Lighter-than-Air System for Electric Power Generation

Hamjadali A. Umachagi

Abstract— **This paper presents a novel design comprising an original use of photovoltaic technologies for utilization of solar energy while satisfying a growing need for a sustainable environment. We suggest using a lighter-than-air helium-filled platform containing embedded thin photovoltaic arrays (PVA) in order to extract electrical power from the incoming solar radiation (insolation). The goal is to develop an efficient, portable, land-area independent, inexpensive and reliable energy source for all. Three concepts are developed: A simple, helium-filled spherical balloon containing a PVA on the outer skin surface; a specialized paraboloidic balloon with a transparent upper part and an opaque lower part containing paraboloid-shaped photovoltaic cells on the inner surface, thus increasing the insolation conversion efficiency; and the same balloon wherein the inner collectors are replaced by flexible thin mirrors, and the upper transparent part contains a PVA at the focus of the inner paraboloid-shaped mirror, thus augmenting the insolation. In both the spherical and paraboloidic configurations, the power output is similar; however, the power-to volume ratio of the paraboloidic design is higher. We present a detailed preliminary design, including a thorough mechanical design as well as an aerodynamic analysis. The mechanical layout consists of three segments: The balloon; an insulated strapping cable system; and a ground segment. The subsequent aerodynamic analysis substantiates the ability of the proposed balloon and strapping cable system to withstand considerable drag and lift forces while maintaining feasible performance.**

Index Terms— **Spherical balloon, Photovoltaic arrays (PVA), Aerodynamic analysis, paraboloid-shaped mirror.**

I. INTRODUCTION

The persistently increasing energy cost and the forthcoming energy crisis necessitates the development of alternative energy resources. Ultimately, the goal of alternative energy is to provide clean, inexpensive, reliable and sustainable energy to every consumer on the globe. Solar energy is one of the most promising clean energy sources. Numerous applications and technologies utilizing the photovoltaic effect, ranging from cellular phones to geostationary satellites have been developed in recent decades. The solar radiation reaches the Earth's upper atmosphere at a rate of 1,366 W/m2 [5]. While traveling through the atmosphere, 6% of the incoming solar radiation (insolation) is reflected and 16% is absorbed, resulting in a peak irradiance at the equator of 1,020 W/m² [6]. Average atmospheric conditions (clouds, dust, pollution) reduce insolation by 20% through reflection and 3% through absorption. In North America the average insolation lies between 125 and 375 W/m² (3 to 9 kWh/m²/day) [7]. Photovoltaic panels currently convert about 15-25% of incident sunlight into electricity; therefore, a solar panel in the contiguous United States delivers on average 19 to 100 W/m² or 0.45-2.7 kWh/m²/day [8]. In addition, the DC/AC conversion incurs an energy penalty of 4-12%.When grid connected, solar electric generation can displace the highest cost electricity during times of peak demand (in most climatic regions), can reduce grid loading, and can eliminate the need for local battery power for use in times of darkness and high local demand. The main disadvantage of solar electricity is limited power density, requiring relatively large collecting sites, occupying considerable land. In this work, we propose to mitigate this deficiency by designing a lighter-than-air system for collecting solar electricity. This concept may be used to backup existing power plants or as a primary energy sources in countries where land resources are scarce.

The lighter-than-air craft technology has been proven useful for various commercial, military and civil applications, including meteorological balloons, intelligence blimps, and stratospheric observatories [1]. To date, however, there are no existing balloons comprising embedded solar cells for electricity generation; existing technologies, developed over 25 years ago, propose either connecting an *exterior* solar array attached to airborne platforms such as balloons, kites and general aviation aircraft [2], or to use a *ground* system comprising a balloon with an embedded solar array [3]. Others proposed using a lighter-than-air airship to collect solar power and to beam it back to Earth using microwave radiation [4].

