High Altitude Wind Power

Goal

Develop a lower cost, higher capacity factor, higher power density wind energy system than current state of the art horizontal axis wind turbines.

Background

Recent advances in kite aerodynamics and control have resulted in extremely low mass, low cost, highly maneuverable kites which are now being used for ship propulsion and a new genre of kite powered sports such as kite boarding and kite buggying. The shipboard kite systems (Figure 1) are capable of producing thousands of horsepower of propulsive power to substantially reduce fuel use. Several independent groups (non-NASA) have begun to develop concepts for and prototypes of high altitude (>2000m) electrical power generation systems that can tap into the steady, high power winds of the middle and upper troposphere.

Figure 1
Kite Propulsion for Ships and Recreation

The potential advantages of the high altitude systems over current state of the art wind turbines are:

1. **Higher wind energy per unit area -** This is mainly due to the higher wind velocities available at high altitudes [Figure 2]. As wind power is a function of velocity cubed, the higher velocities result in a much higher wind energy density. Available wind energy density at 10000 meters altitude can be 2 orders of magnitude higher than those at the current average turbine height of 50 meters [Figure 3].

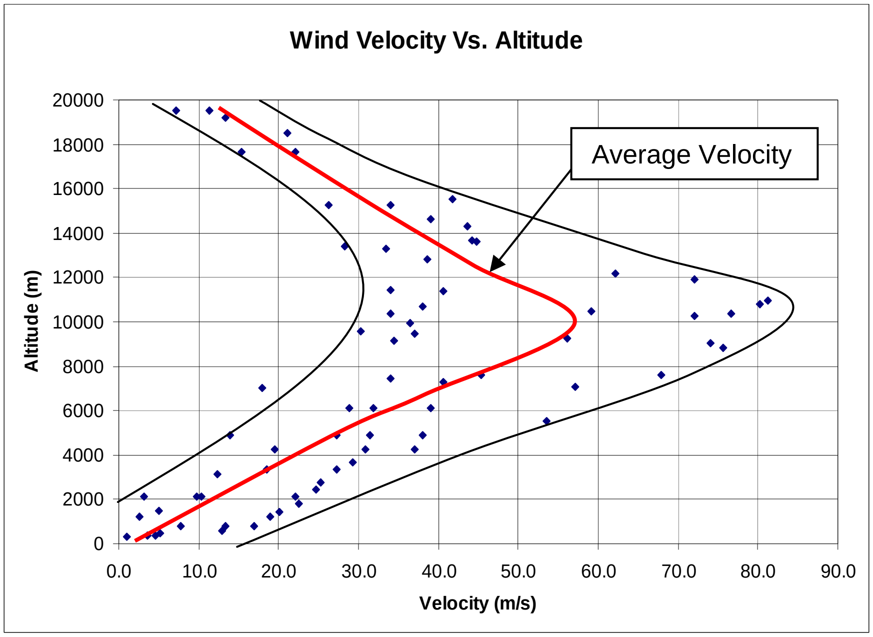


Figure 2
NOAA Radiosonde Data from a Random Sample of U.S. Sites

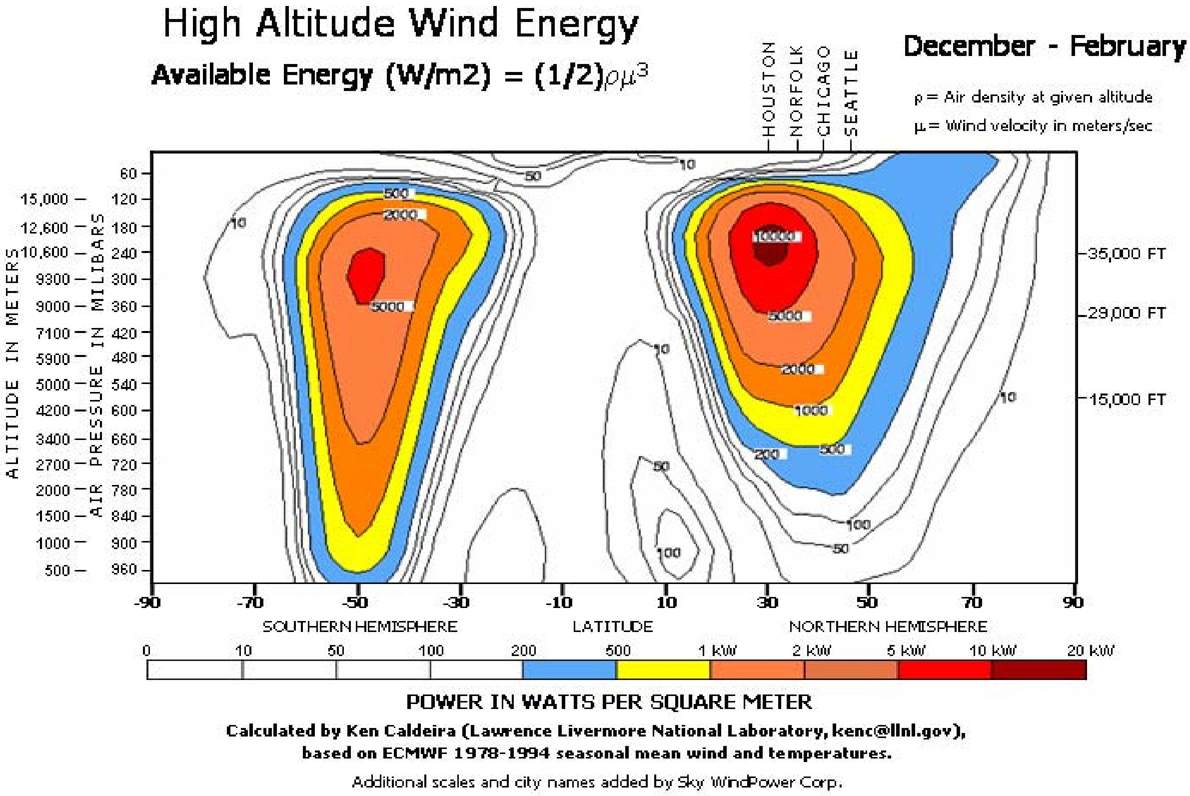


Figure 3
Wind Energy Density as a Function Altitude and Latitude

