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DESIGN AND RESOURCE REQUIREMENTS FOR SUCCESSFUL WIND ENERGY PRODUCTION ON MARS

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ABSTRACT

Manned Mars missions (and some unmanned precursor missions) are expected to be long duration expeditions that rely on the utilization of *in-situ* resources to the maximum extent possible. Traditionally, nuclear energy has been suggested as the power supply of choice for such missions. However, in the event that nuclear power is unavailable, solar energy is the only alternative power source that has received significant study to date. Unfortunately, the periodic and long duration dust storms on Mars drive the need for extensive solar arrays to provide energy needs. This work considers the possibility that wind energy may provide a secondary power source in an all-solar mission.

Previous studies have shown that a viable Martian wind energy system must be ultra-lightweight, deployable, and robust. In this study, the possibility of meeting these criteria with buoyant wind energy conversion structures is studied. Conceptual designs have been assessed in terms of mass, volume, and power production. Based on current estimates of solar energy production efficiency during dust storm conditions, the design constraints on a complimentary wind energy system are determined. Using system mass per kW-hour as a figure of merit, the feasible wind speeds for three Martian buoyant wind energy conversion systems (a Savonius, a Darrieus, and a spherical) were determined and compared to previous rigid designs. The large sizes required for buoyant systems resulted in large turbines producing 10 to 30 kW in 25 m/s winds. The efficient inclusion of the buoyant chambers into the structure was found to be critical, as the mass of the balloon is significant. As a result the spherical system was seen to provide the best design. Although it is aerodynamically inefficient and untested, it was found to be feasible in a 29 m/s wind based on an estimated mass of 429 kg and 19 kW estimated power.

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MARTIAN WIND AND POWER PRODUCTION

Mars Energy Needs and Applications

A critical aspect of Mars mission planning is the development of efficient and cost effective sources of electrical power. Nuclear power represents the current baseline for long duration habitable missions. However, the technical and political issues of emplacing and maintaining a nuclear reactor on the surface might be detrimental to a near term Martian outpost. Alternatively, solar and wind-generating systems are secondary and tertiary options that utilize the readily available natural resources. Solar power is abundant, inexpensive, and can be used with few safety concerns or technological risks. However, solar power is a relatively variable source of energy since Mars is farther from Sun, has an atmosphere which is prone to seasonal dust storms, exhibits continuous surface dust accumulation, has a substantially eccentric orbit, and has a twelve hour night (Haberle et. al., 1993; Landis, 1997; James et. al., 1998). Power output, for example, from solar photovoltaic cells would be expected to degrade by up to 85% during dust storm conditions. In addition, findings from the Pathfinder mission have shown that dust accumulation can obscure as much as 30% of a given surface over a 100-day period (Landis, 1997). Hence, a manned all-solar Mars mission requires extremely large arrays that have built in routines for maintenance and cleaning.

Wind energy represents an alternative power source that can offset the size of the solar arrays by reducing dust storm interference (i.e., due to the increased scattering of incident light and dust deposition), and nighttime losses (James et. al., 1999). There are two primary lines of query that are needed in order to determine the feasibility of wind power production on Mars. First, in-situ measurements, global monitoring/prospecting, and analytical model development are needed to effectively characterize the Martian wind as a potentially extractable energy resource. Second, novel designs (and design tools) specifically suited to Martian environmental conditions are required to establish wind energy production systems.

Wind energy generation has several niches in Mars mission planning and implementation:

1. a tertiary power supply in a primarily nuclear mission to emphasize safety, reliability and mission success;
2. a secondary power supply in an all-solar mission to reduce the effects due to dust-storm power reductions and day/night cycles;
3. a primary power supply in an early Martian settlement with an emphasis on rudimentary *in-situ* construction capabilities;
4. a mobile power supply option to enhance and/or enable long-distance rover operations;
5. a cooperative power supply to expand the potential and duration of non-nuclear unmanned precursor missions; and
6. a stand-alone power source for the development of portable in-situ fuel and life support resource production facilities (i.e., methane, oxygen and water).

The work detailed herein is focused on determining resource needs and developing design tools and criteria chiefly to explore application number two above. However, the results are applicable to each of the scenarios listed.

The current estimates of energy needs for an all-solar mission call for an energy budget of 17 kW continuous energy during clear day conditions and 9 kW continuous energy during the night (Hemmet et. al., 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. However, due to losses during dust storms (solar 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. Hence, the daily solar power produced during clear conditions is 8 x 300 = 2400 kW-hr. (James et. al., 1999).

Therefore, for 600 Martian days, total baseline energy requirement is 600 x 300 / 1000 = 180 MW-hr. Additionally, daily rover operation requirements during a clear 12 hour day equals 12 kW-hr or 5 MW-hr for 450 clear days of the mission. Also, (Zubrin et. al. 1991) propose that return propellant can be produced on Mars at a cost of 370 MW-hr over the 600-day mission. Hence total energy needs for the entire 600 day mission is 180 + 5 + 370 = 555 MW-hr. Assuming a worst case scenario in which a planet encircling dust storm occurs for 150 Martian days (i.e., the entire length of the storm season), 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. Therefore, the excess energy production capability 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.

