Assessing the Viability of High Altitude Wind Resources in Ireland

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Abstract: The modern wind energy industry exploits the wind resource in the lower 150m-200m of the atmosphere. The wind energy in the atmosphere increases significantly with increasing altitude from ground level, but no electrical power is currently generated from higher altitudes. The wind resource at higher altitudes is less well documented from an energy production point of view and no commercial products currently exist to exploit this resource. The wind resource at 750m will be modelled for Ireland using recent data and comparisons to the existing wind-energy map will be made. Different candidate technologies for exploiting the resource are discussed. A kite-based system is studied in more detail. The capacity factor and performance curves for such a system are calculated.

Keywords: Wind energy, high altitude energy, kite/airfoil.

1. Introduction

The aim of this paper is to assess the high-altitude wind resource in Ireland and analyse the existing research focussed on exploiting such a resource.

In the context of this report, the high-altitude wind resource refers to the energy in the wind at an altitude of 750m for which historical windspeed data is available[1].

The reasons for focussing on this altitude are two-fold. In the first instance, it is known that wind-speeds increase with increasing altitude but little research has been done on estimating the wind-energy resource at altitudes higher than existing wind-turbines and up to the limits of the planetary boundary layer.

Secondly, the rate in increase in size of individual terrestrial wind-turbines is being affected by a number of factors including prohibitive engineering/materials costs, difficulties in site accessibility for larger structures and increasing environmental concerns. Future increased penetration of terrestrial wind-energy may thus be based on the use of a larger number of sites rather than the use of larger turbines. In order to exploit the energy resource that exists at higher altitudes, new technologies must be developed to complement terrestrial wind-turbines.

Terrestrial wind energy has been considered the cornerstone of Ireland’s path to a renewable energy future. The current grid connected and operational installed wind capacity on the island of Ireland is 1086.37 Megawatts (MW) which will on average generate 2,950,146 Megawatt hours (MWh) in a year given a 30% load or capacity factor. While this fast-growing figure represents 68% of the total renewable energy used for electricity generation, it still only represents 9% of the total electricity demand [2].

The proposed EU2020 directives covering member state effort-sharing and renewable energy directive stipulate that Ireland must obtain 16% of its total energy needs from renewable resources, this figures is currently 3.4% leaving a distance to target of 12.6% by 2020.

Wind is the leading renewable energy type in Ireland, as well as being the least expensive and most abundant. Sustainable Energy Ireland (SEI) resource studies indicate that it is an order of magnitude greater in potential than other renewable energy source in Ireland, as well as being larger than all other renewable energy resources combined[3]. Ireland has a national goal of 33% of electricity from renewable sources by 2020 which is largely expected to come from wind. Future issues relating to a major expansion of wind generating capacity, the location of wind farms in remote areas of the electricity grid and the inevitable impact on grid quality remain to be dealt with. The European commission has, in September 2008, adopted a text [4] recommending that high-altitude wind energy be part of the target of 20% of total energy needs being met through renewable sources in 2020.

A large body of research and commercial activity exists for renewable energy technologies such as solar, hydro, geothermal, biomass and low-altitude wind energy. The energy source which is high-altitude wind is still untapped for want of a proven technology.

2. Methodology

2.1. Wind-resource evaluation

The evaluation of the wind-resource at an altitude of 750m is done using the NCEP/NCAR[1] Reanalysis I dataset [1]. This dataset contains a 40-year record of global analyses of atmospheric variables such as wind and temperature on a 208km resolution grid with over 18,000 points. The dataset generation process included all available radiosonde (weather balloon) and pilot balloon data as

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[1] National Center for Environmental Prediction

well as observations from surface, ship, aircraft and satellites. The dataset provides windspeed data at different pressure levels and for the purpose of this report the data from pressure levels 1000hPa and 925hPa are used. Using the standard hydrostatic equation these pressure levels correspond to altitudes of approximately 110m and 750m above mean sea level (amsl). Data is available for four readings per day at 00, 06, 12 and 18 hours Greenwich Mean Time.

The binary data output from the dataset can be manipulated using NetCDF4Excel tool which is available for free.

