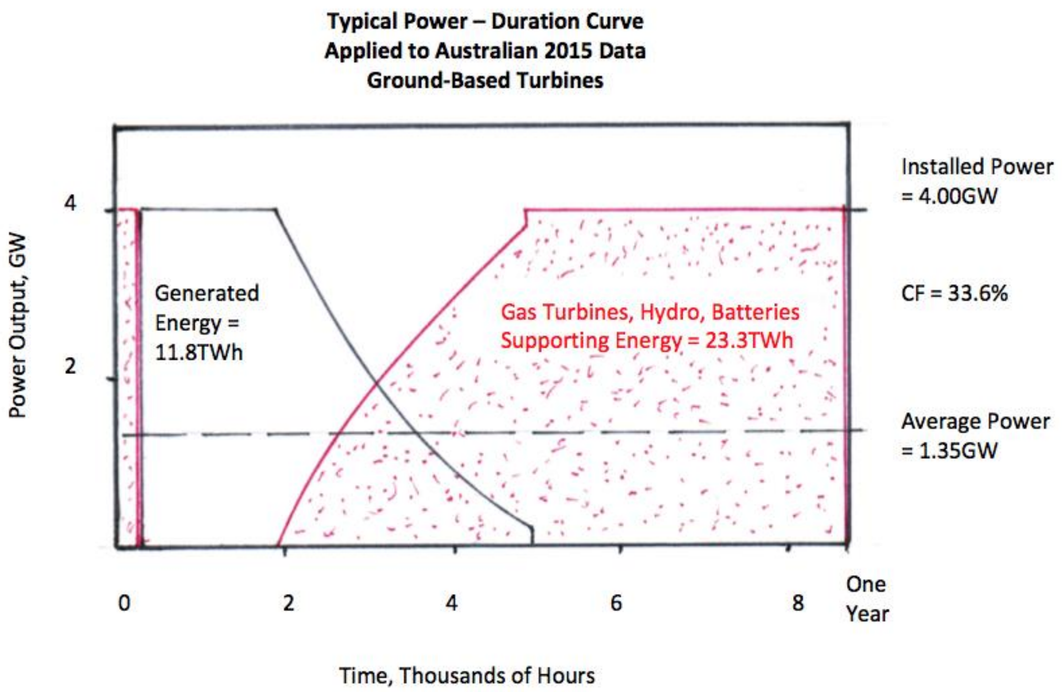


*Figure 5*

Turn now to Figure 5 which gives the wind turbines' Power-Duration Curve (PDC), shown as the black curve in the figure. Here it can be noted that the vertical line on the extreme left of the black curve gives the time for which, on average, the turbines are 'shut-down' due to high wind speeds. The knee of the black figure represents the average time that the turbines are at or above 'rated condition', while the small vertical line in the figure at about 5,000 hours represents the average time that the turbines are in operation following after the so called 'cut-in' wind speed. At this cut-in wind speed the turbines are just beginning to produce power. The area under the black curve is 11.8TWh, the total generation, while the shape of the black curve has been constructed similar in shape to that for typical ground-based turbines. Any point on the black curve represents, as before, the total number of hours in the year that the generated power was at or above a certain value. For example in Figure 5, the system was at or above its rated power output for about 1,900 hours. The black curve has been carefully drawn to give the above capacity factor of 33.6%. On the far right-side of this figure the average power generated for the year is given at 1.35 GW.

The red-curve in Figure 5 has been drawn on the assumption that we want to use supporting generators to maintain the power output at 4,000 WM throughout the year. The object of the red power output being to give reliability and security to the wind turbine system. This supporting system might be hydro driven electric generators, gas turbine driven generators or electric batteries. Again, as discussed in the previous section of this submission, the favoured supporting system appears to be open-cycle, gas turbine driven generators. The advantage is these can be started or closed down in a matter of seconds to support, or fill-in, the intermittencies in the overall wind turbine output. The annual energy generated by the supporting generators needs to be 23.3 TWh per year to maintain the combined power output at 4.0 GW throughout the year. The annual supporting energy at 23.3 TWh is 1.97 times larger than the renewable energy developed in the first place.

If we again use a price of $3.65/MBTU for the gas used in the open-cycle, gas turbine facility, where the conversion efficiency is 39%, then total gas cost will be $0.743 billion per annum. To this figure must be added the cost of the purchase and installation of the new gas turbine machinery. This cost is estimated to be of the order of $7.2 billion amortised over the life of the turbines.