Environmental Conditions Favoring Wind Energy Production

With an atmospheric density 1/75 of the Earth, Mars would at first appear to be an unlikely candidate for wind energy. However, Mars has several advantages for successful wind energy extraction: less gravity (less massive components), large temperature and pressure swings (producing high winds), and tremendous surface relief and low atmospheric thermal inertia (produces consistent wind patterns). Also, the extraction potential for wind power is a function of velocity cubed and only proportional to density as shown in equation (1):

$$P = \_\ C\rho A v^3 \tag{1}$$

where, P is power produced;
C is an efficiency coefficient that ranges from .2 to .6;
ρ is the density of the Martian atmosphere;
A is the swept area of the turbine; and
v is the wind speed.

To date, the most direct observations of wind speed on Mars are limited to the Viking landers and from Pathfinder (as of the production of this paper). Wind speeds at these locations were observed to average about 5 m/s, with a peak of 25 to 30 m/s recorded at the Viking Lander 1 site (measured 1.6 meters above the surface). As observed from orbit, a local dust storm over Chryse Planitia accompanied these peak readings (Greeley, 1982). The Viking landing sites, however, were selected on the basis of mission safety, which precluded the exploration of the more complex or steep terrain that is more likely to harbor the high winds of interest. Other contributors to wind production, variation and localization include boundary layer turbulence, surface roughness, local topography and the traveling planetary waves that are responsible for short–period fluctuations in the daily averaged surface pressures and temperatures (Keiffer et. al., 1992). Computer models of the Martian atmosphere based on remote sensing data and extrapolations from the wind blown sand streaks on Mars have predicted significantly larger values for surface wind speeds (Haslach, 1989). It has been estimated that a well-chosen site could harbor sustained speeds approaching 14 m s^{-1}. Possible sites include the horseshoe vortices around raised rim craters (as seen by dark streaks), and natural wind channels due to the topography of hills and valleys (such sites have been used successfully on Earth). Also, regions such as Hellas basin (the lowest region on Mars) have up to a 44% denser atmosphere (and hence a 44% increase in power). These regions would be favorable sites if high local wind speeds can be identified. Long low angle slopes (as seen on the shield volcanoes or slopes of large basins or plateaus) may produce winds of 25 to 33 m s^{-1} at approximately 25 meters above the surface. It should be noted that the wind patterns at the Viking 1 landing site were believed to be dominated by this type of slope wind pattern (Zurek, 1992). Recent measurements made at the nearby Pathfinder landing site further support this conjecture (Schofield, 1997). Additionally, these winds are expected to operate at pre-dawn and during dust storms (times when solar energy is reduced or ineffective).

Our emphasis here is to develop the cursory design and analytical techniques used to support wind energy production for a manned mission in light of differential production levels between clear and dusty conditions. The effects of dust (solid, dark, μm diameter particles) and seasonal dust storms directly relate to the work at hand in that they affect both the performances of solar collecting devices as well as alter atmospheric structure and circulation patterns. Current theories (positive feedback models) show that increased levels of suspended dust may cyclically amplify the diabatic drive for wind production (Keiffer et. al., 1992). Dust storms of various size, distribution and place of origin have been recorded in observations since the late 1800's. Planet-Encircling dust storms have the propensity to directly affect surface solar energy production for up to several months at a time, and current data show that the storm season may be as long as 1/3 of a Martian year. Providing a solar alternative energy source that work within the boundaries of the aforementioned environment conditions and takes advantage of in-situ resources should prove to be more effective, efficient and cost effective.

WIND TURBINE DESIGN

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.

Drag type turbines have lower rotation rates than the corresponding wind speed with relatively high shaft torque. Lift type turbines have high rotation rates (linear speed of blades is generally faster than the wind speed) and low shaft torque (Walker and Jenkins, 1997). The lift devices are generally more efficient and therefore smaller for a given power output. However, the design of the airfoil components for the specific atmospheric and wind speed conditions are important. Also, the drag devices tend to produce power at lower wind speeds.

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. A Horizontal Axis Wind Turbine (HAWT) typically has blades that can pitch to extract energy over a broad range of wind speeds. However, the blades are cantilevered from the hub, which is at a significant height. Likewise the generator and critical rotating components are at height. HAWT's must be slewed into the wind unless the resource is relatively unidirectional. Our previous work considered an 18-meter diameter Horizontal Axis Wind Turbine (HAWT) that 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. This work utilized a modified code developed for terrestrial turbine design. Therefore, the airfoils and blade twist parameters were all optimized for terrestrial not Martian conditions (Ferrell, et. al., 1998).