The Reanalysis I dataset has been used previously in the analysis of vertical wind profiles [5] and also in studies comparing its accuracy with that of ground based observations[6] with satisfactory results particularly for north-western Europe.

The windspeed values derived from the Reanalysis I dataset will be compared with data from the Irish Wind Atlas[7] which provides annual wind-speed figures at 50m, 75m and 100m covering the Republic of Ireland. Comparisons will also be made with radiosonde data (i.e. wind sensor/transmitter units used in weather balloons).

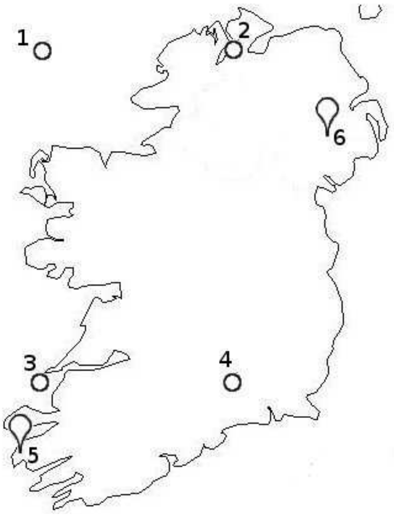

Figure 1 : Locations of data sources for high-altitude wind

The locations covered by the Reanalysis I dataset include four sites of potential interest in studying the high-altitude wind resource in Ireland. These sites are numbered 1 to 4 in Figure 1. Since no data is available for comparison with offshore locations only Sites 2 & 4 will be evaluated. These sites are situated at 10 m amsl and 60m amsl respectively.

Radiosonde data is available for two sites on the island of Ireland, numbered 5 and 6 in Figure 1.

The data from the Reanalysis I dataset is limited by the lack of vertical resolution in the lower 1000m of the atmosphere i.e. only two pressure levels/altitudes are available. The corresponding data for North America contains 5 pressure levels up to 1000m but this level of details is not available elsewhere. Since the effects of surface roughness have long since been overcome at this altitude it will be assumed that the windspeeds calculated for 750m apply from that altitude to the top of the boundary layer.

A full year of Reanalysis I data, from 2008, for both sites 2 & 4 has been used as the basis for this report.

2.2. High-altitude wind technology

The study of technologies to exploit the wind resource at high-altitudes has been ongoing since the 1930's with a resurgence of interest following the oil-crisis of the 1970's, [8,9,10] focussing on airborne versions of terrestrial horizontal-axis wind-turbines. The potential for the use of rotorcraft, semi-permanently located in the upper atmosphere, has also been studied [11,12]. These rotorcraft consist of an airframe with two or more rotors which have the dual function of providing lift to support the airframe and generating electricity when inclined at an angle to the wind.

The major drawback of the aforementioned systems is the fact that the power generating equipment is located at the energy source, i.e. at high altitudes. This means that the energy extracted from the wind must first be sufficient to keep the power-generating equipment airborne before any excess is available for transmission to the ground via the tether. The safety concerns raised by heavy airborne systems coupled with the risks/costs associated with prototype development have hampered the development of these proposed systems.

Other proposed technologies de-couple the energy extraction from the electricity generation through the use of kite/airfoils creating tension in a tether causing the rotation of a ground-based generator as the tether reels out from a drum.

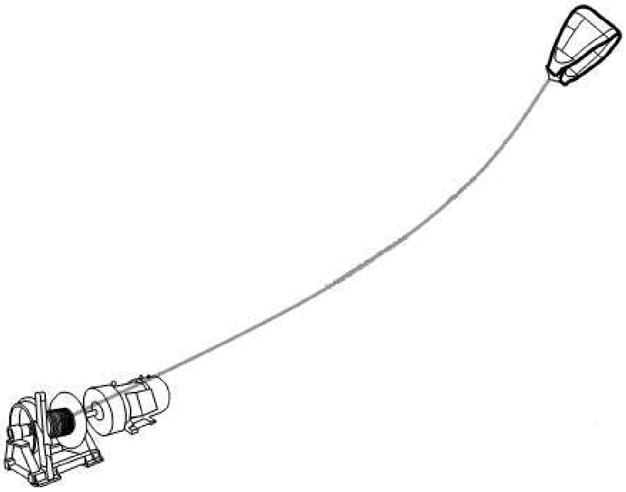

Figure 2: Airborne kite, ground-based generation

Such proposals fly the kite in a crosswind, figure-eight pattern which is shown to increase the apparent wind experienced by the kite [13] by a ratio defined by the lift-drag ratio of the kite. Typical lift-drag ratios for the surf-kites used in simulations and prototyping are 5.8 meaning that a kite will experience an apparent wind of 58m/s when flown in a true wind condition of 10m/s.