2. **Higher capacity factor-** Due to the planetary boundary layer, surface winds are turbulent, intermittent, and slow. These properties of low altitude winds pose major problems in the design of ground based wind turbines. Wind velocity intermittency and limited wind velocity operating range due to structural constraints for tower mounted wind turbines result in low capacity factors (average power output / rated power output) and unpredictable power supply to the grid, drawing into question the penetration capability of wind power. Some experts believe wind power market penetration can never exceed more than 20% of the overall electrical power supply (currently it is at 1%). High altitude winds are both strong and steady with much less turbulence and daytime to nighttime velocity variability. Several studies have shown that capacity factors for high altitude winds systems would most likely be in the 70-80% range vs. 20-30% for ground based wind turbines.

3. **Lower cost –** Kites, being a simple tensile membrane structure with a tether, have the possibility of drastically reducing the capital expenditure for wind power systems. Generator costs would be comparable to wind turbine generators, but weight constraints and maintainability are much improved for the kite/tether generator because it is mounted at ground level. Current best estimates for this type of system project a life cycle cost at 0.5 to 1.5 cents per kilowatt hour compared to current costs of 5 to 12 cents per kilowatt hour.

4. **Siting –** Current wind power statistics at 50 meters altitude show that only a fraction of the land area of the United States is suitable for large scale wind farming [Figure 4]. Most of these regions are in western states which are far from populated areas or are offshore. However, the subtropical jet stream which typically is found between latitudes of 30 to 50 degrees north covers large portions of the northern region of the U.S. including the densely populated areas of the Midwest and Northeast [Figure 5].