A Vertical Axis Wind Turbine (VAWT) can accept winds from any direction. Also the primary generator and bearing components are located at ground level. A VAWT with straight lift type blades is called a giromill. Although a straight blade is more susceptible to rotational fatigue stresses, such a devise can change blade pitch to capture low speed winds. Haslach (1989) introduced a concept that called for a 17.25-meter tall giromill turbine situated atop a 21.5 meter landing vehicle with an estimated weight of 175 kg. Using an efficiency value of C = 0.47, as is common on terrestrial turbines, such a 200 m^2 turbine could produce 2 kW in a 14 m/s wind and 12 kW in a 25 m/s wind. The authors' previous work produced a Darrieus style VAWT with troposkien-shaped blades that was 30 meters tall and produced 14 kW in a 25 m/s wind. The turbine was designed using a modified terrestrial wind turbine analysis code. In addition, this work developed a strategy to assess feasibility and subsequently showed that a feasible Martian wind turbine would need to be of an ultra-lightweight design. Assuming lightweight blades, the mass of such a system was estimated at 944 kg (Hemmet et. al., 1999, James et. al., 2000). The work presented herein is a further extension of the work that explores a VAWT design specific for Mars utilizing a buoyant configuration.

BUOYANT WIND TURBINE DESIGNS

Design Considerations for This Study

A set of Martian-specific design tools is under development to allow trade-off studies, prototype development, resource prospecting, and feasibility analysis. A VAWT design is the current baseline due to the advantages of keeping the heavy components at ground level as well as the simplicity of the rotating sub-systems. A buoyant design is being studied in this phase of the work. The initial assumption was that buoyant structures would allow large deployable capture areas to be emplaced using pressurized minimum weight structures. Also such gas-filled structures may provide significant stiffness and rigidity with little weight penalty, thus the possibility of using in-situ atmospheric materials. Thermal structural stresses might be controlled with pressure variations of the inflation medium. The most significant issue with this design will be the structure needed to transfer the torque to the generator on the ground. However, a buoyant structure will place the torque transfer structure in tension as opposed to compression. A hollow cylinder is currently baselined. This structure may be inflated or foam-filled as needed to maintain stability under torque. The next section will review the lift capabilities of balloons in the Martian atmosphere.

Lift Capability of Hydrogen-Filled Balloons on Mars

The estimation of buoyancy forces due to hydrogen filled structures on Mars is provided by the following equation:

$$B_F = (\rho - \rho_i) g_M V; \tag{2}$$

where B_F is the buoyancy force;
ρ is the ambient atmospheric density;
ρ_i is the internal gas density;
g_M is the acceleration due to Martian gravity; and
V is the volume of the balloon.

The mass of the balloon skin is calculated using a small thickness approximation:

$$M_B = 4\pi R_B{}^2 t_B \rho_B; \tag{3}$$

where M_B is the mass of the balloon;
R_B is the radius of the balloon;
t_B is the thickness of the balloon material; and
ρ_B is the density of the balloon material.

The mass that can be lifted by the balloon is then given by the following:

$$M_L = {B_F}/{g_M} - M_B; \tag{4}$$

where M_L is the mass that can be lifted by the balloon.

Using the appropriate values for Mars, a hydrogen filled interior, a balloon density of 1250 kg/m^3 and a thickness of 0.00005 meters, a series of calculations were performed to estimate the lift potential (Figure 1).

It can be seen from Figure 1 that there is a radius below which the balloon cannot even lift itself. For the parameters chosen above this occurs at a radius of around 12 meters and a corresponding mass of 60 kg. However, reducing the thickness, reducing the material density, or heating the inflation gas can improve this situation. Above this threshold, the mass of the balloon is roughly equivalent to the lift capability over the range of radii shown above. Hence, a buoyant system must either be able to tolerate the addition of such a mass or integrate the buoyant chamber into the primary structure.

