BENEFICIAL APPLICATIONS OF INFLATABLE HELIOSTATIC MIRRORS

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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 inflatable heliostatic mirrors both for central receiver powerplants and for concentrating photovoltaic modules. In each case a concentrating reflective mirror, typically a frame supported reflective membrane, is contained within an inflatable envelope. Prototype development and testing of inflatable heliostat technology was originally accomplished under a DOE-sponsored prototype project. The inflatable concentrating reflector technology is now being applied to Research, Development and Demonstration (RD&D) work on evolving innovative solar power systems aimed at dramatically improving cost-effectiveness. Designs will be discussed for a refined lightweight, low-cost inflatable heliostat for central receiver solar thermal powerplants; for a stand-alone inflatable concentrating photovoltaic module for ground or rooftop applications; and for a floating hybrid solar power system synergistically integrating concentrating photovoltaic (CPV) and solar thermal subsystems.

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 (Ref. 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 (Ref. 2). World solar energy distribution is shown in Figure 1 from Ref. 3.

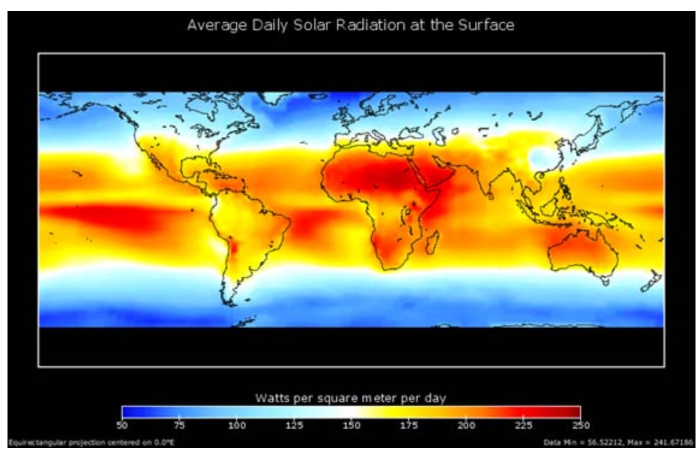

Fig. 1

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; Ref. 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.

It is evident that dramatically increased global utilization of solar power is highly desirable as solar power (i) is essentially inexhaustible, (ii) produces no carbon dioxide that contributes as a greenhouse gas to climate change, (iii) does not contribute to pollutants associated with fossil fuel power including unburned hydrocarbons and NOx, and (iv) can help reduce dependence on fossil fuel supplies from geopolitically volatile sources.

2. INFLATABLE HELIOSTATS FOR REDUCED COST SOLAR THERMAL POWER

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 (Ref. 4), and a very recent study by the Melbourne Energy Research Institute validates that heliostats remain the single largest cost element of central receiver solar thermal powerplants (Ref. 5). As a key enabler for low cost solar power, the inventive use of inflatable heliostats for large central receiver solar thermal powerplants has been documented in the foundational U.S. patents 5,404,868 (Ref. 6) and 8,127,760 (Ref. 7).

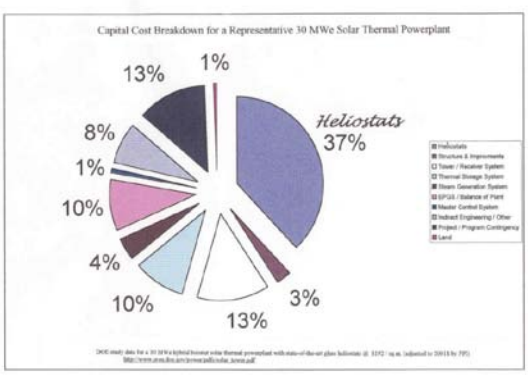

Fig. 2

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 initial design for a near-spherical inflatable heliostat was prototyped for proof-of-concept testing under DOE funding. This prototype is shown in Fig. 3 below.

Fig. 3

Key objectives of this prototype design included:

- Simple drive system using only two motors with low torque requirements
- Inertia and aerodynamic loads act directly through the support system
- Aerodynamic loads from winds and gusts are relatively low due to low drag coefficient of a near-spherical shape
- The membrane mirror can be focused using differential pressure
- The inflated domes protect the membrane mirror from exposure to weather and winds
- A combination of low loads, direct load paths, and the inherent efficiency of inflated structures enables a lightweight, low-cost design

The revised prototype 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 4.

