CONCEPTUAL DESIGN OF A MARTIAN POWER GENERATING SYSTEM UTILIZING SOLAR AND WIND ENERGY

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Abstract

An all-solar manned mission to Mars must overdesign the photovoltaic array in order to handle dust storm conditions. Wind energy extraction is proven terrestrial technology which can offset the dust storm (and night-time) reductions. A multi-phase project is underway to assess the feasibility and drive the development of wind energy extraction systems for Mars. This project has specifically addressed the design of a Darrieus-style Vertical Axis Wind Turbine (VAWT). The project assumed that wind energy extraction would be a secondary production system to the photovoltaic array. Energy production of 300 kW-hr per Martian day is required for this application. The wind turbine is designed by iteratively stepping through the following tasks:

1. Choose a blade shape;
2. Calculate the aerodynamic loads (primarily to estimate performance);
3. Design the guy cables;
4. Design the blades;
5. Design the tower; and
6. Choose support equipment.

The resulting system was estimated at 944 kg. Based on the feasibility assessment mentioned above, a wind speed of 28 m/s or higher must be seen for at least an hour each day. This wind speed is in the realm of possibility as the expected slope winds on Mars will likely be this high or higher. In order to meet this feasibility, the following design trends were seen: low pre-tension guy wires; ultralight blades; and thin lightweight towers. This work also found that if 25 to 35 m/s winds are available for at least one hour during a Martian day (during a dust storm), then wind energy extraction can be expected to be at least as mass-efficient as solar arrays (during a dust storm). Significant issues such as structural dynamics, thermal expansion/contraction, fatigue, blade struts, deployability, and maintainability were not considered at this time.

Introduction

The objective of the project was to produce the conceptual design of a power generating system for Mars, which combines solar and wind energy. The design of the wind power generating system was of primary concern. The wind and solar power generating systems are excellent methods for the utilization of the available natural resources on Mars. However, these energy sources are highly variable. The production of energy through solar arrays is dependent on the availability of sunlight. Similarly, the production of energy through wind turbines is dependent on favorable wind conditions. With an atmospheric density 1/75 of the Earth, Mars would at first appear to be an unlikely candidate for wind energy. However, the extraction potential of power from the wind is a function of velocity cubed and only proportional to density. Therefore, high winds can make-up for low density. Fortunately, some models suggest that Mars is subjected to regular high velocity winds in some locations. Additionally, these winds are expected to operate at night and during dust storms (times when solar energy is ineffective). A study of the wind energy option has been initiated and is currently underway with input from a variety of organizations including the University of Houston, NASA-JSC, Sandia National Laboratories, the Texas Space Grant Consortium, and ETM, Inc. (James, et. al., 1999). The overall project includes several phases:

(1) an initial assessment of the solar and wind resources,
(2) an assessment of the energy needs for various applications,
(3) a conceptual design of a traditional Horizontal Axis Wind Turbine (HAWT),
(4) a conceptual design of a traditional Vertical Axis Wind Turbine (VAWT),
(5) development of novel construction and wind turbine design concepts,
(6) a feasibility assessment of power generation using a solar/wind hybrid system, and
(7) the specific development of Martian as well as terrestrial systems.

The immediate objective of this work is to provide mission planners with sufficient information to consider the inclusion of wind energy in Mars mission planning and to target precursor mission objectives. The design work presented in this report primarily addresses phase four of the above list. However, aspects of the other topics listed above will be discussed as they relate to primary objectives of this work. The final design will be used to drive feasibility studies of the solar/wind production concept as well as to drive the development of novel construction/design concepts that will further enhance the feasibility of *in-situ* Martian power-production systems.

Supporting Information

Initial Assessment of Solar and Wind Resources

Martian Solar Energy Resources

Solar power will make an essential contribution to the success of Martian missions. Solar power is abundant, cheap, and does not involve safety concerns. More importantly, proven technology for its application in space missions already exists. The use of solar arrays made up of photovoltaic cells is the most ideal solar power generating system for Mars since photovoltaic cells do not depend on a single point light source. In spite of all these positives, Mars is farther from Sun, has an atmosphere, prone to seasonal dust storms and dust accumulation, and Mars' orbital eccentricity make solar power a highly variable source. These factors must be carefully considered in designing a solar power generating system for Mars.

The incident radiation on Mars (irradiation), S is given by

{ EMBED Word.Picture.8 **}**
(1)

where μ is the cosine of the solar zenith angle, $S_0 = 590$ W/m^2 is the solar irradiance at Mars' mean distance **{** EMBED Equation.3 **}** from Sun (Haberle, et. al. 1993). This solar irradiance is subject to high seasonal variations due to Mars' high orbital eccentricity relative to that of earth. The maximum available irradiance at perihelion (point of orbit nearest to Sun) is 717 W/m^2, whereas at aphelion (point of orbit farthest from Sun) the maximum available irradiance drops down to 493 W/m^2 (Haberle, et. al. 1993). The daily average insolation **{** EMBED Equation.3 **}**is described by the following equation:

$$\overline{S} = \frac{S_0}{\pi}\left(\frac{\overline{r}}{r}\right)^2 \left(\cos\delta\cos\theta\sin H + H\sin\delta\sin\theta\right) \qquad (2)$$