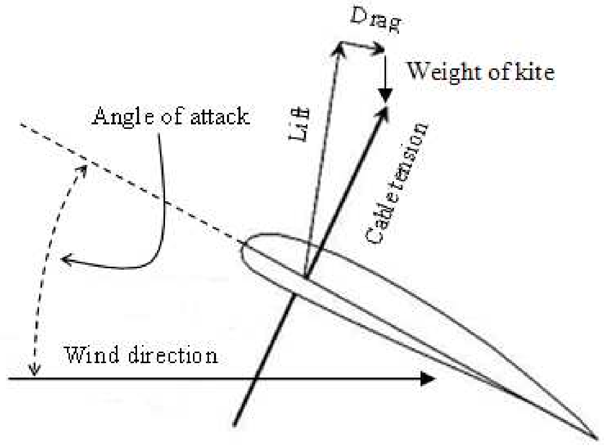

Figure 3 : Cross-section of kite

The efficiency of the figure-eight pattern has been corroborated by research on the control systems used for flying a kite for the purpose of energy generation [14,15]. Once the tether is unwound to a certain point the kite is reeled in to a lower level, consuming energy, and the reel out phase begins again. The kite-based system would be controlled in such as manner that more electricity is produced in the reel-out phase than is used in consumed in the reel-in phase [16,17] by altering the angle of attack as seen in Figure 3.

No experimental data is available for the different variations of kite-based systems, as no permanent real-world installations exists at the moment but extensive modelling has been carried out [16,17]. These results indicate that the kite-based system are feasible and scalable and form the basis of the data-analysis/discussion section.

3. Data analysis, discussion

3.1. Wind-resource evaluation

The wind-speed readings from the Reanalysis I dataset at 110m and 750m have been averaged on a monthly basis for Site 2 and 4.

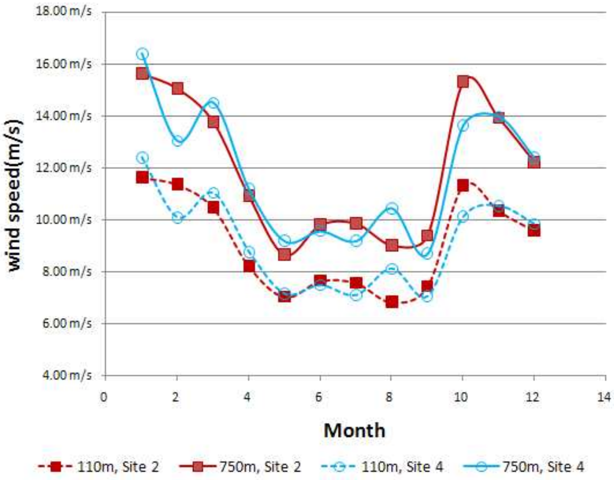

Figure 4 : Monthly average windspeeds, Sites 2 & 4

The chart shows that wind-speeds at 750m are consistently higher than wind-speeds at 110m and that this difference in wind-speed is consistent throughout the 12 month period covered by the dataset.

For Site 2 (located at 55°N,7.5°W) the average windspeed at 110m is 9.13m/s and at 750m the average windspeed is 11.98m/s. This indicates a 31% increase in wind-speed which translates to a 109% increase in the wind-energy potential at the higher altitude, (using the equation Energy = ½ ρv^3 and allowing for the decrease in density at the higher altitude)

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From the wind-atlas data [7] the average windspeed at Site 2 is 8.25m/s at 100m. Using the power law equation [18] the windspeed at 110m is estimated to be 8.36m/s. This shows a 0.8m/s difference between the windspeed calculated from the Reanalysis I dataset and the wind-atlas. The data from the wind-atlas is averaged over a number of years whereas the calculated wind-speed is specific to 2008. More years of data should be analysed to ascertain the extent of the difference between the Reanalysis I results and the observed windspeeds.