Fig. 4

The prototype tests indicate that the heliostat pointing system does accurately aim the heliostat without distorting the reflective surface, and achieved a good near-circular beam shape with concentration ratios of up to 8.7 using differential pressure between the upper and lower hemispheres of the inflatable structure housing the reflective membrane. Encouraging results were obtained in the presence of environmental factors such as winds, gusts, temperature variations and precipitation.

Building upon the prototype work, further development was undertaken to design a larger production-scale inflatable heliostat. A design constraint for the production-scale design, in order to contribute towards lowered total costs, was the constraint of ability to ship many heliostats in a compact deflated configuration, in standard 8 foot wide shipping containers that are transportable at low cost by rail or truck.

While many alternate configurations and embodiments of inflated heliostats are shown in the Ref. 7 recent patent, preliminary analyses show that a more preferred configuration to minimize cost while meeting performance and transportability constraints, is the somewhat elongated inflatable heliostat configuration shown in Figure 5.

The light-weight, low-cost preferred inflatable heliostat design shown above has 15.6 square meters of reflective area, is designed for good wind and weather resistance, and is easily transportable with ten units transportable in a single 53 foot long “high cube” standard shipping container, with the heliostat deflated and packed in on edge.

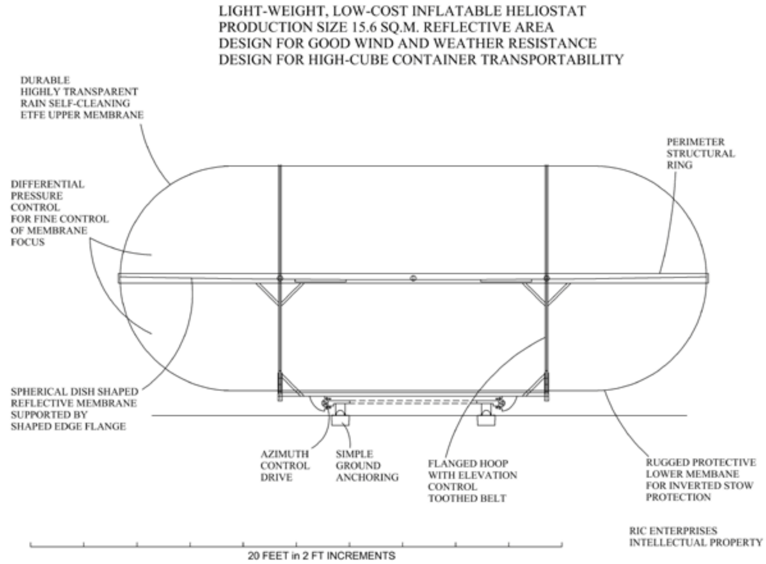

Fig. 5

While the reflective area is smaller than that of conventional steel and glass mirror heliostats, a recent optimization study indicates that even conventional heliostats will cost optimize at smaller than traditional sizes, at 20 to 40 sq.m. (Ref. 8), and with the present inflatable design the optimum becomes even a bit lower, to get the advantage of multiple heliostat shipping in standard containers. Recent heliostat cost studies (Ref.s 8, 9, 10) indicate that a large part of heliostat cost is still driven by the mirror modules and pedestals and drives having to withstand severe wind conditions, both in operational mode for gusts below 30 or 50 mph, and in survival mode with gusts up to 90 mph. The rounded configuration of the inflatable heliostat of Fig. 5 sits very low to the ground in the boundary layer, and has low drag coefficients especially in the pointed into the wind survival mode. This shape of the inflated module, the small size, and the low-to-the-ground installation all have synergistic benefits in enabling much lighter structures and much less powerful actuators being needed, and the pedestal is eliminated altogether. Installation costs will also go down correspondingly. With all these improvements, the inflatable heliostats in volume production should be able to achieve an installed cost level of $100 / sq.m, as compared with around

$170 / sq.m. for conventional heliostats in volume production (Refs. 8, 9).
Collaborative efforts are currently underway with an Australian company, to finalize the design, then build and test a pre-production prototype of this new improved design.

