Inflatable Membrane Solar Concentration
Systems for Space-Based Applications

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Abstract. A major focus of our course has been the $/Watt$ metric used to evaluate photovoltaic (PV) technologies. However, this metric does not necessarily apply when analyzing non-terrestrial PV systems. When the deployment environment is in space (or on other planets), there are many new challenges. The first challenge is related to the PV systems traveling away from the Earth, where distance from the sun is increasing. In these scenarios, the amount of incident solar radiation drops off quickly, by $1/d^2$, where $d$ is the distance between the PV system and the sun. In order to produce the same amount of electrical energy, the PV system must be scaled accordingly. However, this is hampered by the second challenge, which is related to volume and mass – namely, modern launch payload costs exceed $10,000/kg! For a PV system, this figure clearly overshadows the $/Watt$ metric used during class. This illustrates that a more important metric, either $$/kg$ or weight-to-area scaling in kg/m$^2$, is probably better suited for non-terrestrial PV systems. With this in mind, the goal of Space-Based PV systems is to maximize efficiency while minimizing volume and mass. This paper will discuss a possible solution to these challenges – inflatable membrane solar concentrators.

In this paper, I will elaborate on the challenges associated with space-based PV systems, demonstrate the scaling factors involved, discuss the fundamental principles of inflatable membrane concentrators, compare terrestrial and non-terrestrial inflatable membrane systems, and will conclude with several potential applications for future research directions.
1 Space-Based Challenges, Motivation, & Background

Consider the challenges brought up in the abstract. For space-based PV systems, the final destination has three possible locations: closer to the sun than Earth, near Earth, or farther from the sun than Earth. In the first two cases, the incident solar radiation is at or better than $1.2 \text{ kW/m}^2$. However, with NASA plans to have manned Mars mission by the year 2020, many if not most space-based PV systems are outward-bound. In this case, the amount of incident solar radiation drops off quickly, by $1/d^2$, where $d$ is the distance between the PV system and the sun. Near Earth, the PV system will be 1.0 Astronomical Unit from the sun (the Astronomical Unit, or AU, is the distance between the Earth and sun), and the incident radiation is $1.2 \text{ kW/m}^2$. However, on Mars, which is 1.52 AU from the sun, the exact same PV system will only output $1.2/1.52^2 = 0.519 \text{ kW/m}^2$. This relationship is shown in Figure 1. In order to produce the same electrical output on Mars as on Earth, the PV system would need to be twice as large!

However, larger PV systems exacerbate the issue of payload volume and mass costs (which as mentioned, exceed $10,000/kg$)! For a space-based PV system, the payload cost clearly overshadows the $\$/W metric used during class. This illustrates that a more important metric, either $\$/kg or weight-to-area scaling in kg/m$^2$, is probably better suited for non-terrestrial PV systems. With this in mind, the goal of Space-Based PV systems is to maximize efficiency while minimizing volume and mass. One possible solution to the scaling problem is to increase the effective area of the solar cell by employing a concentrator. Consider a comparison between the weight-to-area scaling in kg/m$^2$ of 200 $\mu$m thick
crystalline silicon solar cells (with density 2330 kg/cm³) versus a 200 µm thick mylar film (with density 1393 kg/cm³)[1].

\[
\text{Silicon Scaling : } 2330 \, \frac{kg}{m^3} \times 200\mu m = 0.466 \frac{kg}{m^2}
\]

\[
\text{Mylar Scaling : } 1393 \, \frac{kg}{m^3} \times 200\mu m = 0.279 \frac{kg}{m^2}
\]

\[
\text{Mylar Scales } \frac{0.466}{0.279} = 1.67 \text{ times better than Silicon!}
\]

Even this estimate of weight-to-area scaling is optimistic. The mylar film scaling does not suffer from large module-mounting scaffold weight (only out the outer rim instead of on each module), and the mylar sheet folds up nicely for volume savings (and protection) during launch. All things considered, the solar concentrator (for large systems) scales by 1-to-2 orders of magnitude compared to PV modules!

Concentrator technology is not new; there has been an abundant amount of research in different types of terrestrial-based concentrators, as shown in Figure 2. In fact, very high net efficiencies have been achieved for large utility-scale (1 GWatt) systems[2] [3].