Similar calculations for Site 4 (located at 52.5°N, 7.5°W) give the average windspeed at 110m is 9.16m/s and at 750m the average windspeed is 11.86m/s. This indicates a 29.5% increase in wind-speed which translates to a 101% increase in the wind-energy potential at the higher altitude.

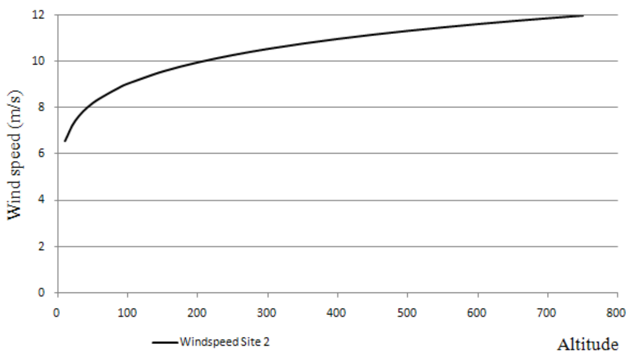

Figure 5 : Windspeed vs. altitude using power law

The calculated wind speeds provide an almost exact fit with a windspeed curve derived using the power law equation [18], as seen in Figure 5 although it is assumed that the power law equation is more suited to the lower 150m of the atmosphere.

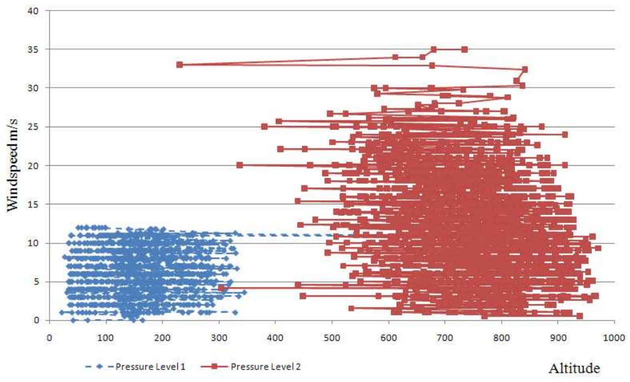

Figure 6 : Scatter chart of Radiosonde windspeed data

Direct comparisons with wind-speed data derived from radiosonde observations are complicated by the raw nature of the radiosonde data. While Reanalysis I data is normalised to ensure that pressure readings correspond to a consistent altitude above mean sea level, the radiosonde data is not. Figure 6 shows the altitude and windspeed values corresponding to readings for the first two pressure levels in the radiosonde dataset for Site 5,Figure 1 .

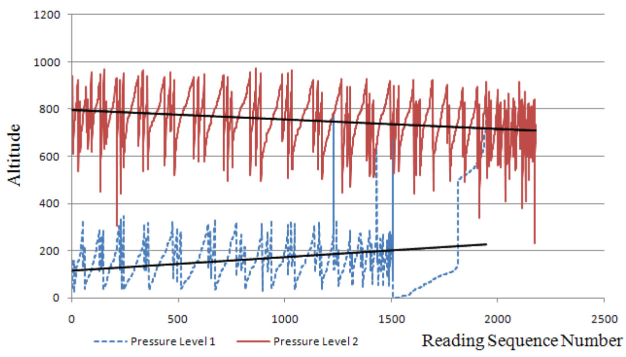

Figure 7 : Linear regression of altitudes for Level 1 and Level 2 readings

In order to allow comparison with the Reanalysis I results a linear regression was applied to the readings at the two pressure levels and only those wind-speed readings within the resulting range were studied. This gave an average windspeed of 8.45m/s at a height of 165m ±25m and an average windspeed of 11.62m/s at a height of 745m ±25m. Using the power-laws to derive wind-speed values for 110m and increase in wind-speed of 45% is seen between 110m and 745m. While this also indicates a significant increase in wind-speed/-energy at 750m it is difficult to draw direct comparisons with the results of the Reanalysis I dataset owing to the geographic location of the readings. i.e. 197 km from Site 4 and 387 km from Site 2.