As previously, the above figures can be linearly extrapolated to a condition where 50% of the national energy generation comes from the above system, namely the ground-based wind turbines supported by the gas turbine assembly. If figure 5 were to be extended to cover the 50% renewable situation sometime in the future, we would need to produce about 120 TWh/annum. This represents an expansion of Figure 5 by a factor of 120/(11.8 + 23.3) = 3.42. In this situation the total emissions per annum from the wind turbines would be zero, with emissions of 49.4 million tonnes per annum from the gas turbines. If we again assume that all the energy in this 50% scenario previously came from coal-fired power stations, then the emissions per annum would reduce from 112.8 million tonnes to the above 49.4 million tonnes. This represents an emissions reduction of 63.4 million tonnes per annum at a cost of $2.54 billion per annum for the purchase of gas turbine fuel. In addition, there is the additional cost for the purchase and installation of the gas turbines, which is estimated to be $24.6 billion.

Finally, the size of the generating ground-based turbines needs to be expanded by a factor of (3.42 – 1), namely by 9.7 GW. The associated purchase and installation cost is estimated at $15.1 billion amortised over the life of turbines.

In conclusion the following parameter list shows the advantages of using a combined ground-based wind turbine/gas turbine system to replace 50% of the country's current electricity usage.

**Security and Reliability of Supply:**

Capacity factor of ground-based wind turbine system acting alone = 33.6%

Percent of national network's energy from a genuine renewable resource = 16.8%

Installed power of supporting gas turbines = 13.7 GW ‡

**Relevant Energy Costs:**

Prime cost to expand the wind turbine facility = $15.1 billion ‡

Prime cost of the supporting gas turbines = $24.6 billion ‡

Cost of the supply of gas fuel= $2.54 billion/annum

**Carbon Savings to Achieve Greenhouse Abatement:**

Total coal-fired emissions prior to the 50% installation = 112.8 million tonnes/annum

Total emissions after the 50% installation = 49.4 million tonnes/annum

Emission savings from the 50% installation = 63.4 million tonnes/annum

‡ The items marked with this caption are subject to the comments made under the same caption at the end of the prior section on solar PV use.

## 4. THE FUTURE USE AND COST OF HARVESTING WIND POWER AT ALTITUDE:

A study will now be made of a quad-rotorcraft system tethered in the very powerful and persistent wind system above Australia. We will assume that a suitable number of craft are in operation aloft to give a rated power output exactly equal to the 2015 annual average installed power of the Australian ground-based wind turbines, namely 4.0 GW. This then allows a comparison, given herein, between ground-based wind turbines and altitude wind turbines. The power-duration curve (PDC) for this 4.0 GW rotorcraft system at altitude is shown in Figure 6 below.

