PROTOTYPE DEVELOPMENT AND TESTING OF INFLATABLE CONCENTRATING SOLAR POWER SYSTEMS

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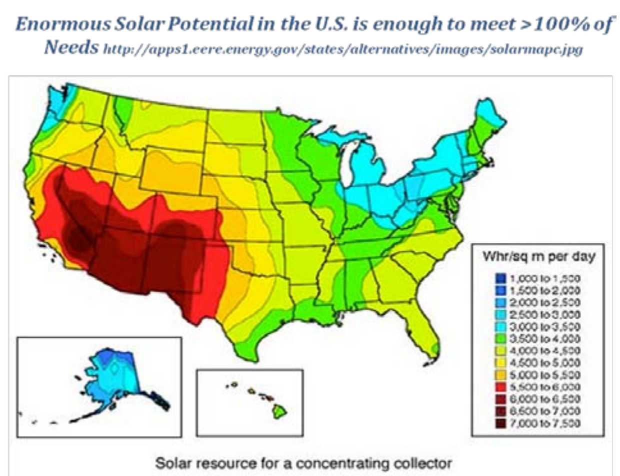
ABSTRACT

It is widely acknowledged that the cost per kilowatt-hour for solar energy must be substantially reduced to make accelerated deployment a reality. This paper presents innovative applications of low-cost concentrating reflective membranes both for central receiver powerplant heliostats and for concentrating photovoltaic modules. In each case the concentrating reflective membrane is contained within a dual-chamber inflatable envelope. Prototype development and testing of inflatable heliostat technology was accomplished under a DOE-sponsored research project, the results and next steps of which will be described. The inflatable concentrating reflector technology is similarly being applied to a new class of smaller-scale concentrating photovoltaic (CPV) modules and systems for rooftop and ground-mounted applications. This class includes electricity generation systems designed for net-metered or off-grid private homes as well as for commercial and industrial customers. Liquid-cooled versions can synergistically provide hot water for in-home / in-building use or for swimming pool heating, in addition to photovoltaic electric power. More economical air-cooled CPV modules are also described. Cost-effective leverage of high-efficiency silicon solar cells is enabled through the use of a simple but robust inflatable linear concentration system with concentration levels ranging from five to fifteen suns. A low-cost one-axis tracking system maximizes energy harvest for a given power-rated module by receiving sunrays normal to the effective plane of the concentrating reflective membrane during all daylight hours. This paper will present a description and photographic record of prototype development of one preferred full-scale embodiment of the inflatable CPV invention. Conclusions will be shared, leading to some recommendations for next steps in research, development and deployment of this technology to help accelerate widespread implementation of cost-effective solar energy systems in the U.S. and around the World.

1. INTRODUCTION

World marketed energy consumption in 2010 is estimated at 508.3 quadrillion BTUs per year and projected to grow to 678.3 quadrillion BTUs per year by 2030 (Reference 1). In terms of average continuous power these figures translate into 17,000 and 22,700 gigawatts (GW) respectively. Total solar radiation at the surface of the Earth amounts to 90,000,000 gigawatts, with about 1,000,000 GW potentially recoverable with solar powerplants, far exceeding Humankind's total energy needs for as far into the future as we can contemplate (Reference 2). Similarly, solar potential in the U.S.A. also far exceeds total U.S. energy needs (Reference 3).

FIGURE 1



The amazingly large potential for zero-carbon renewable solar energy also far exceeds the potential for any other type of renewable energy, with the second most available being wind energy with about 10,000 GW potentially recoverable (~1% of solar; Reference 2).

With these extraordinary statistics well-understood, why do solar powerplants account for less than 0.01% of world energy consumption (< 1 gigawatt of installed powerplant capacity)? Most of the answer lies in the much higher cost per kilowatt-hour of solar energy relative to other energy sources, combined with loss of harvestable solar energy during the night and during cloud-cover periods. Recognizing cost as a major inhibitor to much more rapid deployment of solar power collectors, progressive governmental and nongovernmental organizations are providing financial incentives to accelerate development and widespread deployment of more cost-effective solar power.

It is evident that dramatically increased global utilization of solar power is highly desirable as solar power does not contribute to pollutants associated with fossil fuel power including unburned hydrocarbons and NOx, and most importantly as solar power produces no carbon dioxide that contributes as a greenhouse gas to climate change.