![Figure 2. “Classic” terrestrial concentrator types [4]. (Left) Heliostat with central receiver (Center) Dish-type (Right) Trough-type](image)

Figure 3 shows the approximate concentration ratio for the different technologies. In general, the goal is to concentrate the available sunlight (utilizing a large area) onto a small, high performance, multi-junction solar cell [5]. Unfortunately, many of these systems do not scale well in weight (or mass) due
to the large scaffolding systems employed. However, there is a way to modify the concentrator systems to make them scale well in weight – namely, to use inflatable systems, as discussed in [6]. These systems use minimal volume, and then use compressed air to “blow-up” or expand once in space. Inflatable Fresnel lens techniques have been used with success [7][8], and have demonstrated high net efficiencies (27.4% by [9]) – shown in Figure 4. However, their concentration ratio (and thus maximum weight-to-area scaling) isn’t as attractive as membrane-type inflatable concentrator. Thus, the challenges of non-terrestrial PV systems motivate the use of inflatable membrane concentrators (which is the focus of the remainder of this paper). From [10],

Stretched membranes for concentrating solar collectors offer the prospect of being very lightweight, structurally efficient, potentially low cost, and potentially similar in optical performance compared to the more conventional rigid glass/metal concentrator design approaches used in heliostat and parabolic dish applications.

### 2 Inflatable Membrane Concentrator Fundamentals

Inflatable membranes are a simple physical phenomena wherein the deformation of a thin-film membrane is determined by three parameters: the tension on the thin-film, the boundary conditions, and a uniform applied pressure. The uniform pressure is applied either by a positive pressure (inflation) or by negative pressure (vacuum). In the most simple case (a circular boundary condition), the solution to the differential equations governing this physical system results in spherical or parabolic deformation, as discussed in [12] and [10] and is shown in Figure 5. By applying a reflective coating to the thin film, the parabolic or circular shape can be used to focus sunlight – making it a solar concentrator. It is worth mentioning that although most membranes are static with circular boundaries, it is possible
Fig. 4. “Stretched Lens Array” inflatable Fresnel lens assembly for space-based operations[9].

to create dynamically changing, arbitrary lens shapes. Such systems have been developed to build inexpensive eyeglass lenses, and could also be applied to dynamic, steerable concentration systems [11].

Because of the straightforward physical specification of membrane concentrators, they have also been employed in terrestrial systems. For mechanical

Fig. 5. Shape of a membrane is determined by tension, boundary conditions, and an applied uniform pressure. By controlling these parameters, circular, parabolic, or arbitrary lens/concentrator shapes can be created [11][12].
stability, such systems typically rely on negative (vacuum) pressures, and still use bulky mechanical frames, as shown in Figure 6.

Meanwhile, space-based membrane concentrators (as seen in Figure 7) cannot use vacuum pressures (space is a vacuum after all). Thus, they rely on positive pressures, or inflation. A number of solar, space-based inflatable membrane concentrators have been developed by NASA over the years [14].

3 Challenges (and Solutions) to Membrane Solar Concentrators

As with any technology, membrane solar concentrators have a set of unique challenges. In this section, I will discuss the challenges and cutting-edge attempts to address them.
3.1 Seal Leakage and Puncturing

By their very nature, membrane systems must maintain their constant pressure in order to maintain their optical properties. However, no system has perfect sealing. The constant leaking must be compensated by applying continuous negative pressure (as in terrestrial systems that use vacuum pumps) or by applying continuous positive pressure (meaning continuous gas inflation for space-based systems). The leakage problem can be severely compounded if the thin-film membrane is punctured. This is very serious issue for satellites (due to Kessler Syndrome, the compounding build-up of space junk in low-Earth orbit) and for Mars systems (due to strong winds and flying sand). Once the stored gas reserves are depleted, the solar concentrator is crippled.

The solution to this problem is being addressed by [15], where they rigidize or harden the inflated membrane for prolonged, persistent use without continuous inflation gas. The techniques explored were the work-hardening of an aluminum/plastic laminate, the cold-rigidization of a Kevlar/thermoplastic-elastomer, and UV-hardened resins. They were able to show successful rigidization, though the accuracy probably needs improvement. It is envisioned that once rigidization is performed, the canopy for the inflation chamber can be discarded (for weight and transparency). A hypothetical, rigidized system is shown in Figure 8.

![Fig. 8.](image)

Ultimately, it is desirable to make the membrane rigid – rendering the concentrator unaffected by pressure changes, acceleration, and minor damage [15].