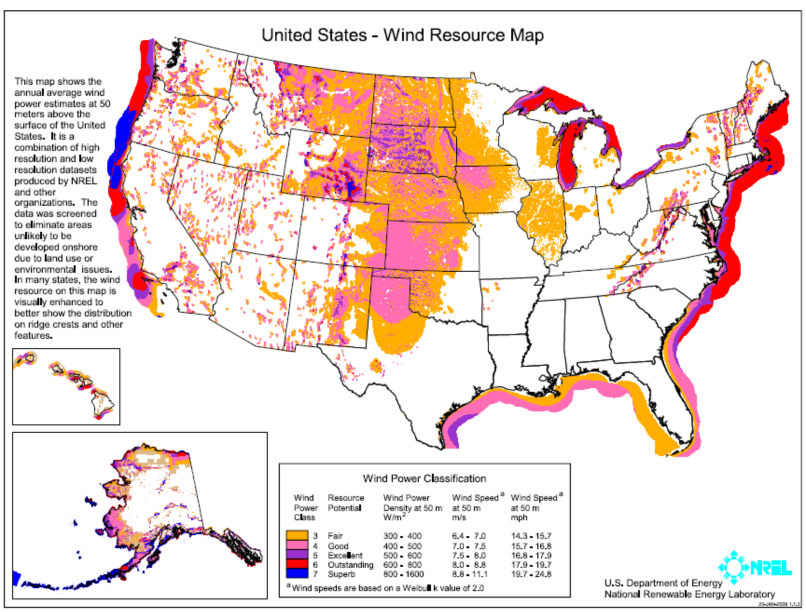


Figure 4
U.S. Wind Resource Map

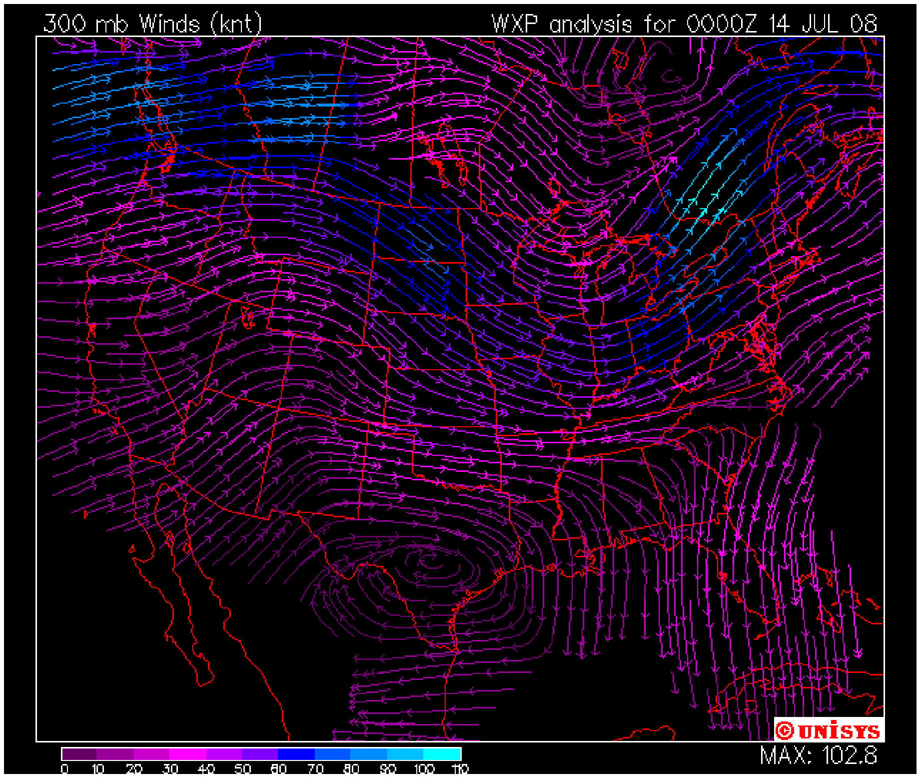


Figure 5
Typical Snapshot of Jet Stream Wind Velocity at 10 km Altitude

<u>Current High Altitude Wind Energy Concepts</u>

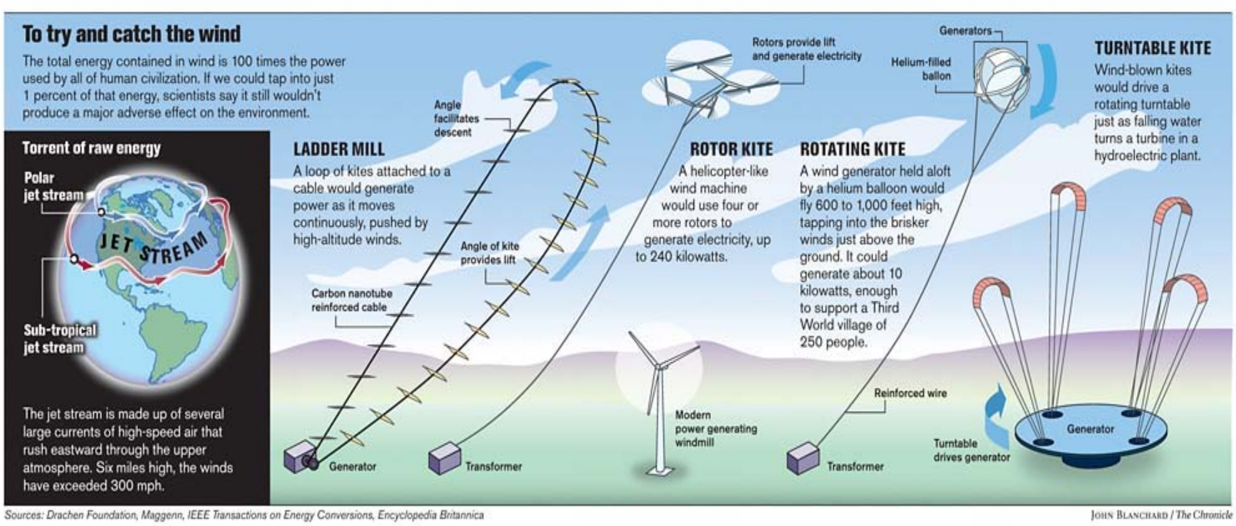
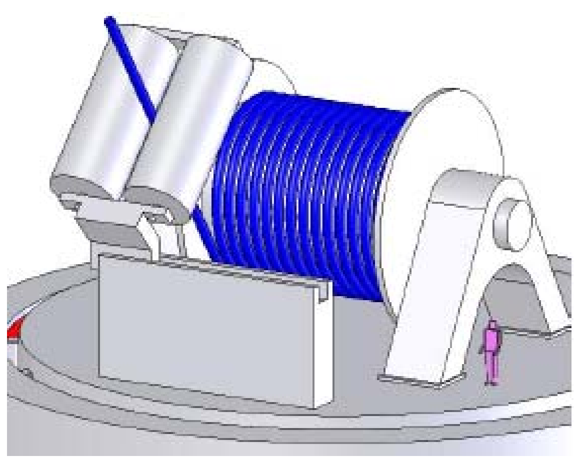


Figure 5
Several Concepts for High Altitude Wind Power Generation

The “Pumping” Laddermill or Kite Reel

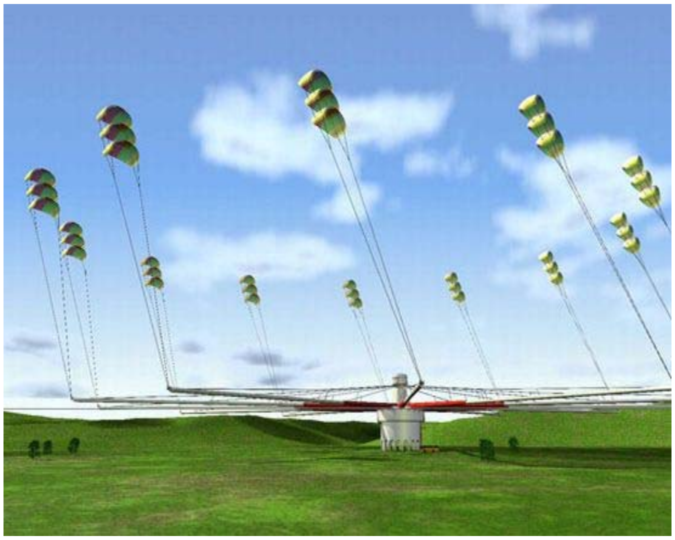
Originally conceived by David Lang, research is being performed by Dr. Wubbo Ockels, a former ESA/NASA astronaut, at Delft University, Netherlands. A low tech approach to high altitude energy, this alternative envisions a stable kite with hard, steady pull. The kite is simply reeled out, then in, using a capstan connected to a generator. During the reel-out or power stroke, the kite is at a high angle of attack and pulls at maximum load. It is then depowered by lowering the angle of attack and reeled back. Power is harvested from the net energy gained during reel out, less than required to reel in. Electrical and mechanical components required are simple. The concept is scalable by increasing kite area and by stacking kites. It is considered to be the most likely to succeed of the many high altitude energy concepts that have been proposed due to its simple nature and higher technology readiness level.