2. <u>INFLATABLE HELIOSTATS FOR REDUCED COST SOLAR THERMAL POWER</u>

Reducing the cost of heliostats, the Sun-tracking mirrors that comprise the largest cost part of central receiver solar thermal powerplants, is vital to increasing cost-effectiveness of such solar thermal powerplants. Figure 2 illustrates a representative cost pie for such central receiver solar thermal powerplants (Reference 4). As a key enabler for low cost solar power, the idea of using inflatable heliostats for large central receiver solar thermal powerplants was proposed in the foundational U.S. patent 5,404,868.

The motivation for using inflatable structures to dramatically reduce cost and weight of heliostats becomes obvious when one considers the heavy metal and glass mirror structures used in conventional heliostats, to enable these to perform their Sun-tracking function properly while being able to tolerate and survive adverse weather conditions such as strong winds, rain, heavy snow and hail. An example of conventional heliostats from Reference 5 is shown in Figure 3.

FIGURE 2

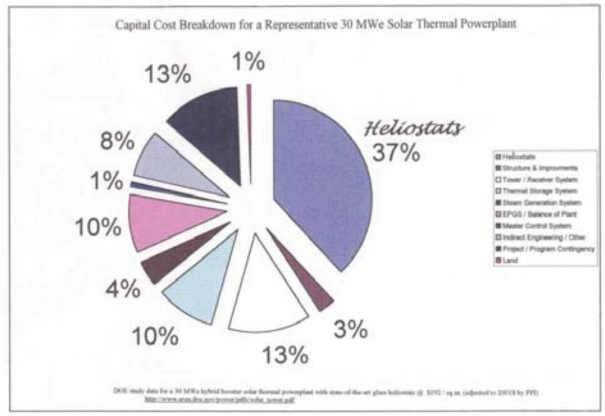
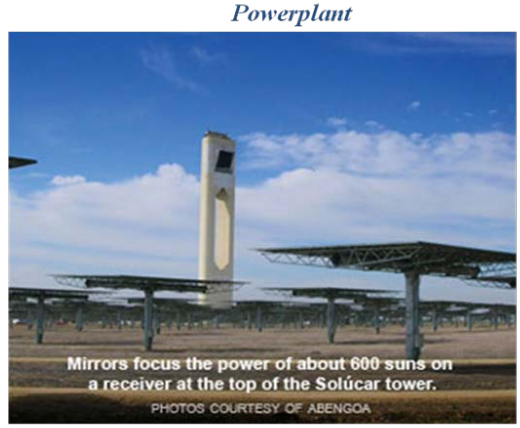


FIGURE 3

First Commercial Central Receiver Solar Thermal Powerplant



http://www.worldculturepictorial.com/blog/content/solar-energy-spain-takes-lead-with-government-commitment-enforces-building-code-erects-more-

A very light membrane mirror can reflect sunlight as well as a heavy and expensive metal and glass mirror, and if protected by inflated chambers above and below, the membrane mirror solution can potentially be equally able to withstand adverse wind and precipitation conditions at a substantially reduced cost.

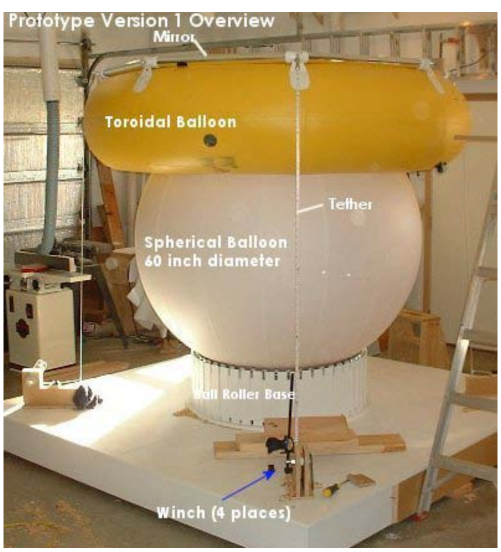
To evaluate the feasibility and benefits of low-cost inflatable heliostats for central receiver solar thermal powerplants, a DOE-sponsored prototype design, construction and testing project was conducted (Reference 6).