3. LOW COST INFLATABLE CONCENTRATING PHOTOVOLTAIC MODULES

As another major step in the utilization of lightweight, low-cost inflatable structures for solar power, an invention called "Surya" has been developed for stand-alone inflatable heliostatic solar power collectors. This invention is documented in U.S. patent U.S. patent 7,997,264 (Ref. 11) and patent-pending US20110277815 (Ref. 12). A diagram illustrating the key features of the Surya concentrating photovoltaic (CPV) module concept is shown in Figure 6.

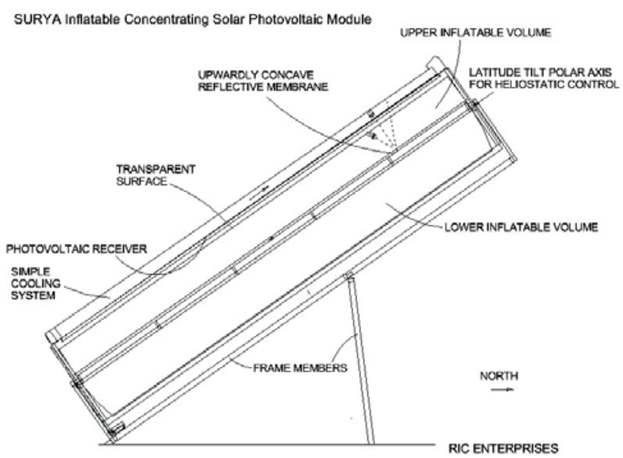

Fig. 6

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 or volumes, and an elongated solar power receiver such as a linear concentrating photovoltaic (CPV) receiver, which receives sunrays reflected and concentrated by the membrane reflective surface. The utilization of modest concentration ratios in the range of 3 to 13 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 or liquid cooling systems. The inflatable structure includes application of simple lightweight and low cost frame members.

A proof-of-concept prototype of the Surya inflatable concentrating photovoltaic module with 6.7 square meters of reflective area has been built and tested to show technical viability of the basic concept and to identify design, build and operational refinements for subsequent prototype, pre-production and production models.

Figure 7 shows photograph views of some key aspects of the Surya proof-of-concept prototype.

Fig. 7

Some specific results are as follows. The proof-of-concept prototype has validated that 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 demonstrated high transparency, strength, and should offer good life in adverse weather conditions. Testing has shown satisfactory performance in 35 mile per hour winds and satisfactory operation of the rain wash self-cleaning feature of ETFE. For hazardous weather conditions 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. 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 was inadequate for the 8+ sun solar concentration.

Note that while the Fig. 6 and Fig. 7 illustrated embodiment of the Surya invention uses a polar tilt axis and one-axis heliostatic tracking, alternate embodiments can use two-axis heliostatic tracking, to further improve energy harvest in seasons spaced away from the baseline seasons corresponding to the set polar tilt (e.g., typically around the vernal and autumnal equinoxes).

Recently design has been completed on such an improved version of Surya with two-axis heliostatic tracking and some other design refinements, and this improved version is shown in Fig. 8.

The Surya class of invention, with one or two axis tracking, is intended to provide great flexibility and value in tailored applications with 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.

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 extractable kilowatt-hours for a given reflector surface size, by the use of 1-axis or 2-axis heliostatic pointing
- Low cost and high efficiency through the use of concentrating photovoltaics with modest concentration ratios (typically in the 3 to 13 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 or commercial / industrial purposes
- 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