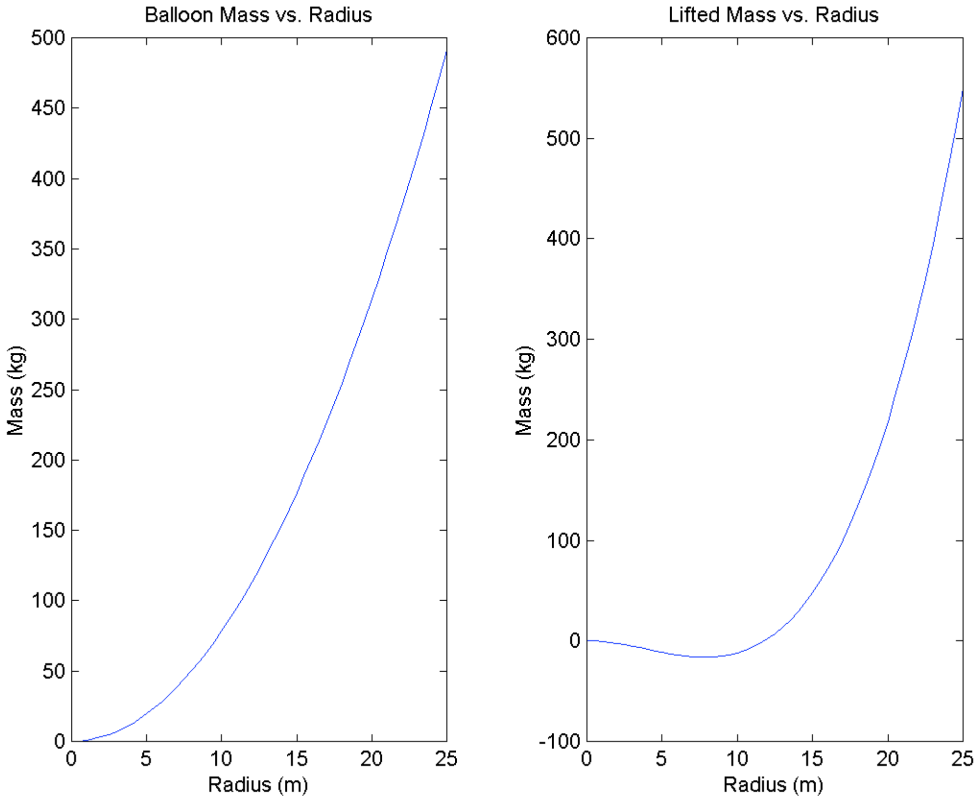

Figure 1. Mass and Lifted Mass for a Hydrogen-Filled Balloon on Mars.

Design of a Buoyant Drag-Type Savonius VAWT

A Savonius turbine is a vertical axis machine that uses alternating blades to capture the wind. Drag forces then rotate the turbine. The primary body of the turbine designed herein is assumed to be a ring-stiffened inflatable cylinder with a spherical chamber on the top. The rings also support vertical members that form attachments for the blades. The construction of the blades and the straight vertical members consist of fabric stretched over semicircular frames. Forces are transferred from the blades to the turbine body via cables attached to the ring stiffeners and the skin of the turbine body. The torque is transferred from the lower ring to a smaller diameter torque tube/tether via a woven and inflated frustum. The hollow or foam filled torque transfer mechanism is assumed to transfer torque but not bending forces. It is also intended to operate under tension due to buoyancy of the main body. A generator/gearbox is situated on the ground.

An optimization code was written which maximized an objective function based on the power to mass ratio and the buoyancy. The code was able to modify the radius and length of the cylindrical body, the diameter of the blades, the length and thickness of the torque transfer cable, and the height of an attachment frustum. The radius of the buoyant chamber was constrained to be equal to the radius of the cylinder plus the diameter of a blade. Skin thickness and support radii were generally allowed to vary to assure stresses remained allowable. However, upper and lower bounds were provided which typically constrained these parameters. The number of blades was variable.

The best results were obtained with two blades. These were half cylinders 7.2 m in diameter attached to the spherical chamber and running the entire length of the 25-meter cylindrical body. This body was 15 meters in radius. The frustum was 1 meter high which gave it the aspect ratio of a plate. All of these components were assumed to have a skin thickness of 0.0001 meters. An aramid material of density 970 kg/m^3 was assumed. The cable was 25 meters long with an outer radius of 1.533 cm and a thickness of 7.633 mm. These torque transfer structure dimensions were chosen based on the ability to handle the applied torque only. No other stability criteria were used in the estimation of the cable dimensions at this time. The spherical chamber was assumed to have a density of 1250 kg/m^3, a thickness of 0.00005 meters, and a radius of 22.2 meters. The total system mass was 997 kg including 48 kg of hydrogen inflation gas. The system had a low efficiency (in terms of power per kg) but produced 29 kW in a 25 m/s wind. Figure 2 shows the dimensions of the structure from the front and Figure 3 shows the dimensions from the bottom.

This example showed that the buoyant turbine structures would, by necessity, be a large system, and would produce power in the 10 to 30 kW range. It should be noted that the optimization process was free to produce a turbine of power output ranging from 0.5 to 30 kW in a 25 m/s wind. However, the buoyancy requirement drove the system to the large size.

Design of a Buoyant Lift-Type Darrieus VAWT

The next design exercise was to modify the previously mentioned Darrieus-type VAWT design to include buoyancy (Hemmet et. al., 1999, James et. al., 2000). The geometric configuration of the previous design was retained. This configuration included a 30.5 meter tall VAWT with two troposkien shaped blades of 19-meter diameter. Figure 4 shows the configuration of the turbine including the 0.3-meter diameter central tower. Three blade sections were used with blade sections of 3.2, 2.8, and 1.8-meter chords. The system was assumed to rotate at 75 rpm. The analytical model suggested that the device would produce 14.1 kW in a 25 m/s wind with a maximum efficiency coefficient of 0.59. This coefficient was the theoretical maximum, and was likely biased by the lack of appropriate Reynolds number information for the airfoils used in the code. The original design used an aluminum tower with guy wire supports.

