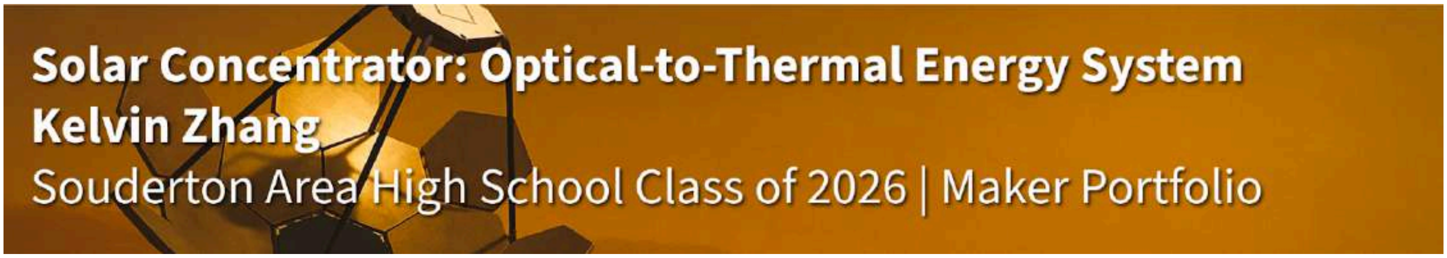


Abstract

Sustained, crewed exploration of Mars presents a fundamental energy challenge, as available solar irradiance is significantly reduced by heliocentric distance and further degraded by dust accumulation and atmospheric scattering. Photovoltaic systems become increasingly area-limited under these conditions, while the scarcity and production limits of suitable radioisotopes constrain radioisotope thermoelectric generators. These opposing limitations motivate intermediate energy architectures that decouple light collection from direct electrical conversion. This project investigates a solar concentrator system that converts diffuse solar flux into thermal energy before electrical utilization. A segmented array of parabolic mirrors is arranged in a hexagonal geometry to focus sunlight onto a centralized interface that serves a dual function: acting as a heat exchanger for a water-based heat pump system and as a mounting surface for thermoelectric generator modules.

The concentrator was developed through multiple iterations of mirror geometry, informed by optical alignment challenges, focal convergence behavior, and fabrication constraints. Rather than maximizing mirror count, the design emphasizes precision alignment and controlled energy flow, supported by a sun-tracking mechanism using light-dependent resistors and servo actuation. Experimental evaluation focused on validating the sun-tracking system and visually observing light convergence behavior at the focal region, revealing strong sensitivity to angular misalignment and surface imperfections.

1. Executive Overview

Problem Statement
Sustained human activity on the Martian surface presents a fundamental surface-energy problem governed by reduced solar irradiance, frequent dust accumulation, and limited resupply capability. Photovoltaic systems scale primarily through increased collection area and become increasingly constrained by deployment complexity and non-uniform illumination under these conditions. At the same time, radioisotope-based systems are restricted by material scarcity and production limits. These constraints motivate investigation into surface energy architectures that can tolerate variable solar input while decoupling collection geometry from direct electrical conversion.

Inspiration
This project originated from a much smaller-scale but structurally similar problem: evaluating affordable heating and cooling options for my mother's restaurant, which lacked a centralized HVAC system. Exploring why many commercial solutions failed to scale economically forced me to confront how energy systems are shaped not just by efficiency, but by geometry, cost, and operational constraints. That realization naturally extended to space-based energy systems, where those same tradeoffs are unavoidable and often define system feasibility.

Proposed Approach
Rather than maximizing photovoltaic surface area or relying on scarce nuclear materials, this project investigates a solar concentrator architecture that converts incident solar flux into thermal energy prior to electrical utilization. A segmented array of parabolic mirrors, arranged in a hexagonal geometry, concentrates sunlight toward a centralized interface that functions both as a heat-exchanger surface and as a mounting plane for thermoelectric generators. By prioritizing optical alignment, controlled energy flow, and tolerance to non-ideal illumination, the system explores an intermediate energy pathway that complements—rather than replaces—existing photovoltaic and radioisotope power systems.

2. Design Motivation & Physical Constraints

Energy Density Limits
On Mars, available solar power is reduced by both heliocentric distance and atmospheric effects such as dust and scattering. As a result, achievable surface energy density is limited and highly variable. Photovoltaic systems typically compensate by increasing collection area, but this quickly becomes constrained by deployment complexity and non-uniform illumination. These limitations motivate energy architectures that increase usable energy density without requiring proportional growth in exposed surface area.

Limits of Direct Photovoltaic Concentration
Under optical concentration, photovoltaic current increases roughly with incident flux, while voltage increases only logarithmically. This leads to diminishing electrical returns at higher concentration levels, as thermal loading and cooling requirements begin to dominate performance. In practice, this places limits on how effective direct concentrated photovoltaic systems can be, especially in environments where precise alignment and active cooling are difficult to maintain.