Key goals for this subscale prototype research were as follows:

- Conduct trade studies and component / subassembly tests to evolve a preferred subscale prototype design for a lightweight, low-cost inflatable-structure heliostat
- Refine the design as necessary, then construct a prototype that will enable achievement of test objectives
- Test the prototype with respect to the ability of the heliostat pointing system to accurately aim the heliostat without distorting the reflective surface
- Test the prototype with respect to beam shape and size (concentration) on a simulated target
- Test the prototype with respect to pointing accuracy and beam shape in the presence of environmental factors, particularly wind and gusts
- Evaluate the ability of the prototype to survive undamaged under adverse environmental conditions such as high winds or precipitation
- Develop a preliminary design for a production heliostat, which applies the technology demonstrated by the prototype
- Develop and document conclusions and recommendations for further work needed for the commercialization of this low-cost inflatable-structure heliostat technology, thereby enabling cost-effective large-scale solar thermal power generation

As a first step towards achieving these objectives, a "Version 1" prototype was designed and built, using a reflective membrane supported by a toroidal balloon, which in turn was supported by a spherical balloon on a ball roller base, as shown in Figure 4.

FIGURE 4



The Version 1 prototype had significant problems associated with a very high center of gravity and associated difficulties in achieving precise pointing using multiple winches. The multiple winches had trouble in adequately counteracting overhanging moments with the challenging geometry and load conditions at low elevation angle orientations.

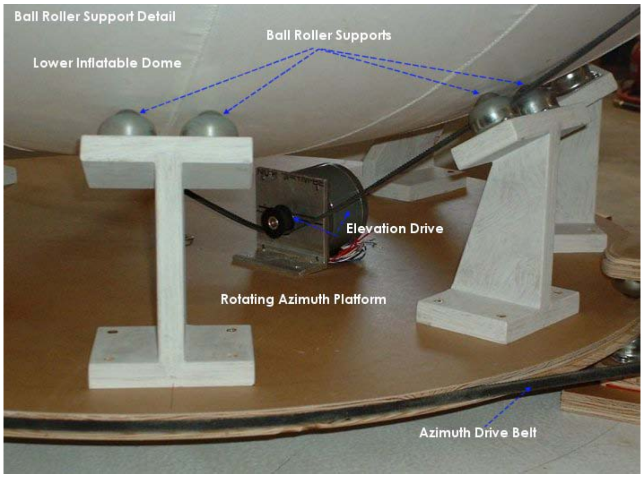
Learning from these problems, a refined design concept was developed with the following additional objectives:

- Simple drive system using only two motors, and having low torque requirements
- Inertia and aerodynamic loads act directly through the support system (no overhanging moments)
- Aerodynamic loads from winds and gusts are relatively low due to low drag coefficient of a near-spherical shape: No unsymmetrical aerodynamic loads regardless of heliostat orientation or wind direction.
- Mirror to be readily focused using differential pressure.
- Inflated domes protect mirror from exposure to weather.
- The combination of low loads, direct load paths, and the inherent efficiency of inflated structures should result in a lightweight, low-cost design

The refined design concept was built and is illustrated in Figures 5A and 5B.

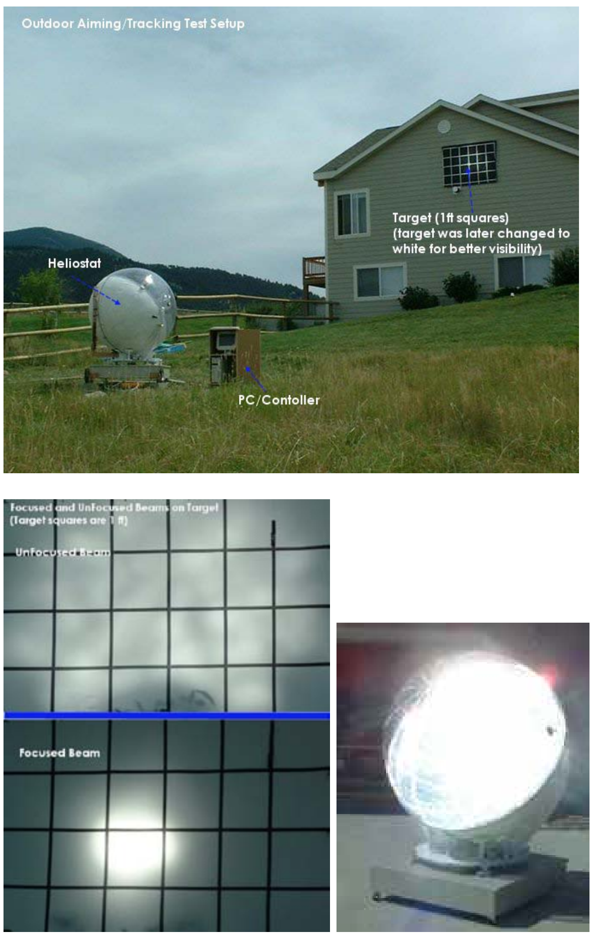
FIGURE 5A

FIGURE 5B



The revised proof of concept design did meet design objectives, utilizing tests in a simulated powerplant layout with a target panel used to simulate a solar thermal receiver, as illustrated in the collage of photographs in Figure 6.