Since the Reanalysis I dataset includes 4 readings per day the average wind-speeds at the different times were charted on a seasonal basis.

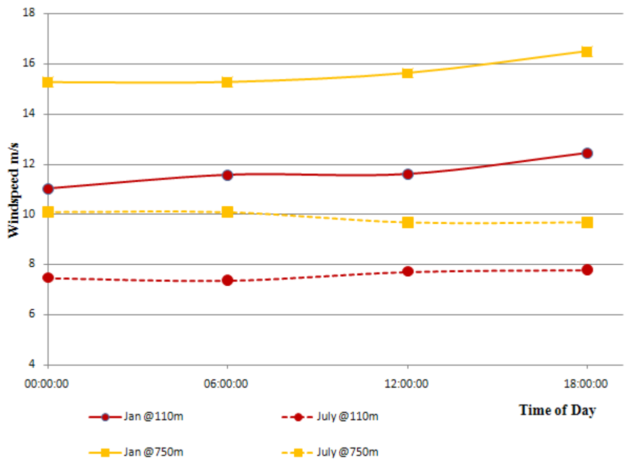

Figure 8 : Diurnal spread of windspeed variations

While showing the same seasonal and altitude related changes as seen in Figure 4 the diurnal spread also indicates that in the winter months average wind-speeds are at their peak for the 18:00 reading at 750m averaging 8% higher than the 6:00 and 12:00 readings. This is of interest in a commercial context as the 18:00 data wind-speeds correspond to peak system demand on UK and Irish electricity grids and correspondingly higher market values per MWh on the respective wholesale electricity markets.

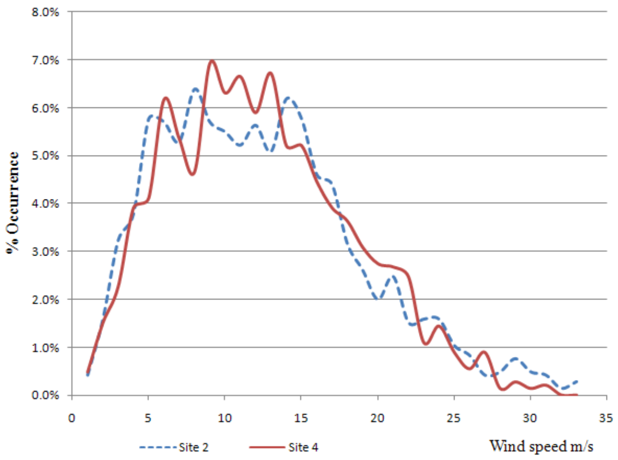

Figure 9 : Windspeed distribution Sites 2 & 4

The Reanalysis I dataset for Sites 2 & 4 allows the creation of wind-speed distribution curves as are seen in Figure 9. The generated curves are similar in form to curves derived from ground-based observations which serve to indicate the reliability of the Reanalysis I dataset. The wind-speed distribution curves will be used to calculate capacity factors for the technologies evaluated in section 3.2.

3.2. High-altitude wind technology

The kite-based systems proposed [16,17] present a number of advantages for the generation of electricity from high-altitude winds. Testing of a prototype [19] has shown the generation of 40kW with a 10m2 kite in line with simulation projections.

The key equations in estimating the power output of a kite-based system with surface area S, lift-coefficient c_l, drag-coefficient c_d , apparent windspeed V_{app} and reel-out cable speed V_{cable} are:

Table 1 : Power equations for kite-systems

Lift Force, L	$\frac{1}{2}\rho {V_{app}}^2 c_l\, S$
Drag Force, D	$\frac{1}{2}\rho {V_{app}}^2 c_d\, S$
Cable Tension, T	$\sqrt{L^2 + D^2}$
Power generated, P	$T.V_{cable} \propto {V_{app}}^2.V_{cable}$

The equations above do not take into account the drag induced by the cable nor the loss of lift due to the weight of the kite. Note that the power produced is proportional to ${V_{app}}^2$ while V_{app} is controlled by c_l/c_d when the kite is flown in a crosswind pattern. The drag and lift co-efficients are controlled by the angle of attack which is set by the kite-control mechanism.