Thermal vs Electrical Energy Pathways
Thermal energy pathways are more tolerant of high local flux, uneven illumination, and transient misalignment than direct electrical conversion. By first absorbing concentrated light as heat, energy can be redistributed or buffered before conversion, reducing sensitivity to optical imperfections and environmental variability. This decoupling allows optical collection and electrical generation to be treated as partially independent design problems.

Off-Earth energy systems must prioritize scalability, material availability, and tolerance to non-ideal conditions. Architectures dependent on scarce nuclear materials or large photovoltaic deployments face limits in long-term expansion and maintenance. Concentrator-based thermal systems offer a complementary approach that leverages abundant solar input while remaining adaptable to harsh and variable extraterrestrial environments.

3. System Architecture Overview

Overall Energy Flow
The concentrator is organized around a simple energy path. Incoming sunlight is collected by twelve hexagonal parabolic mirrors and directed toward a shared convergence region. An offset secondary mirror intercepts the converging rays and redirects the concentrated beam toward the system's central target. At this interface, the optical energy is absorbed as heat and transferred into downstream thermal pathways for use or conversion.

Central Receiver as a Design Interface

In the current prototype, the central receiver functions as a fixed optical reference and thermal absorption surface used to observe convergence behavior and alignment sensitivity. The geometry of this interface was selected to also support future integration as a heat-exchanger surface and as a mounting plane for thermoelectric generator modules. While these dual roles were not experimentally evaluated in this iteration, consolidating them into a single reference point informed the optical layout and mechanical design of the system.

4. Optical Design & Mirror Geometry

Mirror Selection
Parabolic mirrors were used to reflect parallel incoming sunlight toward a predictable focal region without requiring complex optical materials. Each mirror segment was sized with a 250 mm hexagonal edge length, balancing aperture area with manufacturability, stiffness, and ease of handling. Using modular mirror segments also allowed damaged or underperforming mirrors to be replaced without rebuilding the entire array.

Segmentation & Tiling Strategy
A hexagonal mirror outline was chosen to maximize packing efficiency around a central target while minimizing unused area between segments. Hexagonal tiling provides rotational symmetry and allows mirrors to be arranged in concentric rings with repeatable spacing and mounting geometry. Segmenting the concentrator into discrete mirrors reduced fabrication risk and made it possible to tune optical performance through per-mirror adjustment rather than relying on a single monolithic dish.

Focal Convergence Strategy
The twelve primary mirrors are arranged symmetrically and oriented so that each segment directs reflected rays toward a shared convergence region. *(see figure 4.2)* Rather than forcing all reflected light to intersect directly at the receiver, an offset secondary mirror intercepts the converging beams and redirects them toward the central receiver plate. This approach allowed the receiver to remain within the mechanical footprint of the system while separating coarse mirror alignment from fine targeting at the receiver. Mirror tilt angles were defined individually based on ring position, making alignment sensitivity directly observable during testing. *(see figure 4.1)*