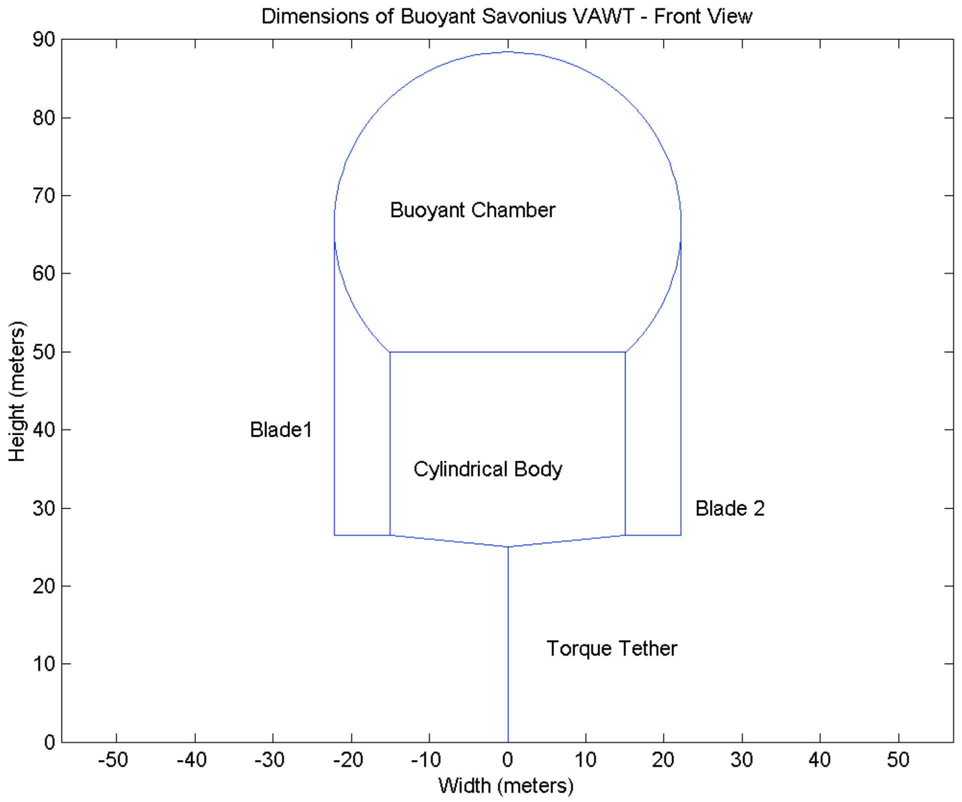

Figure 2. Dimensions of the Buoyant Savonius VAWT – Front View

This study replaces the guy wires with a buoyant support chamber (a balloon) attached to the top of the turbine. The current study assumes that the blades and torque tube are pressure-stabilized although the tools to analyze the stiffening effects have not been produced nor included in the design process. The blade sections were thinned from the previous design from 0.0005 to 0.0001 meters. Using an aramid fiber, these blades were still found to support the rotational stresses. The structural area of the blade section was approximated by the following formula:

$$A_s = 2.08 C_s t_s; \tag{5}$$

where A_s is the structural area of the blade cross-section;
C_s is the chord of the blade section; and
t_s is the thickness of the blade section.

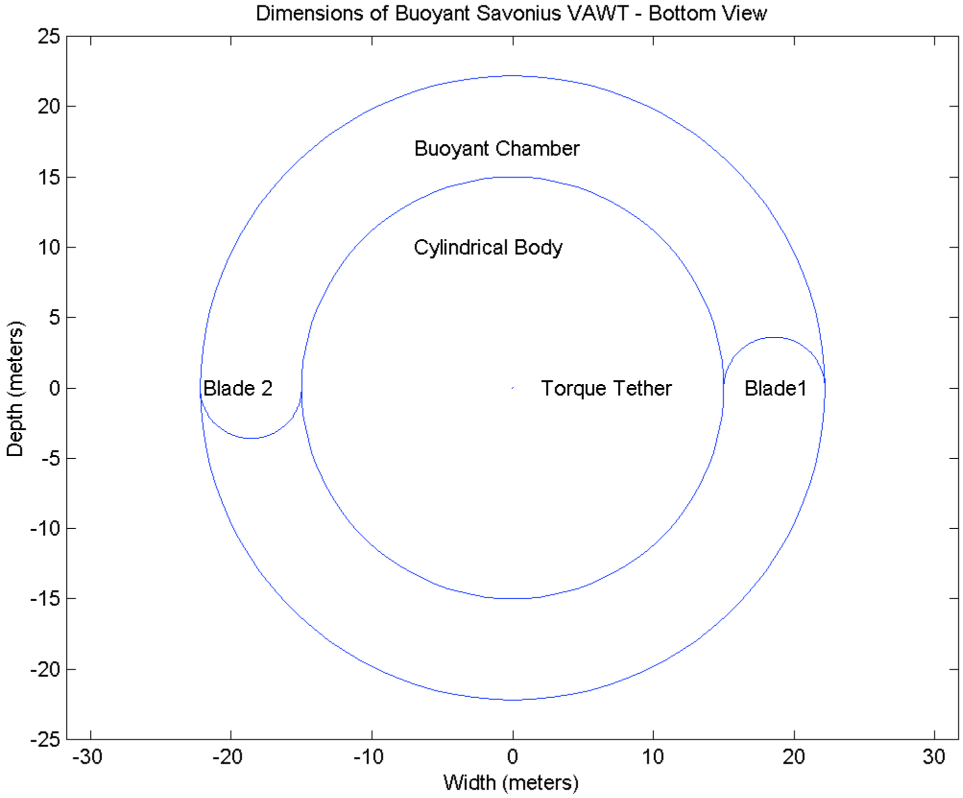

Figure 3. Dimensions of the Buoyant Savonius VAWT – Bottom View.