where θ and δ are latitude and solar declination and H is the half day length. According to Haberle et al the least variation is observed at low latitudes of northern hemisphere and most variation is observed at high latitudes of southern hemisphere (Haberle, et. al., 1993). The amount of solar radiation available is also impacted by the Martian atmosphere as it allows radiation only with wavelengths greater than 200 nm to pass through. The dust particles suspended in the atmosphere scatter the incident radiation and cause a major degradation in the availability of solar power. Figure 1 illustrates the effects listed above. The Viking 2 lander data was used in this example (James, et. al., 1998). The upper left hand plot provides the estimated solar insolation calculated above the Viking 2 lander site. The effects of orbital eccentricity and solar zenith angle variations are seen. Although, this calculation did not depend on measured data, the drop-out regions correspond to times during which the Viking 2 lander was not providing data. The data represents approximately 1.3 Martian years. The upper right hand plot provides the optical depth data as measured by the Viking 2 lander. The higher optical depth values denote times of a dust laden atmosphere. The normalized net irradiance function estimates the solar energy reaching the surface. The instantaneous power, which would have been produced by an 1850 m^2 photovoltaic array with 20% efficiency, is provided in the lower right hand plot.

In addition to the atmospheric conditions impacting the availability of sunlight for use in photovoltaic cells, other factors also effect the performance of solar arrays. The solar cells give the best output at temperature ranges of 150 K to 200 K (Haberle, et. al., 1993). Large solar arrays must be able to withstand wind loads under high winds and wind-blown dust can cause abrasion on the surface of the cells. Dust accumulation resulting from dust storms is one of the major concerns in the use of solar arrays. The performance of the solar cells will undergo significant decline if several monolayers of dust are deposited on the surface. The estimated decline for a two year period is 77 percent (Landis, 1997). Therefore, adequate provisions for dust removal are necessary to harness maximum results from the use of solar arrays.

Martian Wind Energy Resources

Wind results from the motions of the air in the atmosphere which is caused by the variable heating of air from the sun. The wind speed at the surface is zero, it increases with height rapidly when close to the surface, and the rate of increase declines with greater height. The variation of the wind speed with height can be estimated using a power exponent function

{ EMBED Equation.3 **}** (3)

where z is height above the surface, V_r is the wind speed at the reference height z_r above surface, V(z) is the wind speed at height z, and α is an exponent which depends on the roughness of the terrain. Therefore, the above equation can be used for estimation of the mean wind velocity at a certain height, if the mean wind velocity at a reference height is known (Walker and Jenkins, 1997). This relationship is demonstrated in Figure 2.

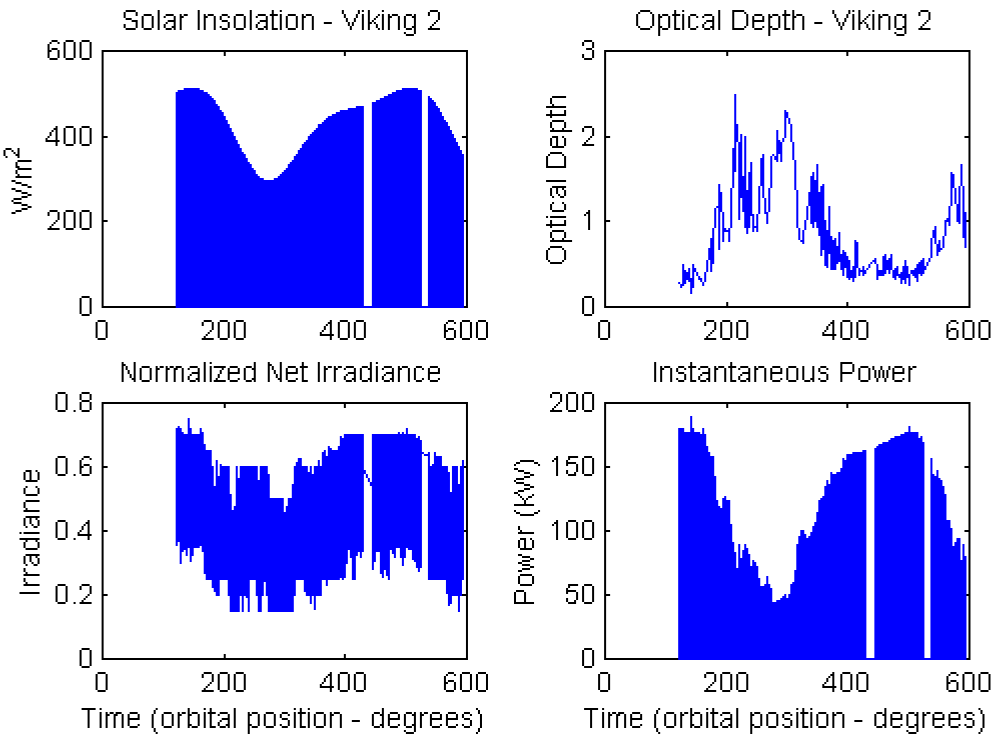

Figure 1. Variation in solar power at Viking 2 Lander Site (Source: James, et. al., 1998)