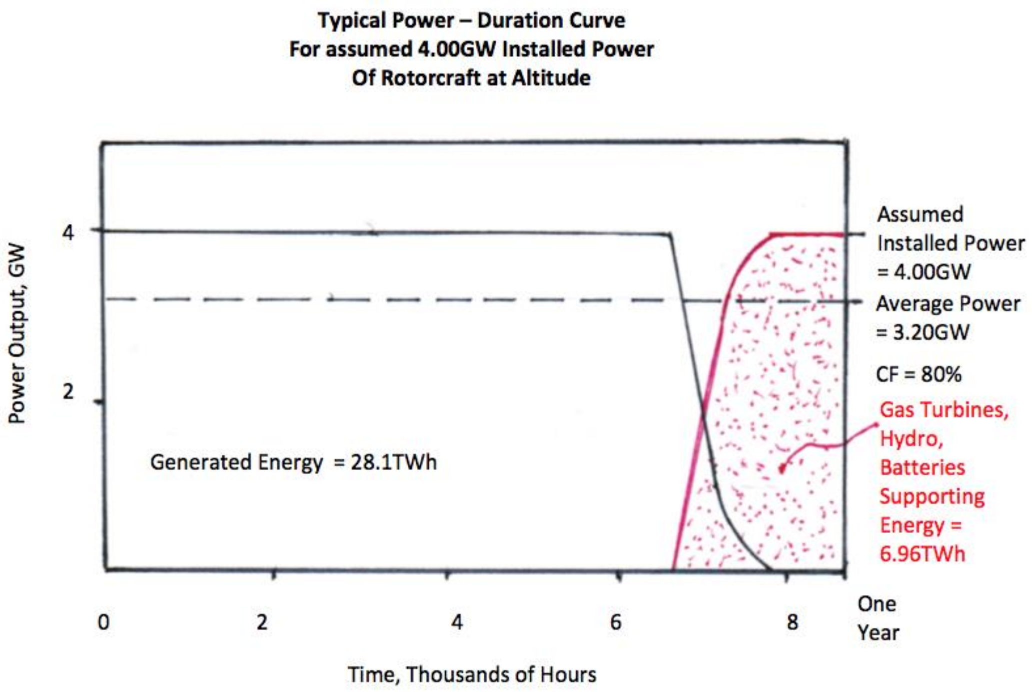


*Figure 6*

Begin by noting that it can be shown from the wind statistics for sites in Australia (1) that the capacity factor (CF) for a quad-rotorcraft system would be between 70 and 80% at favourable altitudes. Thus we will assume in this study that the most favourable conditions exist and that the CF will be taken at 80%. In these circumstances, as shown in Figure 6, for an installed power of 4.0 GW the generated energy per annum will be 28.1 TWh. This generated energy is given as the area under the black curve of Figure 6. The supporting generation, here again derived from a gas turbine facility, is shown as the area under the red curve, namely 6.96 TWh. The shape of the black curve follows theoretical predictions of how such rotorcraft would operate at altitude. The knee of the black curve represents the wind conditions at or above rated power, while zero power output, at around 7,800 hours, represents the craft's autorotation conditions. Again the form of the black curve has been carefully arranged to give a CF of 80%. The average power output is shown as 3.20 GW, with the combined rotorcraft and gas turbine system producing a constant power output of 4.0 GW over the whole year.

Again using a gas price of $3.65/MBTU with an open-cycle gas turbine conversion efficiency of 39%, the cost of gas in support will be $ 0.222 billion per annum. The cost of the purchase and installation of the necessary gas turbines is estimated to be $ 7.2 billion amortised over the life of the gas turbines.

As before the above figures can be linearly extrapolated to the situation where 50% of the national generation comes from rotorcraft at altitude, with gas turbine support. In this 50% case the power and energy levels above should be factored by 120/(28.1 + 6.96) = 3.42. The total emissions from such an arrangement are zero from the rotorcraft at altitude plus 14.7 million tonnes per annum from the supporting gas turbines. If, as previously, the energy was all produced from coal, then the emission savings from the use of these rotorcraft would be (112.8 – 14.7) = 98.1 million tonnes per annum.

In the 50% situation, the power of the generating rotorcraft would be (4 x 3.42) = 13.7 GW, all from new craft, at an estimated cost of $21.8 billion amortised over the life of the rotorcraft. In addition, the estimated cost of the supporting gas turbines would be $24.6 billion amortised over the life of the gas turbines, while the cost of gas turbine fuel would be $0.76 billion per annum.

In conclusion the following parameter list addresses the advantages of using a combined rotorcraft at altitude/gas turbine system to replace 50% of the country's current electricity usage.

**Security and Reliability of Supply:**

Capacity factor of rotorcraft system at altitude acting alone = 80.0%

Percent of national network's energy from a genuine renewable resource = 40.0%

Installed power of supporting gas turbines = 13.7 GW ‡

**Relevant Energy Costs:**

Prime cost to build the rotorcraft facility = $21.8 billion ‡

Prime cost of the supporting gas turbines = $24.6 billion ‡

Cost of the supply of gas fuel= $0.76 billion/annum

**Carbon Savings to Achieve Greenhouse Abatement:**

Total coal-fired emissions prior to the 50% installation = 112.8 million tonnes/annum

Total emissions after the 50% installation = 14.7 million tonnes/annum

Emission savings from the 50% installation = 98.1 million tonnes/annum

‡ The items marked with this caption are subject to the comments made under the same caption at the end of the prior section on solar PV use.

## 5. CONCLUSIONS:

The introduction to this submission describes how tethered quad-rotorcraft, in the common 'drone' configuration, can be used to generate grid-connectable electricity. The fundamental advantage of such a technology is that it harvests the extremely powerful and persistent winds above Australia to dramatically improve the security, reliability and costs of our grid electricity. These winds in Australia are globally unsurpassed as a large-scale renewable energy resource.