In this work, we propose a number of designs for generating electrical power using helium-filled balloons carrying embedded solar cells. These balloons are strapped to the ground using dual-use insolated cables, carrying helium to the balloon and transporting electric charge to a ground segment. The choice of helium rather than a hot-air balloon stems from its unique properties: Low boiling point, low density, low solubility, high thermal conductivity, and inertness. In addition, pressurized helium is commercially available in large quantities. Because of its extremely low index of refraction, the use of helium reduces the distorting effects of temperature variations in the space between lenses in some telescopes. We shall subsequently see that this property is extremely useful for one of our proposed designs. In particular, we develop an aerodynamically-shaped balloon capable of mitigating wind-induced lift and drag, as well as maximizing the surface area (and hence the generated power) while minimizing volume. The balloon contains low-cost, off-the shelf components such as solar arrays and wires. The collected power is delivered to the ground using the balloon cable. It is then converted AC (if needed) and regulated to provide stable user-defined voltage and current. The bulk of the generated heat will be radiated from the balloon surface and hence no additional radiators will be required (the specific heat capacity of helium permits passive cooling).

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II. The Basic Concept: A Spherical Balloon

Consider a spherical helium-filled balloon whose outer surface is covered by a photovoltaic array (PVA), as shown in Figure 1. For a given sphere radius, R, the Cartesian equation is

$$x^2 + y^2 + z^2 = R \quad (1)$$

The surface area of the sphere is given by

$$S = 4\pi R^2 \quad (2)$$

and the volume is

$$V = 4\pi R^3 / 3 \quad (3)$$

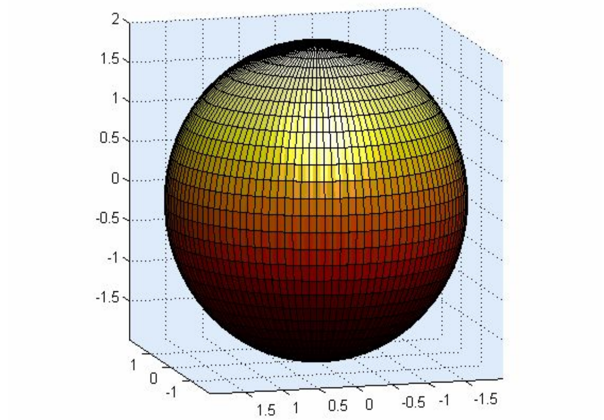


Figure 1: A spherical lighter-than-air balloon covered by a photovoltaic array.

If the balloon is filled with helium, the maximal mass that can be lifted depends on the balloon volume, the air density and the helium density:

$$m = [\rho air\,(H,Ta) - \rho He\,(Ti, Ta)]V\,balloon \quad (4)$$

where m is the total balloon mass, $\rho_{air}(H,Ta)$ is the altitude- and ambient temperature-dependent density of air and $\rho_{He}(Ti, Ta)$ is the balloon-temperature- and ambient temperature-dependant density of helium. The maximal allowable mass can be therefore obtained by substituting the air density at sea-level, ρ_{air} =1.225 kg/m3, and the standard density of helium at room temperature, ρHe =0.1786 kg/m3. For example, if R =2.12m,$V \approx$40m3, and m = 41.84 kg. The helium mass is 7.14 kg, so the total "dry" mass is 34.7 kg.

This mass includes the light-weight structure, wiring, solar panels and radiators. If the total mass is less than 41.84 kg, then the balloon will rise above sea level. The maximum altitude can be obtained by first calculating the density,

$$P_{air}(H,T_a) = (m/V_{ballon}) + P_{he}(T_i,T_a) \quad (5)$$

and then using standard atmosphere tables [12] to convert the resulting air density into altitude. For example, if the total mass (including helium) is 35 kg, then ρair =1.05 kg/m3, corresponding to an altitude of above 1500 m above sea level. The total power generated by this balloon, assuming that only the upper hemisphere is exposed to sunlight, can be obtained by means of the relationship