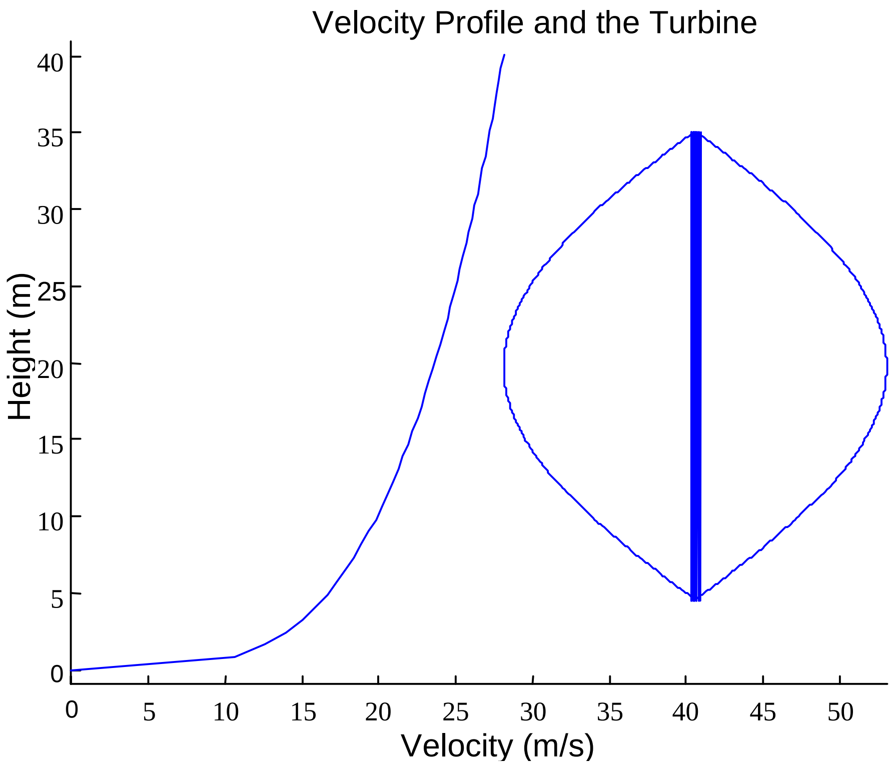

Figure 2. Wind velocity profile compared to local height of the wind turbine.

The wind velocity profile in Figure 2 is typical of the wind velocity profile expected during Martian slope wind conditions. The winds are expected to be nightly conditions which result on the slopes of the large Martian shield volcanoes as well as other regions of low angle yet long distance slopes (Magalhaes and Gierasch, 1982). These winds are predicted to have velocities of 25 to 33 m/s at 25 meters above the surface. These winds have been analytically reproduced using data generated from measurements made by the Viking 1 lander (James, et. al., 1998). There are also suggestions that large diameter craters may produce an increase in wind velocity above the ambient flow (Haslach, 1989). Note that Figure 2 also includes (for comparison) a schematic of a 25 meter tall VAWT positioned five meters off of the ground.

In order to design a wind turbine we must also focus on two fundamental concepts – energy, and power, or energy per unit time. The kinetic energy in a flow of air through a unit area perpendicular to the wind direction is $\frac{1}{2} mV^2$. The power associated with this flow is

$$P = \frac{1}{2} \rho A V^3 \tag{4}$$

Where, ρ is the density of air (Martian air density is 1/75 of that on earth), A is the area, V is the wind speed, and P is the power produced. The above equation can be used to calculate the power density for a given wind speed. It must be pointed out that the wind speed on Mars is equivalent to much lower wind speeds on earth. Figure 3 displays the relationship between the Martian and terrestrial wind velocities.

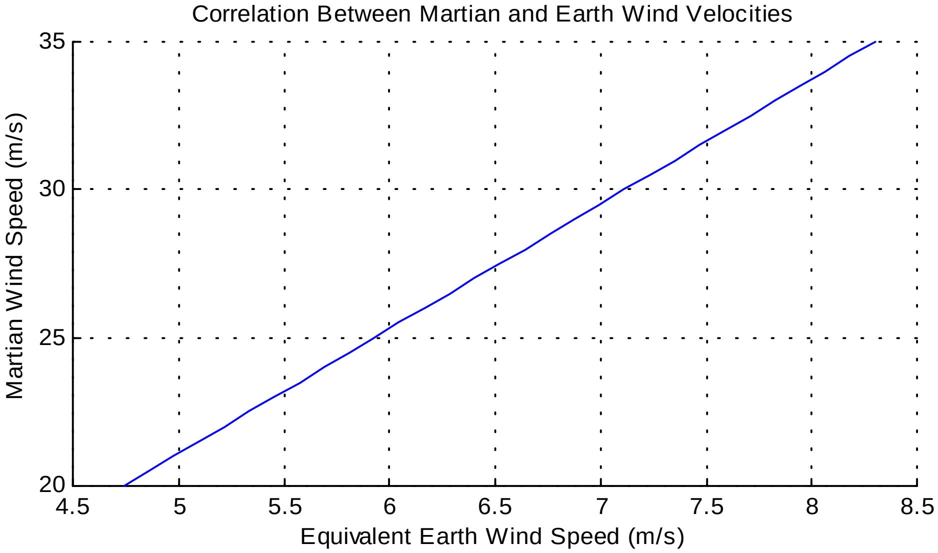

Figure 3. Relationship between the Earth and Mars wind velocities.