This formula was provided in (Sullivan, 1979) for a similarly shaped blade. The length of the each blade was originally estimated at 48 meters (the circumference of a 30.5 meter circle). This was an overly conservative approach and was corrected in this work by assuming that each blade was 40 meters (slightly more than the average circumference of a 30.5 and a 19 meter circle). The total structural mass of the blades was estimated at 50 kg using the largest chord of 3.2 meters. It was found that the performance/mass ratio was not greatly affected by changing the blade thickness from 0.0005 to 0.0001 meters (blade mass reduced from 250 kg to 50 kg).

The torque tube from the previous design was chosen to carry the torque and carry the appropriate buckling loads. Therefore, the dimensions were retained and the material was assumed to be an aramid material of 970 kg/m^3. An additional 15 meters of tube was added to eliminate potential ground interference. The resulting component weighed 205 kg and produced a lifted mass of 255 kg. Equations (2-4) were used to estimate the turbine size needed to lift this mass (plus 50 kg of additional mass as a safety margin). The resulting 0.00005 meter thick chamber was 367 kg. Assuming an additional 150 kg of ground support material and 36 kg of hydrogen gas, the total mass was 808 kg. This compares to the 944 kg of the original design. Figure 5 shows the resulting system with the 21.6-meter radius buoyancy chamber and 15-meter torque tube extension.

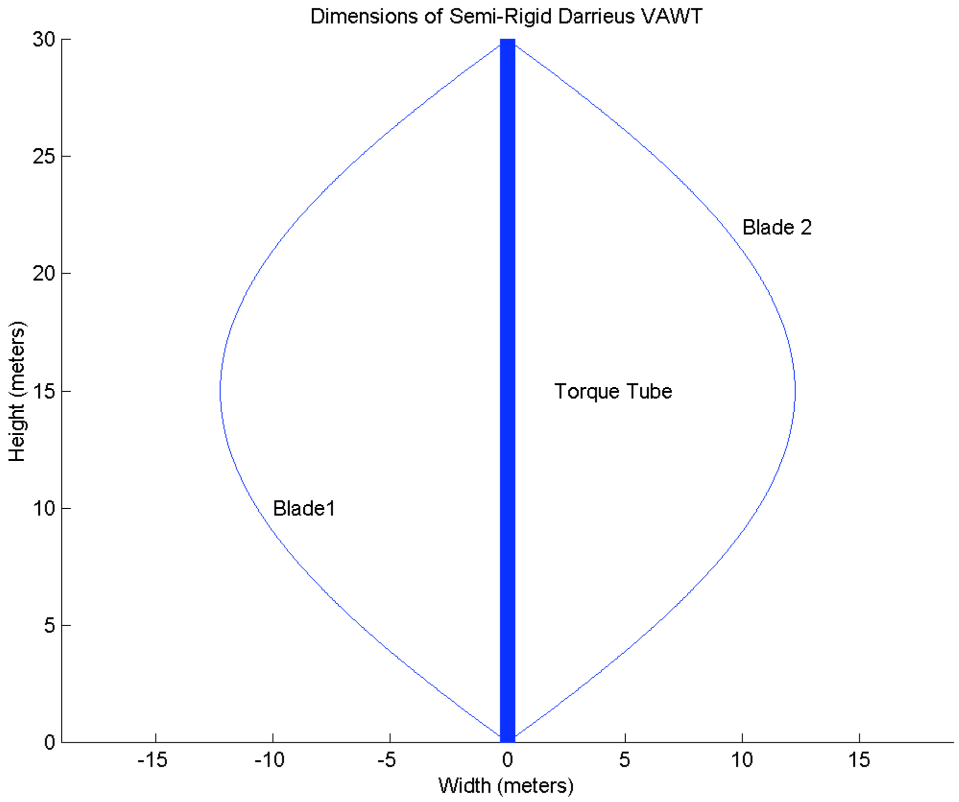

Figure 4. Shape and Dimensions of the Baseline Vertical Axis Wind Turbine.