$$P = Psun \cdot S \cdot \eta PVA / 2 \quad (6)$$

Where $Psun$ is the total energy flux from the sun, and η_{PVA} is the Silicone or Gallium- Arsenide semi-conductors photon-to-voltage conversion efficiency (usually in the range 0.15-0.25). Substituting R = 2.12 m into Eq. (2) yields S = 56.54m2. The average incoming solar radiation is assumed to be $Psun$ = 500 W/m2. Let ηPVA = 0.15 (this value is typical for a standard design of solar arrays). Substituting these values into Eq. (6) yields
P = 2.12kW. Hence, the balloon in our example is capable of supplying about2 kW of electrical power. The power per unit volume is then

$$P/V = 53 W/m^3 . \quad (7)$$

III. The Advanced Concept: A Paraboloidic Reflector - Collector

While the spherical balloon offers the simplest implementation of a lighter-than-air PVA, it is more susceptible to aerodynamic forces (lift and drag). More importantly, the ratio of surface area to volume can be optimized to yield a much better power return per unit volume. Consequently, we propose herein two alternative designs:

1. A balloon comprised of two paraboloids wherein the upper part is transparent and the bottom part contains embedded paraboloidic collectors to increase the insolation conversion efficiency. The resulting electric power is then collected and conducted to a ground system, containing a DC/AC inverter and power regulation and control unit.
2. A balloon comprised of two paraboloids wherein the upper part is transparent and the bottom part contains an embedded paraboloidic reflector. The incident light is reflected onto the transparent part, which contains a PVA at the focus length of the bottom reflector. The resulting electric power is then collected in conducted to a ground system, containing a DC/AC inverter and power regulation and control unit.

These ideas are inspired by the observation that the solar radiation can be focused using a parabolic mirror, similar to the method of concentrating streaming light in optical telescopes: A parallel beam of light incident on the paraboloid is concentrated at the focal point (this applies for other waves, hence parabolic antennae).

Alternatively, a parabolic design of the solar cells can increase the insolation-to electricity conversion efficiency. Keeping this fact in mind, we suggest using a paraboloidic lighter-than-air inflatable helium-filled structure in which the bottom paraboloid comprises a collector/reflector, and the upper paraboloid is transparent to visible wavelengths.

The resulting three-dimensional designs are depicted by Figures 2 and 3, showing the bottom and upper circular paraboloids, whose geometric properties are determined so as to guarantee that the focus length of the reflector coincides with the vertex of the upper paraboloid.

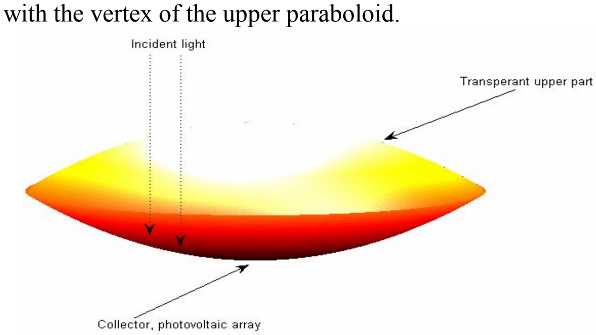


Figure 2: The paraboloidic balloon. The upper part is transparent to visible wavelengths, while the bottom part is a parabolic photovoltaic collector.

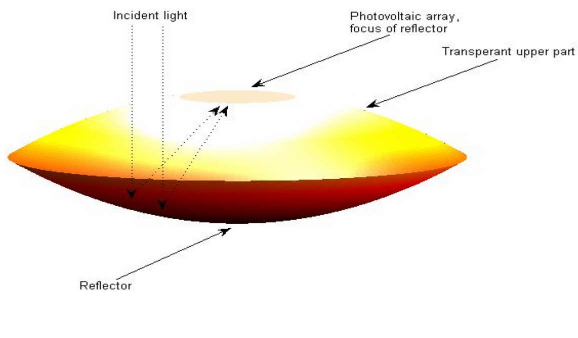


Figure 3: The paraboloidic balloon. The upper part is transparent to visible wavelengths, while the bottom part is a parabolic mirror. The transparent part comprises a PVA at the focus length of the reflector, thus collecting the reflected light.