Only a portion of the total available energy can be converted to useful energy by a wind turbine. The power available to a wind turbine is equal to the change in kinetic energy of the air as it passes through the rotor. The fraction of energy extracted by the wind turbine from the total available energy is called the coefficient of performance C_p, given by

$$C_p = \frac{1}{2} (1 - b^2)(1 + b) \tag{5}$$

Where, b is the ratio of upstream and downstream wind speeds (refer to Figure 4).

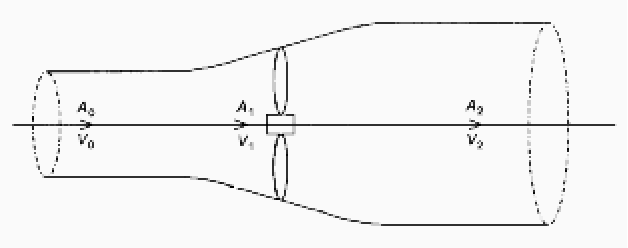

Figure 4. Typical air flow through a wind turbine (Source: Walker and Jenkins, 1997)

$$b = V_2/V_0 \qquad (6)$$

Differentiation of C_p with respect to b shows that this coefficient is maximum when b=1/3, giving

$$C_p \approx 60\ \%$$

The above value of coefficient of performance is known as the Betz limit. Hence, the real power output of a wind turbine is given by

$$P = C_p\,(½\ \rho A V^3) \qquad (7)$$

Modern designs of wind turbines operate at C_p values of about 0.4. The above equation does not actually produce a true cubic relationship between the power output and wind speed because C_p varies with the wind speed. The above equation can also be used to determine the swept area of a wind turbine for a particular wind speed at a given coefficient of power.

Asessment of the Energy Needs

Wind Energy Applications

Some critical objectives of initial manned Mars missions will be to establish a human habitat, power life support systems, enable science and exploration activities, and produce propellant. The achievement of these objectives is dependent on the ability to generate sufficient power to meet the energy needs of the systems and processes involved. The type and design of a power generating system is interrelated with specific mission scenario considered. However, the following three energy needs are assumed for a Mars mission: baseline life support, science/exploration activities (such as rover operations or drilling), and ascent vehicle propellant production. The relative requirements and timing of these needs will determine the niche wind energy will fill. As such, the following niches for wind energy generation in the manned Mars mission planning and implementation are assumed:

1. as a tertiary power supply in a primarily nuclear mission to enhance the safety and reliability as well as limiting abort-to-orbit scenarios;
2. as a secondary power supply in an all-solar mission to lessen the effects of dust-storm power reductions;
3. as a primary power supply in an early Martian settlement with rudimentary *in-situ* construction capabilities;
4. as a mobile power supply option to enhance and/or enable long-distance rover operations; and
5. as a cooperative power supply to enable non-nuclear unmanned precursor mission of extended surface duration.

This project will consider only scenario number 2 listed above.

Energy Needs for an All-Solar Mission

The current estimates of energy needs for an all-solar mission call for an energy budget of 17 kW continuous energy during the day and 9 kW continuous energy during the night for clear conditions (George, 1999). This includes 1 kW continuous energy during the day for rover operations. During dust storm conditions, the daytime utilization needs drop to 16 kW continuous, as rover operations will be curtailed. Hence, the baseline energy needs for an initial outpost are assumed to be 16 + 9 = 25 kW continuous during daylight hours (assuming no energy storage losses). Hence, if a Martian day is assumed to be 12 hrs per day, the daily energy needs are 25 x 12 = 300 kW-hr. Therefore, for 600 Martian days, total baseline energy requirement is 600 x 300 / 1000 = 180 MW-hr.

However, due to losses during dust-storms (radiation reaching the array may drop to 15% of clear condition values), an all-solar mission must utilize a solar array eight times larger than needed for the baseline requirements during clear conditions. Given this requirement, the daily solar power produced during clear conditions is 8 x 300 = 2400 kW-hr. Assuming that dust storms could operate for up to 150 Martian days, the total energy production over 600 Martian days with such a production system would be: (450 x 2400 + 150 x 300) / 1000 = 1,125 MW-hr.

Additionally, daily rover operation requirements during a clear 12 hour day equals 12 kW-hr. Over the course of 450 clear Martian days, the total rover energy requirement is 5 MW-hr.

Also, (Baker and Zubrin, 1990) and (Zubrin, et. al. 1991) propose that 107 tons of methane/oxygen propellant (for ascent and Earth-return) can be produced on Mars from 5.7 tons of hydrogen brought from earth and carbon dioxide from Martian atmosphere. The energy needs for this activity are 370 MW-hr over the 600 day mission. There is expected to be sufficient excess energy production during clear conditions to meet these needs.

Hence total energy needs for the entire 600 day mission is 180 + 5 + 370 = 555 MW-hr. Therefore, the excess energy production is 1,125 – 555 = 570 MW-hr. The utility of wind energy production systems in an all-solar mission would be to allow the reduction of mass (and therefore cost) of the solar arrays needed to meet dust storm conditions.