Design of a Spherical Drag-Type VAWT

Based on the information gained during the last two design exercises, the most efficient use of a buoyant chamber is to integrate it directly into the body of the turbine. A third design exercise was undertaken which assumed the blades were directly attached to the spherical shell. These blades were assumed to be flaps that are shaped like a geometric lune around a spherical body. They were each of 15-degree angular extent that covered one quarter of the surface area. One side of each flap was tightly attached to a cable running a great circle. The other side was loosely attached to a series of netted cables that were eventually tied into the torque-bearing tether. The flaps were assumed to create pockets that caught the wind on the downwind side and closed on the upwind side. The same tether design as was used in the Savonius design was assumed: 25 meters long, 1.53 cm radius, .77 cm thickness, and 13.43 kg. Assuming the same material as the buoyant chambers in the other design problems, the required sphere was 17.76 meters in radius and 247.72 kg. This size was selected to provide 50 kg of extra lift mass. The total mass was 428 kg including 150 kg of ground equipment and 17.75 kg of inflation gas. Since this is a drag-type turbine it can be expected to have a low efficiency. Also the spherical shape is not often used for large-scale wind turbines. Therefore, a turbine efficiency of 0.15 was assumed. Hence, the turbine produced 19 kW in a 25 m/s wind. Figure 6 shows an artist's rendering of such a turbine in use on Mars.

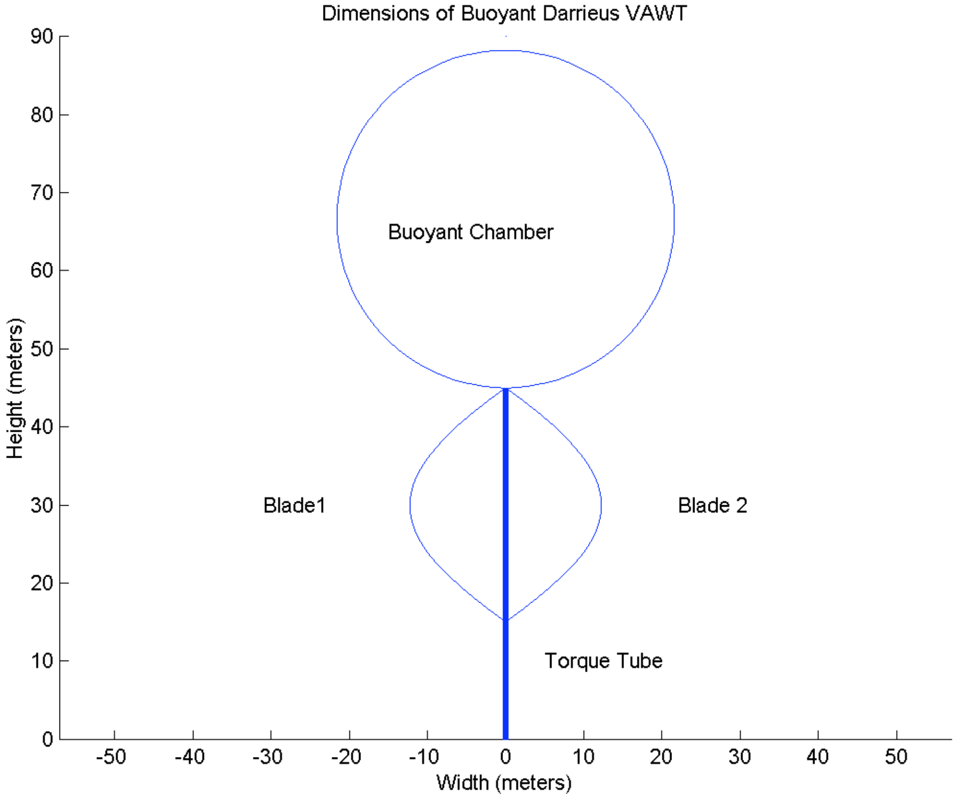

Figure 5. Dimensions of Buoyant Darrieus VAWT.

ASSESSMENT OF WIND RESOURCE REQUIREMENTS

The feasible wind speed selection for the designs discussed above was evaluated using the energy to mass ratio of solar cells as derived during surface dust storm conditions. This process was discussed in previous work (Hemmet et. al., 1999, James et. al., 2000). The mass of a solar-based energy production system for an all-solar mission is estimated to include approximately 6 metric tons of solar photovoltaic cells. The energy output for these arrays per unit mass during dust storms dropped from 400 kW-hr to 50 kW-hr per metric ton. The following relationship was used to define feasibility of the initial design:

$$M_W \text{ (metric ton)} \leq (1/50)\, E_W \text{ (kW-hr)} = .02\, E_W \qquad (6)$$

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 was estimated using equation (1) as the integrated value of power produced over a Martian day. However, 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. A design is feasible if the above inequality holds for a given wind speed. Equation (6) is solved for the wind speed in terms of the other quantities