IV. MATERIALS, MECHANICAL DESIGN, AERODYNAMICS & THERMODYNAMICS

1. Proposed PVA Assembly

In both configurations discussed above, the approximate power output is 2 kW. We shall now estimate the number of solar cells required to generate 2 kW, assuming a voltage output of 1000 VDC at 2 A. The voltage produced by a solar cell is typically 0.6 VDC. If an electrical power system requires a voltage supply of 1000 V, and has 0.6 volt cells connected in series, it will need 1000V/0.6V/cell = 1667 cells connected in series. Since the current supplied by a single solar photovoltaic cell is on the order of 0.01 A, the cells must be connected in parallel to combine the electron flow equivalent to the required current, which, in this example, is 2 A. The total number of cells in parallel would be 2.0 A/0.01 A/cell = 200 cells. The total array would then be 1667 x 200 cells. This would develop 1000V at 2.0A. This amounts to 2A x 1000V = 2 kW of power.

2. Candidate Balloon Materials

One candidate for the inflatable structure is a silicon-impregnated balloon. The material DT891, specifically developed by Linstradt [11] is characterized by an increased tear strength without an increase in weight. The Silicone-impregnation technique is particularly useful for manufacturing a fabric with an embedded flexible solar array, since the most commonly available PVA is silicone-based. We envision two production options:

A. The bottom paraboloid is designed using a photovoltaic fabric;
B. The PVA is embedded onto the skin by adhesives.

The second option offers a simpler and less costly manufacturing process while the first option offers better durability. In both options, it is guaranteed that helium leaks will be kept to the bare minimum through a judicious selection of the fabric, maintaining minimum permeability. Traditionally, manufacturers have used PVC to create inflatable materials. Unfortunately, PVC is heavy and has a high permeability factor. To create inflatable fabrics, urethane, which is lighter, more durable, and has lower permeability than PVC, may be used. Urethane-based inflatable fabrics are substantially lighter, offer greater durability and provide an excellent low-permeable barrier to better retain the helium.

3. Candidate PVA Materials

PVA comes in many flavors, though the bulk of the material in use today is silicon based. In general, PVA materials are categorized as either thick crystalline or thin film (deposited in thin layers on a substrate), polycrystalline or amorphous. The PVA of interest in this study is thin film, since it considerably facilitates integration with the balloon skin. The following types are the most common thin-film PVA materials: **Amorphous Silicon (a-Si)**: A non-crystalline form of silicon, first used in photovoltaic materials in 1974. In 1996, amorphous silicon constituted more than 15 percent of the worldwide PV production. Small experimental a-Si modules have exceeded 10-percent efficiency, with commercial modules in the 5-7-percent range. Used mostly in consumer products, a-Si technology holds great promise in building integrated systems, replacing tinted glass with semi-transparent modules.

Cadmium Telluride (CdTe): A thin-film polycrystalline material, deposited by electrodeposition, spraying, and high-rate evaporation, holds the promise of low-cost production. Small laboratory devices approach 16 percent efficiency, with commercial-sized modules (7200-cm2) measured at 8.34-percent (NREL-measured total-area) efficiency and production modules at approximately 7 percent.

Copper Indium Diselenide (CuInSe2, or CIS): A thin-film polycrystalline material, which has reached a research efficiency of 17.7 percent, in 1996, with a prototype power module reaching 10.2 percent. The difficulty in taking this technology to a production level lies in the difficulty in avoiding the formation of defects during deposition that prevent the formation of uniform layers.

4. Concentrators and Reflectors

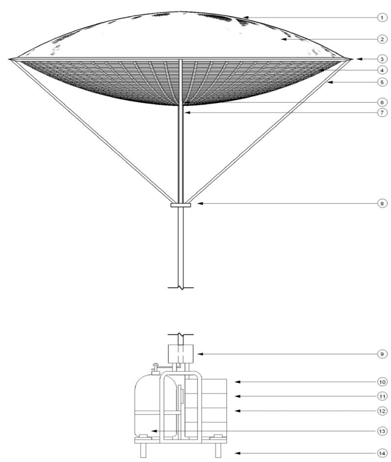
Concentrator systems use lenses or reflectors to focus sunlight onto the solar cells or modules. Lenses, with concentration ratios of 10x to 500x, typically Fresnel linear focus or point-focus lenses, are most often made of an inexpensive plastic material engineered with refracting features that direct the sunlight onto a small or narrow area of cells. The cells are usually silicon. GaAs cells and other materials would have higher conversion efficiencies, and could operate at higher temperatures, but they are often substantially more expensive. Module efficiency can range upwards from 17%, and concentrator cells have been designed with conversion efficiencies in excess of 30%. Reflectors can be used to augment power output, increasing the intensity of light on modules, or to extend the time that sufficient light falls on the modules.