Design of a Horizontal Wind Turbine

Wind turbine designs can be categorized into two different groups – turbines that depend on aerodynamic lift and turbines that utilize aerodynamic drag. For the same swept area the power produced by lift type turbines far exceeds the power generated by drag type turbines. Therefore, due to size constraints on the wind turbine design for Mars, the lift type turbines are preferable. Some of the other important features of the two types that need to be considered in a Martian wind turbine design are listed below:

Drag Type Turbines:
- mainly low speed devices driven by drag forces acting on the rotor
- move slower than the wind, and their motion reduces power extraction
- torque at the rotor shaft is relatively high
- examples include traditional windmills and pumping devices

Lift Type Turbines:
- mainly high speed devices driven by lift forces on the blades
- linear speed of blades is generally faster than the wind speed
- torque on the rotor shaft is relatively lower
- examples include modern electrical power producing turbines

(Walker and Jenkins, 1997).

The wind turbines can be further classified into horizontal axis and vertical axis machines. The horizontal axis or propeller type turbines are more abundant and this technology is highly developed. The previous work by (Ferrell, et. al., 1998) considered an 18 meter diameter Horizontal Axis Wind Turbine (HAWT) which would produce 2.5 kW in a wind speed of 13 m/s. Alternatively, a 30 meter diameter turbine in a 25 m/s wind would produce 28 kW. This design effort suggested that wind turbines with sizes approaching large utility scale terrestrial wind turbines would be required. However, the chord lengths would be three times the values for similar turbines on Earth. Likewise, the thickness to chord ratio could be expected to be 1.5 times that of terrestrial turbines. Also, the power output (and imposed torque values) would be 1/10 the values seen on terrestrial turbines of a similar size.

Design Approach and Results

Design of a Vertical Axis Wind Turbine (VAWT)

This project will design a Darrieus type Vertical Axis Wind Turbine (VAWT) for energy production on Mars. There are some specific advantages associated with the vertical-axis machines, especially the Darrieus type, making the design concept potentially more suitable for a Martian application:

- their symmetry about the vertical axis allows them to operate independent of the wind direction, so a yawning mechanism is not required
- heavy gearboxes and generators may be situated at ground level permitting easier maintenance, a low support platform, and easier deployment
- the device is shaped such that centrifugal loads are balanced by pre tension forces in the blades, thus avoiding bending moments; thus, the turbine shaft carries axial and torque loads only
- the blades do not suffer fatigue stresses from gravitational forces during rotation

(Walker and Jenkins, 1997).

Additionally, the Darrieus VAWT may be much more amenable to a deployable installation.

In spite of the many advantages associated with the Darrieus type vertical axis wind turbine, some of the accompanying drawbacks listed below cannot be overlooked because

- they are not self-starting
- the torque fluctuates during each revolution as the blades move into and out of the wind
- speed regulation at high wind speeds can be difficult.

The next section discusses the steps used in the turbine design.

Typical Darrieus VAWT Configuration

The rotor subsystem consists of two curved blades whose ends are attached to fixed upper and lower hubs. The hubs are attached to the rotor column or the tower. The blades are symmetrical in cross-section and they have a troposkien shape that results in a minimal internal bending stress. The rotor height is usually 15% to 30% larger than the rotor diameter. The power train subsystem consists of mechanical and electrical equipment to convert the rotor's mechanical power into electrical power. The essential power train components are a turbine shaft, a gearbox to enhance speed, a generator drive shaft, a rotor brake, and an electrical generator. All these components are located close to the ground thereby permitting convenient maintenance and deployment. The proximity of the components to the ground also leads to a low support platform. The support structure subsystem consists of a support stand, three structural cables, and the upper and lower rotor bearings. The support cables connect the top of the tower to the ground anchors at an angle of elevation ranging in between 30 to 40 degrees thereby providing stability to the tower by restraining the movement of its center of the mass (Spera, 94). The cable tension results in a downward thrust load on upper rotor bearing which is ultimately transferred to the system foundation through the rotor column, lower rotor bearing, and the support stand. The height of the support stand is such that it provides sufficient ground clearance for the rotating blades.

Wind Turbine Design Process

Overview

The wind turbine design process utilized in this work is based on a series of performance analysis steps covering the major aspects of the wind turbine design. These steps include defining the blade shape, calculating the aerodynamic loads (primarily used to estimate conversion efficiency), design of the guy cables, calculating the axial blade loads, tower design, and estimation of support system mass. As with most design exercises, these steps were performed iteratively. However, the process and the results will be discussed sequentially in this section.

Blade Shape

Darrieus-style VAWTs typically utilize blades shaped to minimize bending stesses (Eggars, 1991). The shape of the blade excluding the effects of gravity is:

$$R = \cos(y/\sqrt{R_{CE}}) \tag{8}$$

where R is the blade radius, y is the height along the tower, and R_{CE} is the radius of curvature at the equator.

Figure 5 shows a typical Darrieus-style VAWT with two blades shaped using the above equation.