These equations can be used to derive a performance curve, and thus a capacity factor, for a 10m^2 kite-system with a rated power output of 40kW located at Site 4 using the following parameters:

Table 2 : Parameters for performance curve calculations

Kite weight	10kg
Tether weight(Dyneema)	264kg (300m * 0.88kg/m)
c_l & c_d	1.05 & 0.21
V_{cable}	50% of true windspeed[20]

Owing to the small size of the kite, and in order to avoid the drag of the tether playing too large a role, the performance curve will be calculated for an altitude of 300m. The windspeed distribution curve from Figure 9 is modified to reflect the lower altitude using the power-law equation which provides a good fit for the vertical wind-profile when compared to the observed wind speeds at 100m and the results of the Reanalysis I dataset.

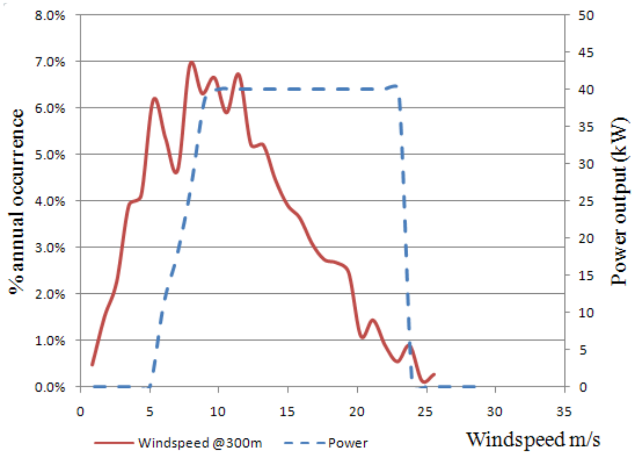

Figure 10 : Performance curve at Site 4

The performance curve data gives a capacity factor of 74.1% for a constant reel-out-phase. Assuming that the ratio of reel-out/reel-in phase duration is 4:1[16] the capacity factor is reduced by 20%. The energy consumed during the reel-in phase, 12% of energy produced in reel-out phase [19] gives an effective capacity factor of 52.2%.

The key factor in such kite-systems is the ability of the control system to adjust the angle of attack while maintaining the crosswind flight pattern. This allows control over the V_{app} experienced by the kite and stabilises both the tension in the tether and the stresses experienced by the kite. Different approaches to the control system exist using neural networks [14] and fast-model-predictive controllers [15]. Both approaches confirm the control of V_{app} by the c_l/c_d ratio and the suitability of crosswind flight-patterns to maximise V_{app}.

From an embodied-energy perspective the proposed kite-systems compare favourably with terrestrial wind-turbines. As the kite/tether replaces the rotor of a terrestrial wind-turbine and no tower structure is required, it is estimated that the embodied-energy would be reduced by 74% [21].

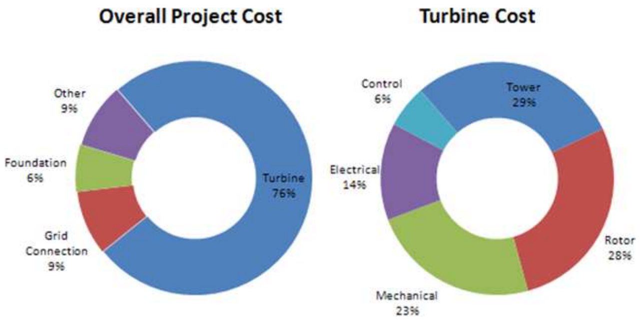

Figure 11 : Turbine cost breakdown[22]

The tower structure and rotor represent 43% of the total project cost for a terrestrial wind-turbine[22], as indicated in Figure 11 indicating the potential for reduced system cost in the kite-based system.

While a number of arguments support the proposed kite-based systems, a number of issues remain to be addressed this novel renewable energy technology gains wider acceptance.