Airfoil Control System Concept



Laddermill Groundstation Concept

KiteGen



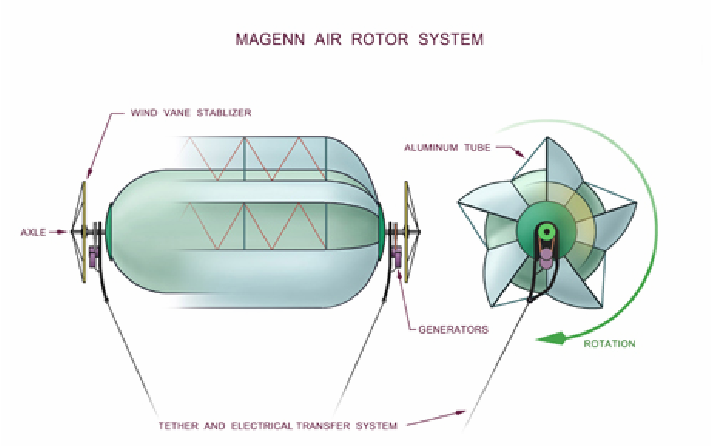
This concept uses a large number of computer-controlled kites to turn a large rotating structure connected to a central generator. Kites would fly at 800 to 2000 meter altitude. Analysis has shown potential to generate up to 1 GW per generator. This concept is currently being developed in Italy by Dr. Massimo Ippolito. Recent prototypes demonstrate sophisticated automatic kite control technology for single kites which will be required for the full-up multiple kite system.

FlyGen

Small Scale FlyGen Prototype

This scheme harnesses the power experienced in traction kiting. It depends upon a maneuver common to traction kiting, the figure-8, in which the kite dives from high to low altitudes. The resulting increase in speed induces high relative winds at the kite and thus high dynamic pressures which result in high lift on the kite, experienced as high tension in the kite lines. A kite with high lift-to-drag ratio is critical to the success of this technique. In this scheme the generators are attached to the kite and are airborne (thus the name Fly Gen). Being developed under a $10 million Google grant to Makani Power Inc..

Magenn



The Magenn concept uses a lighter-than-air helium balloon that is shaped to act as a horizontal Savonius rotor. The generators are located on the balloon which limits their size. The design is mainly for local small-scale power production and is geared toward use in developing countries.

Flying Electric Generator

The Flying Electric Generator (FEG) concept is similar to a gyrocopter that is flown as a kite. Large rotors provide lift for the device to fly at high altitude and also turn generators which are mounted in the structure. Power is transferred to the surface via a conducting tether. Note: This concept is not a flexible wing concept but has aspects similar to the concepts listed above.

Approach for Langley Research Center

1) **Phase 1 (Tier 1)** – Duration: 2 months – Cost: $20K - LaRC Systems Analysis and Concepts Directorate will perform a rigorous systems analysis of current concepts for high altitude energy production. Figures of merit (FOMs) for ranking will include technology readiness, cost, complexity, and LaRC research “fit”. The rankings will allow for “triage of concepts” for focusing future work.

2) **Phase 2 (Tier 2) - Concept development and working prototype** - Duration: 2 years– Cost: $2 - 4 million – The leading concept from phase 1 will be developed into a working design. Prototypes for wind tunnel and field testing will be built. LaRC may choose to collaborate with other NASA centers and/or the research groups mentioned above.

Technical Challenges

The technical challenges for high altitude, tethered flexible airfoil wind energy include:

1) Aerodynamic control of flexible airfoil for maximum energy extraction
2) High altitude airspace restrictions
3) High strength-to-weight ratio tether materials
4) Reversible reeling / generator systems
5) Airfoil / tether recovery and deployment methods (permanent deployment with lighter-than-air features)
6) Optimum power station siting for jet stream

Langley Research Center Organizational Fit for High Altitude Power Research

LaRC is uniquely qualified for research in the field of high altitude energy especially in the field of flexible wing aerodynamics and control. Dr. Francis Rogallo, a NASA Langley researcher in the 1950's and 1960's, pioneered the use of flexible airfoils which has led to the modern high performance inflatable leading edge bow kite. LaRC has extensive low-speed wind tunnel facilities for kite aerodynamics testing [Figure 6]. LaRC also employs aerodynamicists that specialize in low-speed flexible structure aerodynamics.

LaRC Organizational Matches to Areas of High Altitude Energy Research

- Flexible aerofoil aerodynamics (Aerodynamics Research Directorate)
- Aerodynamic control systems (Aerodynamics Research Directorate)
- High tensile strength tether materials (Research and Technology Directorate / Materials)
- High strength flexible airfoil materials (Research and Technology Directorate / Materials)
- Concept generation and evaluation (Systems Analysis and Concept Directorate)
- Systems analysis and optimization (Systems Analysis and Concept Directorate)
- Tether reeling and generator ground station design (Systems Engineering Directorate)

Figure 6
LaRC Has Several Wind Tunnels Suitable for High Altitude Energy Research