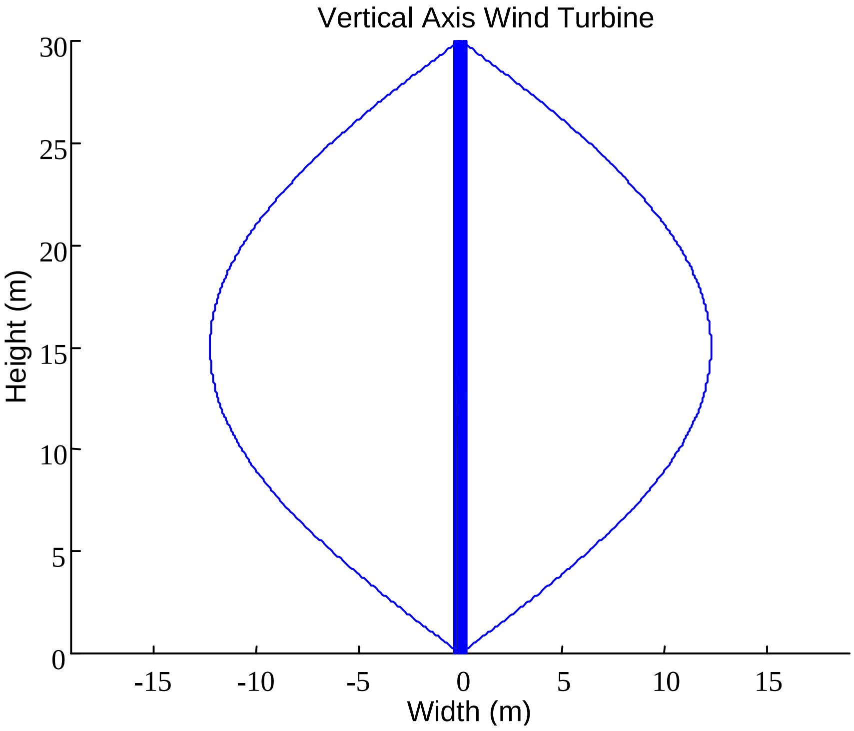

Figure 5. Shape of the Darrieus-type wind turbine.

Aerodynamic Loads

The aerodynamic loads and performance were calculated in this work using the double-multiple-streamtube model as presented by (Paraschivoiu, 1982). Multi-streamtube modeling considers the volume represented by the revolution of the rotor as a series of adjacent, aerodynamically independent stream tubes. The torque and normal forces generated by aerodynamic lift and drag forces are estimated and used to calculate overall turbine performance. It should be noted that the procedure was limited to small set of airfoils designed for terrestrial conditions. Also, the lift and drag coefficients that were calculated for these airfoils may not be completely accurate for Martian conditions. And finally, the double multiple streamtube model is most appropropriate for low solidity turbines (solidity is the ratio of blade chord to total swept area). This may have caused some inaccuracies in the results as the final design had a relatively high solidity.

The performance of the wind turbine was determined using SLICEIT computer code as developed and provided by Sandia National Laboratories (Berg and Rumsey, 1991 and Berg, 1992). The computer program is in FORTRAN consisting of a main program and several text files which store airfoil and input data fields. The program allows a model to be created based on existing data by evaluating number of blade sections and interpolating as a function of the Reynolds number and the angle of attack. The program also uses Martian parameters such as the viscosity, and atmospheric and gravitational data to create a model. Several different airfoil families were included and evaluated by trail runs with the program SLICEIT. These airfoils had been specifically designed for terrestrial vertical axis wind turbines. These include the SNLA 0021/50, SNLA 0018/50, and the SNLA 0118/50. These airfoils were the first to be examined using the SLICEIT.

The calculations were made at 5 mph increments from 20 to a maximum of 100 mph wind speed. The program takes into account the effect of the boundary layer on the velocity profile by a user input of the empirical wind shear exponent. This was ignored in preliminary test cases but was added in later cases. A single airfoil type was used for the entire blade length on initial trial runs. However, the most efficient earth-based wind turbines use two or three different airfoils types along the length of the blade. After unimpressive results, a multiple airfoil type model was quickly adopted. The SNLA 21/50 and the SNLA 0018/50, located along the equatorial region and near the tower respectively, produced the largest power outputs. A chord length to radius ratio as a required input was determined through experimentation and correlating earth based wind turbine parameters. This ratio was also allowed to vary along the blade. The power extraction is obviously higher with three blades as opposed to two, but the added power output is often not worth the weight gain associated with the extra blade.

The final design included the two airfoil shapes (SNLA 0018/50 near the tower and SNLA 21/50 at the equator) and three chord lengths (3.2 m, 2.8m, and 1.8 m) along the blade. The turbine was chosen to rotate at 75 rpm. The turbine height was 30.5 meters and had a diameter of 19 meters. The turbine had a maximum coefficient of power of .59 and produced 14.1 kW in a 25 m/s wind.

Guy Cable Design

The proper design of guy cables is complicated and highly dependent on tower design, structural dynamics, static loads, and temperature cycling. However, (Sullivan,1979) provides some guidelines for an initial guy cable design. The main purpose of this system is to offset aerodynamic loads. Since these loads are an order-of-magnitude less than the corresponding loads on a similar-sized turbine on Earth, the suggested cable tension values were also decreased by an order-of-magnitude. It should be noted that this analysis did not include the critical issues of structural dynamics or thermal changes.