5. Mechanical Design

The cutting-edge PVA and skin materials will be used to create a simple yet efficient mechanical setup as illustrated in Figure 5. This figure shows the following system components:

1. Upper transparent paraboloid of the inflatable balloon.
2. Helium gas.
3. Rigid bend.
4. Lower opaque paraboloid, wherein the inner surface contains an embedded PVA.

5. Strapping cables for statically stabilizing the balloon.
6. Pressure valve connecting the exterior part of the coaxial cable to the bottom part of the balloon, used for initial helium inflation and occasional helium refill/discharge (for altitude control).
7. Central coaxial isolated cable, wherein the inner part conducts the DC current to the DC/AC inverter and the exterior isolated part is helium-filled.
8. Ring bearing connecting the wires to the central cable for wind shear mitigation.
9. Charge controller for regulating and controlling voltage.
10. DC/AC inverter transforming the DC power generated by the PVA to an AC power (optional).
11. Battery for night/clouds operation.
12. Rectifier for on-grid operation (optional).
13. Helium tank.
14. Docking platform.



Mechanical design of the paraboloidic balloon. This front-view diagram shows the mechanical setup including the balloon, strapping cable system, central coaxial cable and the ground segment The coaxial cable is depicted in Figure 6. Helium is transported to the balloon as a means for altitude control. The pressure valve connected to the cable controls helium refill or discharge through activating the helium tank. The inner part of the cable is a conducting wire, used to transport the electric charge to a charge controller and to the DC/AC inverter.

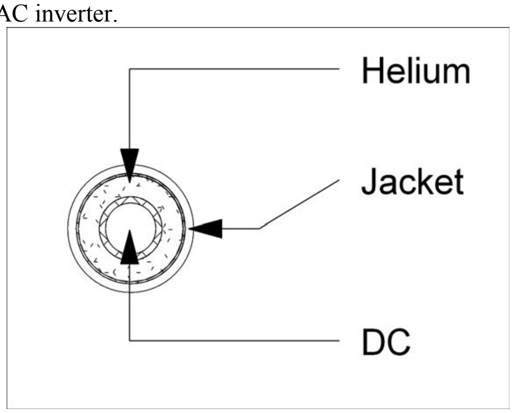


Figure 6: A coaxial isolated cable, wherein the outermost part is helium filled and the innermost part is a conducting wire. One option for assembling the PVA is to use a thin-film silicone, as explained above. This results in a considerable weight reduction and to a marginal loss of efficiency.

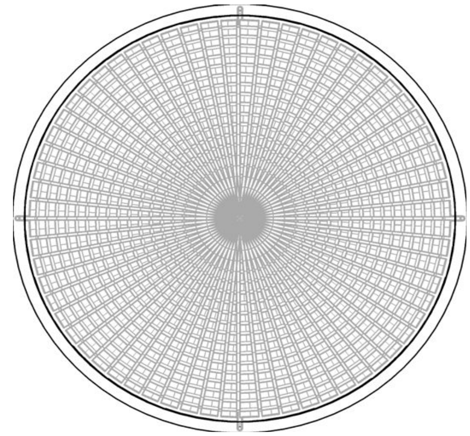


Figure: 7 shows a horizontal cross section of the balloon. The PVA array is arranged so as to produce the required voltage and current