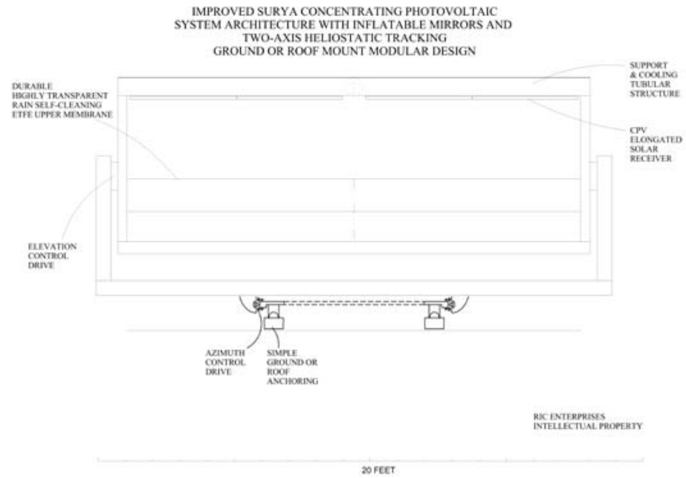

Fig. 8

4. COST EFFICIENT FLOATING HYBRID SOLAR POWER SYSTEMS

An inventive evolution of the Surya inflatable concentrating photovoltaic modules described above, is to mount modules such as this on a floating turntable, and use rotation of the whole turntable on the water for the azimuth control part of two-axis heliostatic control, with the elevation control still done at each module. This embodiment has been described in Ref. 12 and is called the “Concentrating Offshore Solar System” or “COS System.”

Concentrating Offshore Solar (COS) Systems constitute a paradigm-shift new class of solar energy harvesting inventions that use sun-tracking and concentration, offshore siting with near-zero land use, and can combine concentrating photovoltaic and optional solar thermal elements to maximize energy harvest and minimize cost per delivered kilowatt-hour. Desalinized / distilled water and/or solar hot water can also be synergistically produced. Figures 20 through 23D in Ref. 12 describe several embodiments of COS Systems of different sizes and configurations. A representative COS System engineered for an offshore installation with floating azimuth tracking, is shown in plan view in Fig. 9 on the following page.

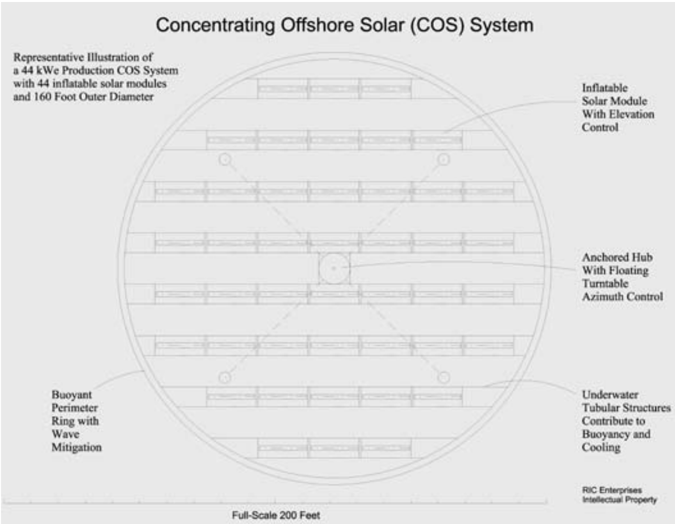

Fig. 9

The operating principles of the floating Concentrating Offshore Solar System are evident from this Figure, with the use of azimuth rotation of the floating assembly combined with elevation rotation of the 44 individual elongated solar modules to achieve true two-axis solar tracking for optimized performance. Some of the solar modules could use bifacial solar cells with one sun on the upper side shining though a transparent water cooling rectangular tube, and between three and thirteen suns concentrated power on the lower side that receives reflected concentrated light from the low-cost inflatable reflector submodules. These concentrating photovoltaic modules use water cooling that keeps the solar cells from overheating, and the heated water is optionally pressurized and fed into downstream solar thermal modules where it is heated further by concentrated sunlight at 60 to 80 suns in boiler tubes and superheating tubes for direct steam generation, and then run through a Rankine cycle thermodynamic powerplant to generate additional electric power over and above that harvested by the solar cells. To increase the solar power harvest still further, future versions may use high temperature solar cells in conjunction with the boiler and superheating tubes, such as graded IndiumGalliumNitride ($In_{1-x}Ga_xN$) photovoltaic devices now under development, that can achieve 40% solar conversion efficiency (Refs. 13, 14). Such future versions, through the combined use of concentrated photovoltaics with both Silicon cells and InGaN cells and the solar thermal Rankine cycle powerplant, could achieve unprecedented solar conversion efficiencies of 40% to 50% in utility-scale offshore powerplants. In addition to the steam cycle heat engine, ancillary submodules may be provided for distillation, desalination and/or hot water production using heat from the steam or hot water in the closed cycle, either directly or through a heat exchanger. The steam runs through a condenser under the floating installation, and the return cycle subsequently provides further cooling of the closed loop water flow substantially down to the sea or lake temperature.