FIGURE 6



The prototype tests indicate that the heliostat pointing system does accurately aim the heliostat without distorting the reflective surface.

A good near-circular beam shape was achieved on the simulated target; and geometric concentration ratios of up to 8.7 were achieved using differential pressure between the upper and lower hemispheres of the inflatable structure housing the reflective membrane.

Encouraging results were obtained on pointing accuracy and beam shape stability in the presence of environmental factors, particularly winds and gusts. Temperature effects also had no adverse impacts on pointing accuracy and beam shapes, to the extent that ambient and heliostat internal (upper and lower hemisphere) temperatures varied during the test period. The heliostat prototype successfully survived some adverse environmental conditions including wind gusts up to 30 mph and precipitation in the form of rain, snow and light hail.

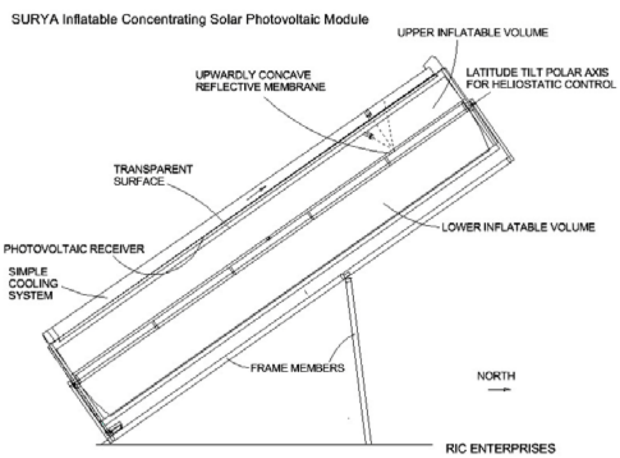
FIGURE 7

The construction and testing of a subscale prototype of a lightweight, low-cost inflatable structure supported heliostat has been successfully accomplished, and has satisfactorily met the test goals. The heliostat was able to track the Sun, to develop a precisely pointed reflected beam, to focus that beam to achieve increased concentration, and to adequately resist deflections due to wind and gust loads. Based on the prototype tests, we conclude that the concept is technically feasible and shows definite promise to enable a paradigm-shift cost reduction for heliostats and solar thermal powerplants. Collaborative efforts are currently underway with another company, to design and build a further refined pre-production inflatable heliostat with greater emphasis on modular construction to permit transportation of deflated heliostat modules in standard shipping containers.

3. REDUCED COST INFLATABLE CONCENTRATING PHOTOVOLTAIC MODULES

As another major step in the utilization of lightweight, low-cost inflatable structures for solar power, a patent-pending invention called "Surya" has been developed for stand-alone inflatable heliostatic solar power collectors. A diagram illustrating the key features of the Surya concentrating photovoltaic (CPV) module concept is shown in Figure 8.

FIGURE 8



Low-cost stand-alone inflatable CPV modules such as Surya can serve large markets for small, medium, or utility scale applications- where central receiver powerplants using inflatable heliostats are best suited only for medium or utility scale application. The inflatable heliostatic power collectors now use membrane reflective surfaces “sandwiched” between upper and lower inflated chambers, and an elongated solar power receiver such as a linear CPV receiver, which receives sunrays reflected and concentrated by the membrane reflective surface. The utilization of modest concentration ratios in the range of 5 to 15 suns, should enable benefits in both reduced cost and increased conversion efficiency, relative to simple prior-art flat plate solar panels. The modest concentration ratios selected enable significant solar cell area reduction relative to flat panel solar modules with no concentration, while still using low-cost silicon solar cells and simple, low-cost forced air cooling systems. The inflatable structure includes application of simple lightweight and low cost frame members. One or two-axis heliostatic aiming is employed, using simple and low cost control using gear motor or stepper motor actuation. The Surya invention is intended to provide great flexibility and value in tailored applications using varying numbers of the low-cost inflatable heliostatic power collectors in varying scalable size designs. Optimal uses can be found in applications ranging from (i) one or a few units for private home installations on a rooftop or back-yard, to (ii) estate, farm, ranch or commercial building installations with a small / medium fields of units, to (iii) utility scale installations with medium / large fields of units. Variants may also use liquid cooling of the linear CPV receiver and provide hot water for home, swimming pool or commercial / industrial use.