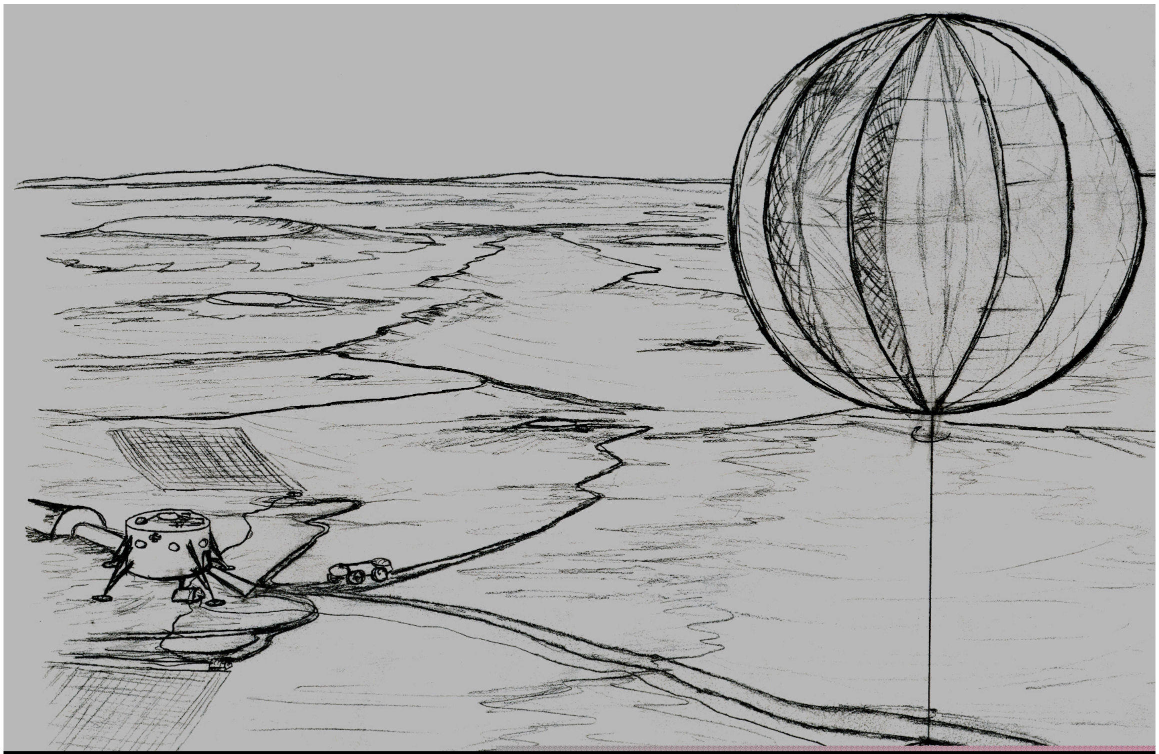

Figure 6. Concept of a Buoyant Spherical VAWT in Operation.

. Table 1 provides a comparison of the turbine designs listed in this work. The information in this table points out the fact that wind speeds in the mid to lower 20 m/s range will be needed for at least one hour per day during dust storm season to efficiently (kW/kg) offset solar energy production losses using wind energy.

Table 1. Feasible Wind Speeds for the VAWT Designs Provided

Design	Mass (kg)	Efficiency	Swept Area (m^2)	Feasible Wind (m/s)
Haslach	175*	.47	198	22
Hemmet et. al.	944	.59	375	29
Savonius	997	.20	1117	30
Darrieus	808	.59	375	28
Spherical	429	.15	990	26

* Assumes turbine is atop a 21.5-meter vehicle.

ONGOING WORK

Design Improvements

The designs provided herein represent work in progress and are not final products. In fact these designs were generally produced with only mass, power, and buoyancy in mind (structural stress was considered in a limited number of components). Critical issues such as robustness, fatigue, elastic stability, structural response, dynamic response, pressure stabilization, partial buoyancy, and gas loss must eventually be considered in the design process. Issues such as airfoil design are needed to produce Mars-specific systems.

Prototype Development/Testing

The entire concept of an inflatable or partially inflated wind turbine is a new concept and will require significant prototype testing. Fortunately, there are terrestrial analogues (such as low wind speeds, stratospheric testing, wind tunnel testing) that can be used for some of this work. However, a test object will eventually need to be emplaced on Mars.

Resource Assessment and Supply

The use of wind power for a Martian outpost will require some significant information on the local, global, and seasonal wind conditions. This means that surface and orbital measurements will be needed. Also, if buoyant structures are to be used then an on-site source of hydrogen (water) will be most advantageous for maintenance, gas loss, and turbine production. This work has not addressed the logistics of the storage and initial supply of hydrogen.

CONCLUSIONS

This project has explored the feasibility of wind power generation on Mars. Three designs using completely buoyant structures were used. This was an attempt to produce ultra-light, and potentially mobile, systems for Mars. It was found however, that there is a significant mass offset that a buoyant system must overcome. Hence, buoyant systems will tend to be large systems in the 10 to 30 kW range. Rigid or semi-buoyant systems will be required for smaller power stations. The Savonius and Darrieus examples required such large systems that they may not be useful. These designs required daily winds of 28 m/s or better for a least one hour to be feasible. The spherical system was the most efficient in its inclusion of the buoyant chamber. Although it suffers from a low efficiency and a lack of operational experience, it was seen to be feasible with a 26 m/s or better wind. Such on going research into a solar alternative/complementary energy source that takes advantage of in-situ resources should prove to be more practical, efficient and cost effective for the establishment of a permanent human presence on the planet Mars.

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