A key technological merit of the COS System is its easy scalability for cost-effective systems ranging from a small 10m radius system providing 2 kWe from a pond or lake or river setting for a personal residence, to a 12 kWe 30m radius system for a ranch or small commercial establishment, to a 240 kWe 120m radius system for larger commercial entities, to a 25 MWe 1 km radius system for utility applications. The most promising utility-scale applications in the U.S.A. would be in offshore salt water locations in Guam, Hawaii, California, Texas, Louisiana, Mississippi, Alabama, Florida, Puerto Rico, Georgia, the Carolinas, Virginia, Maryland, Delaware, New Jersey, New York and New England. With the U.S. offshore exclusive economic zone covering an area of around 11.3 million square kilometers, use of 100,000 sq.km. or only about 1% of this U.S. EEZ area for COS systems could approximately meet the anticipated 2025 average total electric energy demand of the U.S. of around 5200 billion kW-hr. In addition to the huge offshore solar potential, many varied-scale applications on fresh water bodies (e.g., Great Lakes, other lakes, reservoirs, rivers etc.) or salt water bodies (e.g., Salton Sea, Great Salt Lake) in inland states of the U.S.A. are also very promising. A version of the COS system has been designed to enable continued winter operation even on bodies of water that freeze during the winter, as happens in northern states. Location of many ideal sites for COS Systems in the U.S.A. should also help reduce U.S. dependence on expensive, dirty and geopolitically vulnerable foreign fossil fuel sources. Obviously many global applications to meet total global power needs with essentially zero carbon footprint and essentially zero land use, are also very feasible if this new offshore solar technology is advanced to rapid commercialization with mitigated technical risks and reduced delivered energy cost.

Relative to current non-concentrating solar photovoltaic systems, the COS system provides greater energy yield per solar cell through the use of tracking and concentration. Relative to current solar thermal systems, the COS system provides greater net efficiency of the solar thermal subsystem by using preheated working fluid from the CPV subsystem and by the optional use of InGaN or other high temperature solar cells adjacent to the solar thermal direct steam generation pipes. By integrating CPV and solar thermal subsystems, greatly increased energy yield and reduced delivered energy cost are enabled. Use of light weight, low cost inflatable structures for the reflector submodules and use of a simple, reliable two-axis hybrid tracking system further contribute to improved cost-effectiveness relative to current solar power harvesting systems. Dramatic reduction of dedicated land use &

dedicated cooling water use and provision of optional distilled, desalinated or heated water are additional benefit mechanisms of these paradigm-shift COS Systems.

COS Systems utilize many components that are already in service in other applications, such as various types of solar cells and solar thermal receivers, direct steam generation powerplant subsystems (Refs. 15, 16), Sun-tracking control systems, cooling systems, and electrical power systems. However, the integration of these components and subsystems into an effectively engineered and synthesized floating Offshore Concentrating Solar system that will function reliably in a potentially hostile environment at the water surface (subject to waves, swells and spray under storm conditions), is judged to be only at Technology Readiness Level TRL 4. RIC Enterprises with collaboration from Florida Atlantic University and Columbia University is planning development and test of a Proof-of-Concept prototype of a COS System to advance technology to TRL 7, subject to winning funding from ARPA-E. Testing of a fully functional COS System prototype is planned in a real waterborne operating environment in Florida. Supporting objectives include demonstrating configuration integration and proof of wave-mitigation, buoyancy, structural, mechanical, bearing, stabilization, control and electrical subsystems. A technology roadmap and a product development plan, also incorporating risk identification and mitigation elements, will be formulated to enable subsequent advancement of COS Systems to a targeted entry into service of fully operational initial production systems by 2015, with low risk.

5. 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.

An additional important application of inflatable concentrating devices is to a new type of floating solar power system, the Concentrating Offshore Solar System or COS System. While this concept is still in a relatively early stages of development, it holds high promise for future applications ranging from small-scale private installations on ponds or lakes, to giant utility-scale installations that can set a new standard of solar power harvesting efficiency and cost-effectiveness. The next step for COS Systems development is the design, fabrication and test of a proof-of-concept prototype.

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