The final guy cables were chosen as aluminum (although no detailed materials selection process was performed). For this size turbine, (Sullivan, 1979) suggested 15,000 lbs of pretension. However, it was pointed out that the suggested values were conservative and successful applications existed with ½ of the suggested tension. Hence, 7,500 lbs was chosen as the appropriate value of tension for a terrestrial turbine. Since the aerodynamic loads on Mars are expected to be 1/10 of the terrestrial values, 750 lbs was chosen as the pretension value. Three cables were chosen with a 30 degree angle. A .004 meter radius was chosen. The resulting mass of the cable system was assumed to be 24 kg. An additional 50 kg was added for anchoring systems such as augers.

Axial Load on Blade

The calculations of the axial loads on the blades are examined as presented by (Eggars,1991). The initial calculation of axial loads on the turbine blades can be made without considering the aerodynamic forces normal to the turbine blade as the inertial forces tend to dominate. Equation 9 was used to estimate axial loads:

{ EMBED Equation.3 } (9)

where m is the mass per unit length of the blade, g is the acceleration due to gravity, Ω is the rotation rate, and R is the radius at height y, R_E is the radius at the equator, and R_{CE} is the Radius of curvature at the equator. Investigations of the effects of gravitational and inertial forces acting on the blades reveal that the effects of gravity on the blade are also modest in comparison to the inertial forces. To completely examine the effects of gravity and centrifugal loading, the mass distribution needs to be known. A force to mass per unit length ratio was assumed constant based on a requirement that the local stresses on the beam element are constant everywhere. This assumption allows a simplified model to be developed for the wind turbine to assess the effects of gravity and inertia. It should be noted that axial loads only were used to design the blade (material properties and wall thickness). Aerodynamic loads were not considered at this time. Structural dynamics issues were not addressed either.

It was quickly determined that an ultralight blade design was required in order to approach mass feasibility. Hence, the final design resulted in a thickness of .0005 m and a material density of 1100 kg/m^3. This material could be met with a variety of synthetic materials including nylon, rubber, neoprene, or polystyrene. It should be noted that such a design would invariably need to be inflated and supported with an internal frame or external strut. The next design iteration would necessarily include these structures. The mass of the blades was therefore 284 kg.

Tower Design

The parameters needed to define the tower include the optimal tower diameter , its wall thickness, the material, and the imposed axial load. The relationships, which take into, account the critical buckling loads, compressive stresses, and shear stresses, are found in (Sullivan, 1979 and Beer and Johnston, 1981). Neither, structural dynamics nor thermal changes were considered in the design. The final design was a .3 m diameter aluminum tube with a .002 inch wall thickness. Approaching mass feasibility was the primary driving factor in this design. The final design was 435 kg.

Total Mass

An additional 150 kg was added for support equipment such as the generator, gearbox, bearings, and brakes. Therefore, the total mass of the system was found to be 944 kg upon summing the estimated masses from the above sections.

Feasibility Verification

The feasibility of the initial design was evaluated using the energy to mass ratio of solar cells during dust storm conditions. The resulting solar array size for the scenario listed in the previous section is expected to be six to seven thousand square meters (George, 1999). The mass of such a system is estimated to be 11 to 13 metric tons. One half of this mass results from the solar cells and the support structure. Assuming a 12 metric ton system, this would suggest six metric tons of solar array. The remaining six metric tons would be dedicated to fuel cells and power conditioning equipment. Therefore, energy output for these arrays per unit mass during dust storms = 300/6 = 50 kW-hr per metric ton. For comparison, on a clear day the energy output per unit mass = 2400/6 = 400 kW-hr per metric ton. Hence the following relationship will be used to define feasibility of the initial design:

$$M_W \text{ (metric ton)} \leq (1/50)\, E_W \text{ (kW-hr)} = .02\, E_W \qquad (9)$$

where M_W is the mass of the wind turbine, and E_W is the energy produced in one day. The energy produced by the wind turbine would be estimated as the integrated value of power produced over a Martian day. A typical approximation is to define this energy based on the maximum wind speed the turbine sees for at least one hour in a given Martian day. Figure 6 shows the variation in the minimum sustained wind speed of 28 m/s needed to assure feasibility of the turbine design described above. It should be noted that this value falls in the range of the expected slope winds on the planet.