6. **Aerodynamics in the Pitch Plane**

The balloon is subjected to a number of forces during operation. In order to guarantee durability and robustness of the mechanical design, these forces must be calculated. To that end, we shall now derive the total force balance in the pitch (vertical) plane (a similar analysis may be performed in the yaw plane, but is omitted here for the sake of conciseness), computed in a body–fixed reference frame as discussed below. Consider a body-fixed coordinate system, centered at the balloon's center of mass, whose $\hat{x}$ -axis points rightward along the horizontal symmetry plane and whose $\hat{z}$ - axis points upward along the vertical symmetry plane. Let Vw denote the wind velocity vector, and α be the angle of attack, as shown in Figure 8. The drag force, D , is then given by

$D= 0.5\,\rho V_w^2 S_{ref} C_D V$ (18)

where ρ is the atmospheric density, $Sref$ is a reference area , CD is the drag coefficient and $\hat{v}$ is a unit vector along the wind velocity vector, as shown in Figure The lift force due to wind is given by

$L_w= 0.5\,\rho V_w^2 S_{ref} C_L n$ (19)

where CL is the lift coefficient and $\hat{n}$ is a unit vector normal to wind velocity direction. In addition to the aerodynamical lift, a gas buoyancy lift force, $B\,L$, acts upon the balloon due to the lighter-than-air medium. This force is given by

$LB = g\,(\rho - \rho He)\,Vballoon\,\hat{z}$ (20)

Finally, the balloon weight is $W = -mg\hat{z}$ (21)

The above forces are balanced using the strapping cables tension forces, $T1, T2, T3, T4$ If equilibrium is assumed, then writing the moment equation about the center of mass will yield

$T1 \approx T2 \approx T3 \approx T4$ (22)

Let δ be the angle between the strapping cable and the balloon horizontal cross section, as shown in Figure 8. The equilibrium force equation in the $\hat{z}$ direction under the constraint (22) is given by

$LW\cos\alpha + D\sin\alpha + LB = -4T1\sin\delta - W$ (23)

Substituting the expressions in Eqs. (18)-(21) yields

$0.5\rho VwSrefCL\cos\alpha + 0.5\rho VwSrefCD\sin\alpha +$
$g(\rho - \rho He)\,Vballoon = -T4\sin\delta + mg$ (24)

Similarly, the equilibrium force equation in the $\hat{x}$ direction is

$LW\sin\alpha + T2\cos\delta = D\cos\alpha + T1\cos\delta$ (25)

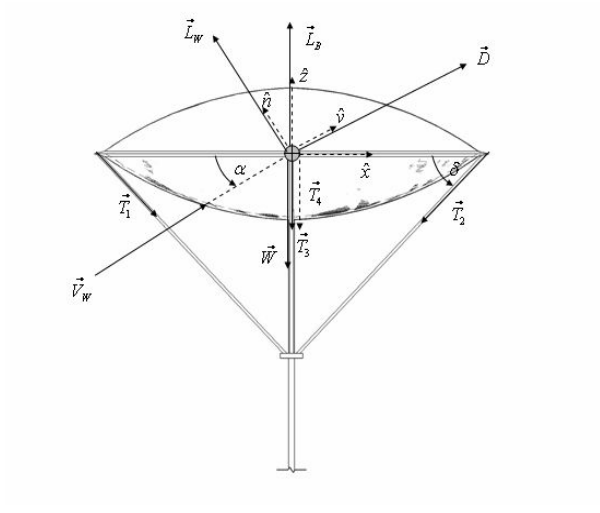
wherefrom we find that

$0.5\rho V^2 wSrefCL\sin\alpha = 0.5\rho V^2 wSrefCD\cos\alpha$ (26)

For small angles of attack, we may use the approximation $\cos\alpha \approx 1$, $\sin\alpha = \alpha$. Under
this assumption, Eq. (26) simplifies into

$$\alpha \approx CD / CL \qquad (27)$$

the simplication of the above equations can also yield us the tension in each cable.
A negative tension implies that the balloon operates at some designated altitude, while
a positive tension implies that the balloon is below the desired altitude. For example, using the numerical values from Section 3, and assuming that
$CL = 0.5$, $CD = 0.1$, $\delta = 45$□ yield a tension force of about 13 kg in each cable for a
wind speed of 30 m/s.