From an operational point of view, a launch/recovery mechanism must be designed to allow the automated operation of kite-based systems. While examples exist of launch/recovery mechanisms used in marine traction applications [23], the impact on kite-design, and thus efficiency, of such a mechanism is unknown in an electricity generating context. An automated launch / recovery mechanism is crucial to the requirement to be able to land all kite-based systems prior to extreme weather conditions thus avoiding the need to over engineer systems to survive such weather conditions.

The suitability of different kite-steering mechanisms must also be studied. While small kites flown at lower altitudes may be controlled from the ground, as the systems scale upwards in size and fly higher the responsiveness of ground based steering will pose problems to overall system stability and performance. The use of an airborne steering mechanism located close to the kite [23] will have an impact on the lift/drag characteristics and the overall system complexity/cost.

The planning of groundstation configuration for a group of operational kite-based systems will depend to a great extent on the level of control provided by the control systems. Where permitted, groups of kite-based systems may be flown in formation, thereby reducing the overall land requirement. The possibility of flying stacked kites on a single tether would serve to further reduce the land requirements.

Land requirements will also depend on the altitude range chosen for operation. The windspeed distribution curve in Figure 10 shows that between altitudes of 300m and 750m windspeed increases by 12%. This translates to an increased theoretical power output of 25% (since $P \propto V_{app}{}^2$). It remains to be ascertained whether the 25% extra power is worth the increased system costs, due to longer tether(s), and operational complexity. Operation at higher altitudes also increases the time needed for launch and recovery of the system. Operation at lower altitudes will increase the tension on the tether per unit length and will cause extra operational costs in terms of tether replacement and lower capacity factor.

The risk posed by lightning must be addressed in any operational system. Although the proposed tether material, Dyneema, is not itself a conductor, a wet tether will provide a route to ground for lightning. The option of landing all kite-based systems prior to lightning conditions may have a serious impact on the overall capacity factor and may be an important element in site selection.

During short periods of calm the kite-based systems will have to be reeled in to maintain lift. This problem could be overcome by the use kites based on the principle of tensairity [24] whereby the different sections of the kite could be filled with helium to provide constant lift even in calm conditions. Such a kite would greatly facilitate the launch/recovery phases as the issue of a minimum windspeed to allow control would no longer exist.

Further research and commercial prototyping will determine the most suitable applications for such kite-based systems. Potential for utility scale generation (>1MW) can be seen if the control systems prove themselves to the point to allow scaling up of the systems through increased kite surface area and/or stacking of kites. The largest existing kite application uses a 160m2 kite to generate 600kW of traction power for marine propulsion[25]. Alternately, the automated launch/ recovery mechanism may allow for use at times of peak grid demand. The smaller physical footprint of the system when compared to terrestrial wind-turbines, may suggest mobile applications such as humanitarian or military operations. Powering remote communities in a diesel-hybrid configuration is another possible application.

Different applications may require different control algorithms. No real world data is available from either of the proposed control systems and real-world testing is of critical importance for the development of robust control systems.

The potential of the high-altitude wind energy resource requires a rethink in engineering terms. Current wind and hydro technologies are based on building structures which can withstand the full force of nature, while harvesting a fraction. High-altitude wind-energy systems need to be more flexible, more controllable to allow the efficient extraction of energy in this heretofore untapped environment..

4. Conclusions

The wind resource for Site 2 and Site 4 calculated using Reanalysis I data shows a clear increase in wind speed with increasing altitude. Between 110m and 750m wind-speed is seen to increase by an average of 30%. The wind speeds at 110m are within 1m/s of observed wind-speeds at the two sites. Radiosonde data for a separate site shows a 45% increase in windspeed between 110m and 745m. The power law equation show a close fit to Reanalysis I data for windspeed at 750m.

The kite-based system is an appropriate technology for extracting the wind-energy at high altitudes. The capacity factor calculated of 52% compares favourably with terrestrial wind-turbines with other potential benefits of a 74% lower embodied energy and lower cost per MWh.

These results are based on modelling and theoretical calculations. The reliability of these results needs to be tested by experimental methods using kites of increasing scale, at increasing altitudes and with different kite-steering mechanisms. This will be necessary to determine the correct balance of system components for maximum efficiency and dependability. Further work on the control systems required to manage such a flexible technology are a primary priority in the quest to harness the wind-resource at high altitudes.

5. Acknowledgements

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