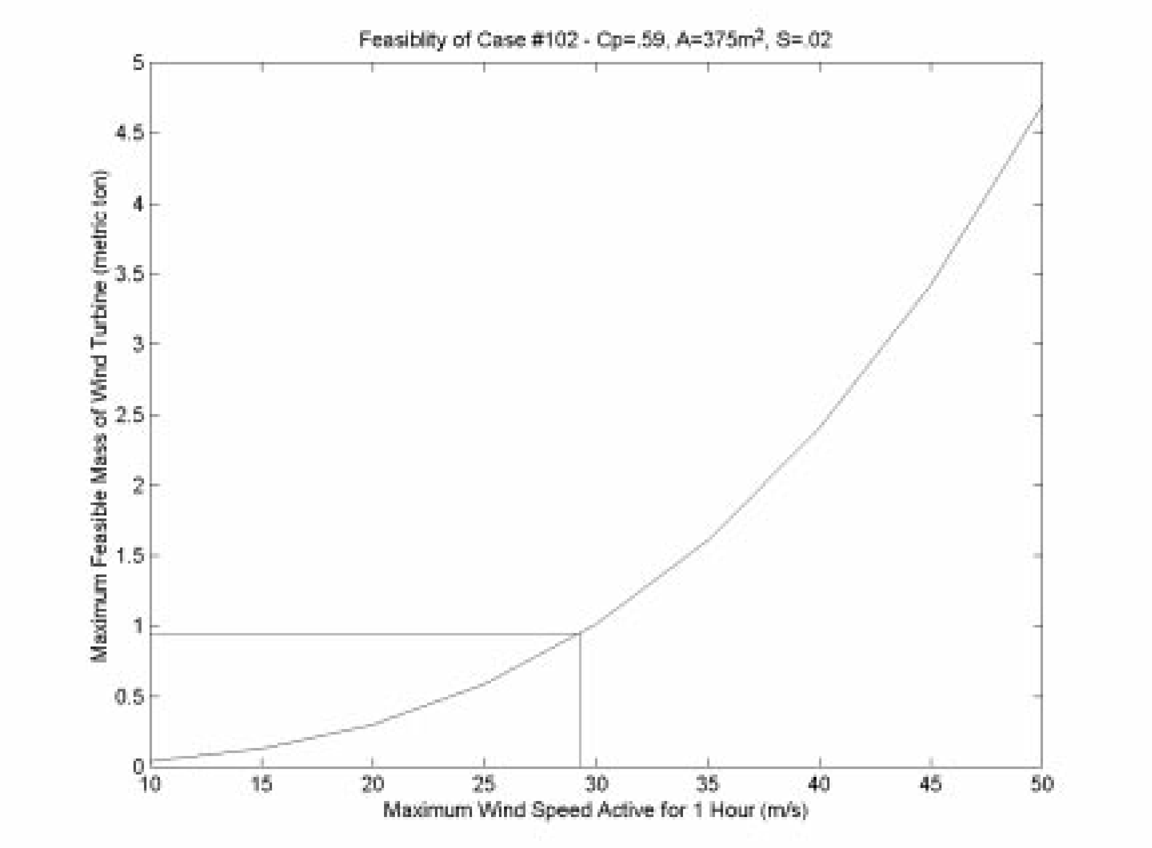

Figure 6. The mass feasibility curve for wind turbine performance characteristics determined from Test Case 102.

Feasibility of the system will include other aspects such as reliability, maintainability, packaged volume, and deployability as other design constraints. Although, these issues were not studied in detail in this work, some tantalizing directions to explore can be gleaned from the effort. Figure 7 illustrates a packaging deployability concept that can be considered given the design presented above.

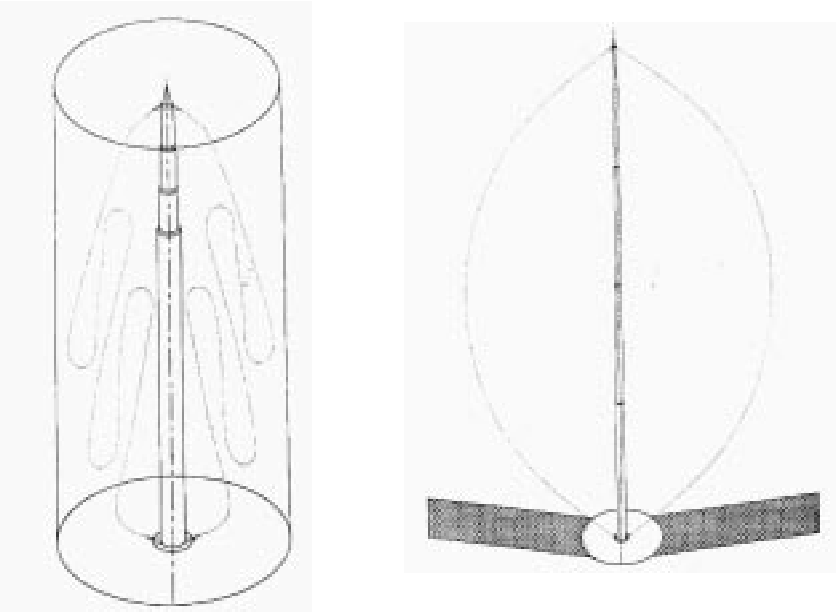

Figure 7: A conceptual design for a vertical axis wind turbine with inflatable blades and a deployable tower.

Conclusions and Recommendations

This project utilized modified tools drawn from the state-of-the-art in vertical-axis wind turbine design to study the feasibility of a wind power generation on Mars. The following findings were significant:

1. Wind energy generation is at least as mass-efficient as solar arrays in dust storm conditions;
2. The above statement is dependant upon the presence of regular high-winds which are sustained for at least an hour each night (especially during dust storm conditions);
3. Feasibility of wind energy generation on Mars will be enhanced by reducing the mass (or utilizing in-situ materials) in the structural systems;
4. This work suggests ultralight blade construction techniques, small guy cable tensions, and thin towers as viable design trends; and
5. Terrestrial design tools are useful in designing for Mars but care must be taken as the initial assumptions in the code development may be invalid.

The following recommendations may be made:

1. Ultralight designs should be developed for Mars including dedicated airfoil shapes;
2. Mission planning studies should explore the solar/wind energy option;
3. Options to perform wind energy mapping and system verification should be considered;
4. Ultralight terrestrial designs should be developed to gain operational experience and to fund development of the Martian systems; and
5. Modified terrestrial design codes and experienced wind energy technologists should be used as resources.

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