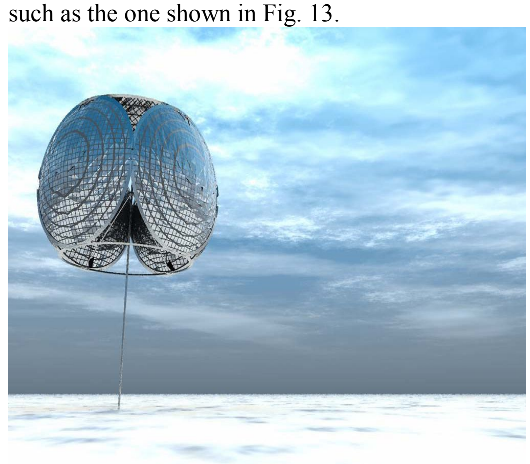
V. Societal Impact

Our proposed balloon constitutes an efficient, infrastructure-free energy source for the following potential users:
1) Underprivileged third-world communities and disaster regions, in which the existing power infrastructure is deprived or heavily damaged (e.g., East-Asian countries struck by tsunamis, American cities hit by hurricanes).
2) The balloons can be delivered from the air to the above areas (by changing the volume of the balloons one can determine the exact altitude to which the system will descend after an airborne delivery).
3) The balloons can be used at sea on marine vessels or on remote islands.
4) Government agencies can purchase bulk quantities of energy-generating balloons to be used in emergency situations.
5) The balloons are highly portable and can thus be mobilized in compact backpacks by individual users, ground vehicles, ship and aircraft. The proposed design is highly portable, versatile and adaptable and can thus be utilized in diverse applications, ranging from street lighting through cellular phone receiver-transmitter antennae to emergency power generation. Our system occupies virtually no area on a roof. This area can be used for alternative urban functions such as roof gardens. In hot regions, the balloon can be used as a shelter and can be also used for advertisement. In wooded areas, the balloon concept considerably facilitates the extraction of solar power. We have created a number of renderings of the balloons, showing the potential applicability of the project as well as possible environments for locating balloons.

VI. Compound Balloon Concepts

The proposed balloons may be used in a variety of compound design concepts:

1. Balloons can be assembled to form a spatial structure such as the one shown in Fig. 13.



   This assembly will increase the power return and will enable to increase the floatation weight of the system.
2. Balloons may be interconnected to form elongated lighter-than-air structures, thus maximizing the power return while minimizing the environmental signature. Such a structure is shown in Fig shown below

Discussion and Conclusions

This paper presented a feasibility study of a novel platform for transforming solar power into electricity. It was proposed to design a helium balloon with an embedded photovoltaic array (PVA) in order to collect the incoming solar radiation. Three main design alternative were proposed: A spherical balloon containing an embedded PVA on its outer skin; a double-paraboloidic balloon with a transparent upper part and a PVA on the inner surface of its bottom part; and an advance design, wherein the inner PVA is replaced by concentrating mirror, reflecting the incoming solar radiation on a PVA located on the upper paraboloid. The new design developed herein has several clear advantages: First and foremost, the balloon concept transforms light into electricity without occupying precious land area. It constitutes an accessible, portable and infrastructure-free access to electric power that could be used in diverse locations, including remote areas and at sea. Basic balloons can be used as either a primary or a secondary reliable electric energy source in tents, condos, residential areas and high-rise buildings. The advanced balloons, comprising a paraboloidic balloon with a bottom collector and an upper transparent part or a bottom reflector and an upper collector provides a smooth aero dynamical design. This design is ideally suited for marine vessels. Future applications may include flocks of balloons which are inter-connected and/or inter communicating. Moreover, an ensemble of balloons floating in various altitudes can create a lighter-than-air mini power station. The present study has dwelt upon the preliminary design and the balloon geometry, the mechanical design, aerodynamics and materials. It was shown that a relatively simple technology, most of which is accessible through commercial-off-the-shelf products, could be used.

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BIOGRAPHY

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