In reference (1) levelised cost of energy (LCOE) calculations show that due to the persistence of these winds the basic cost of altitude generated electricity was $64/MWh in 2011. This cost is equal to that from coal generated power, but well superior to the LCOE cost of power from ground-based wind turbines at $127/MWh in 2011, and considerably less than that from commercial solar power systems.

This submission used 2015 figures to calculate the reliability, the costs and the greenhouse gas savings from three renewable resources. These calculations relate to solar PV systems (Section 2 above), ground-based turbines (Section 3) and quad-rotorcraft at altitude (Section 4). These three methods of electricity generation will be referred to below simply as solar, ground wind and altitude wind systems. In these three cases data for the solar and ground wind systems was extracted from the 2015 figures published by the Clean Energy Council. In the case of altitude wind the data assumed that altitude wind's installed power was the same as for ground wind. Altitude wind generation was analysed with a capacity factor of 80%. Capacity factors in the 70 to 80% range are obtainable from such altitude systems. This CF range is vastly superior to that which can be obtained from solar or ground-based turbine systems.

In each of the three cases the data was linearly extrapolated by suitable factors to generate 50% of the nation's grid energy at a constant rate of 120TWh per annum. In each case rapid response supporting generation was required to give absolute reliability of supply. This supporting generation might be obtained by the purchase of gas turbines, or the provision of special storage facilities such as hydro-dams or electrical batteries. In each of the three cases examined, gas turbine support was chosen for analysis purposes. The storage systems mentioned above, if chosen, could have been used in a similar calculation procedure to verify the superior outcomes from electricity generation at altitude.

The results of the calculations, replacing 50% of the national generation, can be used to address the **Australian grid situation**. These results are as follows:

(1) The solar system, with its gas turbine support, gives a reliable and secure generation system at a total capital cost of $42.6 billion, with the turbine gas costing $3.17 billion per annum. This produces a greenhouse gas saving of 51.5 million tonnes per annum in replacing the original coal-fired generation. This annual gas cost is likely to escalate in the future due to fluctuating world gas prices.
(2) The ground wind system, with a lesser amount of gas turbine support, gives a reliable and secure supply at a total capital cost of $39.7 billion, with a greenhouse gas saving of 63.4 million tonnes per annum. Turbine gas costs are $2.54 billion per annum.
(3) The altitude energy system, requiring the least amount of gas support, gives a reliable and secure supply at a total capital cost of $46.4 billion, while giving the best of all greenhouse gas savings at 98.1 million tonnes per annum. Turbine gas costs are $0.76 billion per annum, being the least of all the systems considered.

From the above figures the preferred means of addressing the nation's grid problems is to advance to an altitude generating system. The overall capital cost of the altitude system is somewhat higher than the other two cases, primarily because in the solar and ground-based wind cases a large number of generators are already in existence and thus are not included in the capital costings herein. In spite of this, the on-going costs are the exact reverse. In an analysis (1), based on 2011 data, it was shown that the cost of electricity generated from altitude wind was $64/MWh, the cost from ground-based wind was $127/MWh and much higher from solar. In addition, the cost of the supporting turbine gas is $3.17 billion/annum and $2.54 billion/annum for solar and ground-based wind respectively, while altitude wind is only $0.76 billion/annum.

The submission demonstrates the supreme position of Capacity Factor (CF) in determining answers. For example, a CF of 80% for altitude energy generation compared to CFs of 17.6% and 33.6% for solar and ground-based wind turbines means that for equal installed power levels, at more or less identical installation costs of around $2,000/kW, the grid energy produced per annum will be respectively 4.5 and 2.4 times greater using the system at altitude. This gives more saleable energy arising from similar capital cost expenditure on each. This leads directly to lower and highly favourable LCOE electricity costs for the community. In addition, high capacity factor generation brings superior greenhouse gas savings and improved security through the need for much lower levels of supporting generation from gas turbines, pumped-hydro or batteries.

While Altitude Energy Pty Ltd. cannot at this time offer rotorcraft at altitude for grid generation, we suggest that our technology be advanced through an appropriate Commonwealth agency as a matter of urgency. An application of the technology in the near future, both nationally and globally, will make a huge contribution to solving grid-related issues.

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