3.2 Environmental Resistance

As mentioned, environmental factors (like space junk for satellites and flying sand on Mars) are very serious concerns. One way to mitigate damage is to rely on redundant smaller concentration systems. This approach is utilized by an innovative, new company called Cool Earth Solar out of California [16]. They use arrays of low-cost, 2-meter diameter, inflatable membrane concentration systems. A system diagram is shown in Figure 9 and product photos in Figure 10.
Curiously, despite the fact that such a system is well-suited for space applications, it is primarily targeted at terrestrial solar installations! Based on corporate guidance [17], their system boasts:

- Inflatable mirrors that are 400x cheaper than polished aluminum mirrors.
- 2-meter diameter concentrators.
- The ability to withstand 130 mph winds.
- Can be repaired with tape, and replaced in 15 minutes.
- Cost of concentrator is a mere $2.
- Rigging requires 60x less steel than truss work (compared to conventional solar).
- System cost is $0.18 / Watt for materials, $0.29 / Watt Installation (compared to $4-5 / Watt for conventional solar).

Unfortunately, their system (for reasons previously mentioned) must service/replace/refurbish the individual modules each year. Despite this drawback, this is an exciting technology worth watching, as it utilizes the inexpensive area scaling of membrane solar concentrators for distributed terrestrial applications!

![Fig. 9. CoolEarth Corp. system overview [16][17].](image)

![Fig. 10. A new type of sealed membrane concentrator by CoolEarth Corp. uses 2-meter diameter inflatable mirrors (one side transparent, one mirrored) that are 400x cheaper than polished aluminum, withstand 130mph winds, require 60x less steel for rigging, and cost are mere $2 each [16][17].](image)
3.3 Solar Alignment and Other Considerations

It should also be noted that concentrators must be able to track the sun within their acceptance angle. Because of this, inexpensive polar tracking is a must. For satellite-based systems, this is performed via attitude adjustment. However, for planetary tracking, a simple and robust system (like Cool Earth Solar’s guy-wires, see Figure 9) should be employed.

Another important consideration for satellite-based systems is the effect of the concentrator on spacecraft design and performance. These issues are covered by [18].

One final consideration is heat dissipation. Luckily, space-based applications have the benefit of extremely cold ambient temperatures, making heat dissipation easier. However, proper heatsinking and/or heatpumping should be employed to maintain optimal solar generation. In many applications, the thermal gradients generated by concentration are actually used via Stirling engines or thermoelectric generators for additional electricity generation. The heat generated is actually the primary electricity generation method for the NASA membranes from [14], and shown back in Figure 7.

4 Proposed Additional Applications

Fig. 11. Other potential applications – beamed power [19] (left) and the space elevator [20] (right).
As already implied, membrane and inflatable concentrator PV systems are particularly useful for situations requiring decent efficiency and minimal weight. There are a whole class of applications operating in the upper troposphere or low-Earth orbit that can benefit from these same requirements. A few of the applications are pictured in Figures 11 and 12. The projects shown include:

– A solar energy harvester being investigated by the Pentagon that collects solar energy in space, beams it via radio waves to the Earth’s surface, then distributes it.
– The space elevator conceived by Arthur C. Clark and the focus of a NASA/DARPA Challenge. Payloads are transferred to low-Earth orbit by a small robot. The robot is power via solar cells illuminated by a ground-based laser. The whole apparatus has its center of mass in geosynchronous orbit.
– NASA’s Helios project, which is a solar-powered, high-altitude, unmanned airplane used for atmospheric science.
– Lockheed Martin’s solar-powered blimp for high-altitude communication relaying.

![Fig. 12. Other potential applications – NASA’s Helios, a high altitude unmanned airplane [21](left) and the “solar blimp” for high-altitude operation [22](right).](image)

5 Conclusions

Using knowledge acquired from class and from the additional referenced literature, this paper addressed the key requirements for non-terrestrial PV systems. We noted how modern launch payload costs in excess of $10,000/kg dictate volume and mass requirements, in addition to efficiency, for such PV systems. I showed that, although alternate systems exist, inflatable membrane concentration systems offer excellent weight-to-area $kg/m^2$ scaling (at 1-to-2 orders of magnitude better than PV modules) at decent efficiency – thus addressing space-based requirements. Via the literature, we showed how such systems are designed using thin-film membranes with boundary conditions and applied pressure. We looked at some of the challenges and cutting-edge solutions to problems
related to inflatable membrane concentrators. Finally, I introduced a few additional application areas that could benefit from the same advances, identifying future research problems. Inflatable membrane solar concentration technology has a bright future.

References

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