In addition to the primary goal of achieving much low cost levels of solar energy per watt-hour, the Surya inventive solar power collectors are intended to achieve the following additional important goals:

- Simple, reliable and robust design suitable for various implementation scales
- Transportability by pickup truck or non-oversize flatbed trucks, for small scale solar power modules
- Increased kilowatt-hours per day extractable for a given reflector surface size, by the use of one-axis or two-axis heliostatic pointing
- Low cost and high efficiency through the use of concentrating photovoltaics with modest concentration ratios (typically in the 5 to 15 suns range)
- Optional synergistic use of a PV receiver water cooling system to provide solar heated water for swimming pool heating or water heater feed
- Optional combination of a solar thermal power system integrated with a concentrating photovoltaic power system, to enhance power output for a given reflector surface size

A full-scale prototype of the Surya inflatable concentrating photovoltaic module with 6.7 square meters of reflective area, has been built and is being tested. The intent of this proof-of-concept prototype, built under funding by RIC Enterprises, is to show technical viability of the basic concept and to identify design, build and operational refinements for subsequent pre-production and production models.

A key attribute of the full-scale Surya prototype is that while it uses only 48 in-line high-efficiency silicon solar cells as compared to 72 solar cells in a comparable state-of-the-art high-efficiency solar panel, it is designed to produce 300% or more annual harvestable solar energy through its combined use of 8x concentration and one-axis Sun-tracking. It is estimated that for use in Southern California or Arizona, a production version of the Surya prototype module could potentially harvest over 3000 kW-hr per year, as compared to just around 530 kW-hr per year for the conventional state-of-the-art high-efficiency solar panel.

Fabrication of the full-size prototype has shown that the basic design of a linear concentrating photovoltaic module with a reflective membrane sandwiched between two elongated inflatable volumes is technically feasible. Low cost should be achievable in a production design, though the full-scale prototype cost was high due to the large amount of hand fabrication needed.

Figures 9 and 10 show photographs of key aspects of the Surya full-scale prototype.

FIGURE 9

FIGURE 10

Some specific results are as follows. The perimeter frame and sandwiching inflatable chambers were able to hold the aluminized polyester reflective membrane in an upwardly concave substantially cylindrical geometry to focus reflected light onto the single row of solar cells. The ethylene tetrafluoroethylene (ETFE) transparent upper surface demonstrates high transparency, strength, and should offer good life in adverse weather conditions. Testing to date has shown satisfactory performance in 35 mile per hour winds and satisfactory operation of the rain wash self-cleaning feature of ETFE. For hazardous conditions (e.g., hail, windstorm etc.) an inverted stow configuration of the module has been demonstrated, with the transparent membrane facing down and a rugged but inexpensive bottom membrane made of reinforced polyethylene material facing up to receive the hazardous precipitation. A high-reduction DC gearmotor and belt drive commanded by a Sun-tracking sensor provided satisfactory accuracy for the one-axis heliostatic tracking function. A significant learning on an area needing further improvement is that the 300 cfm DC cooling fan appears to be inadequate for the 8+ sun concentration, especially when the linear focus beam width was less than the full width of the solar cells for the linear receiver position that was initially tested.

The proof-of-concept prototype has validated that polar axis tilt plus 1-axis pointing offers an effective design solution that strikes a good balance between lower complexity relative to 2-axis pointing on the one hand, and higher solar energy collection relative to fixed orientation conventional solar panels on the other hand.

4. CONCLUSIONS & RECOMMENDATIONS

Prototype efforts on inflatable solar devices including an inflatable heliostat and an inflatable concentrating photovoltaic module have validated that light, low-cost reflective membranes can be used for reflection and concentration of solar radiation, when they are supported by a lightweight perimeter frame and sandwiched between two inflatable volumes to provide robust protection from wind and precipitation.

No technical flaws have been found that would inhibit the development and deployment of production inflatable heliostats for central receiver solar thermal powerplants for cost-effective utility-scale renewable energy. Similarly, no technical flaws have been found that would inhibit the development and deployment of production inflatable concentrating photovoltaic modules, for cost-effective renewable energy for private and small commercial customers.

However, additional design and manufacturing refinements will be required for both categories, based on the detailed lessons learned from the prototype tests and based on design-to-cost principles and practices. The next step for the inflatable heliostat R&D is design, manufacture and test of full-scale prototype or pre-production units. The next step for the Surya inflatable CPV modules is manufacture and in-service evaluation of pre-production units, leading to certification and commercial production of refined design modules.

5. ACKNOWLEDGEMENTS

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