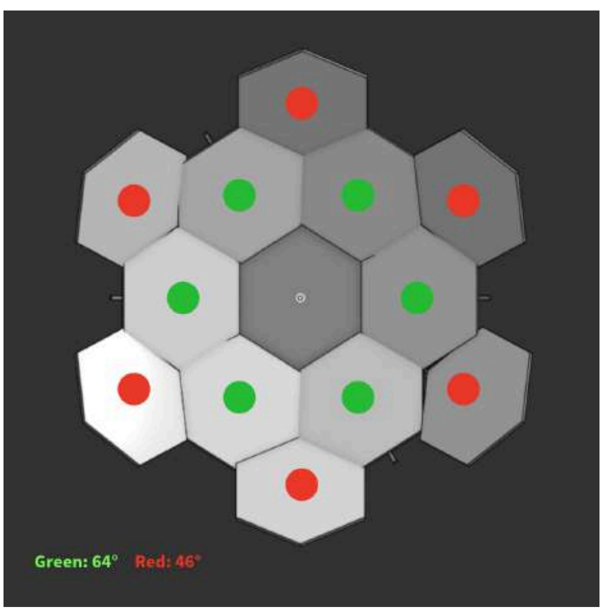


Figure 4.1

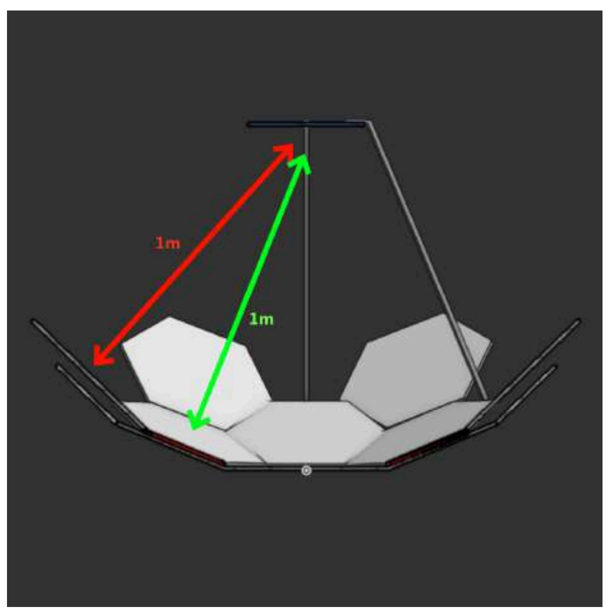
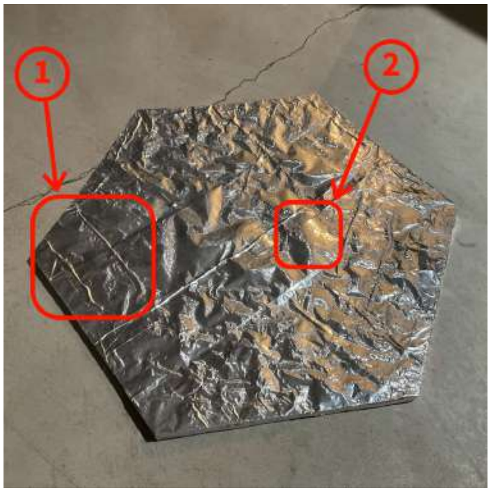
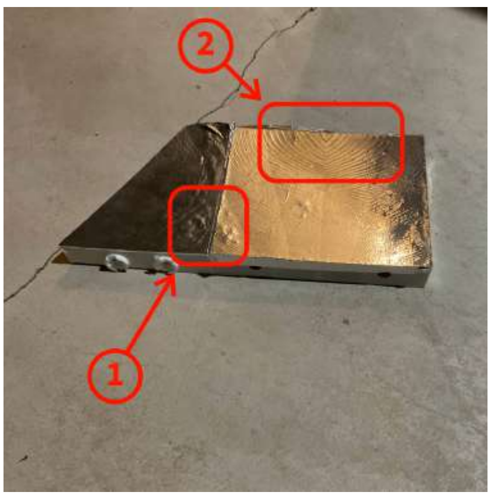
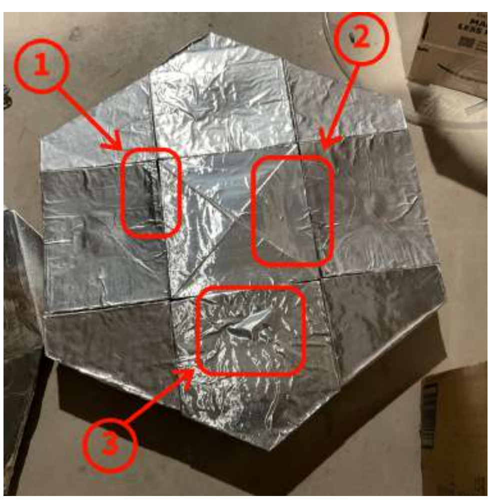


Figure 4.2

5. Iterative Mirror Prototypes

Mirror Design Iteration	Description of Problems
	***Iteration 1*** The first mirror iteration used hot glue to bond aluminum foil to the printed substrate. This introduced localized protrusions at bond points, distorting the reflective surface. In addition, air trapped beneath the foil created uneven contact, producing visible ripples that reduced specular reflection and disrupted focal convergence.
	***Iteration 2*** In the second iteration, mirrors were printed flat with a reduced top-layer count to minimize weight and material usage. However, unsupported bridge regions warped during cooling, particularly near the center of each segment. In shallow regions of the parabolic surface, layer stepping became pronounced, effectively negating the intended optical geometry.
	***Iteration 3*** The third iteration separated the reflective surface from the structural mounting features and printed mirrors on their side to fit all twelve segments on a single build plate. While this reduced print time, large exposed surface areas and ambient air drafts caused edge lifting and print failures. The thin mirror panels also gradually lost their parabolic profile as layers cooled, requiring post-fabrication repairs and manual bonding of mounting hardware.

6. Tracking & Alignment System

Custom-Made Light Dependent Resistor (LDR) Boards
Each light-dependent resistor (LDR) was mounted on a small custom PCB to allow repeatable placement within the tracking assembly. The sensors were wired in voltage-divider configurations, producing analog signals proportional to incident light intensity and readable directly by the microcontroller. A status LED on each board provided immediate visual feedback during setup and alignment. *(see figure 6.1)*

Sun-Tracking Concept
The tracking system is based on four LDRs arranged in a 2×2 quadrant configuration. Rather than estimating the Sun's absolute position, the system compares relative light intensity between opposing sensors. When the concentrator is aligned, all four sensors report similar illumination. Any imbalance indicates angular misalignment along a specific axis. (see *figures 6.2 & 6.3)*

The controller continuously evaluates these intensity differences and commands incremental corrective motion until the differential error is minimized. This approach prioritizes alignment accuracy over positional prediction and remains effective even under changing light intensity.

During development, Processing.org was used to visualize live LDR readings from the Arduino, enabling real-time interpretation of the controller's perceived light distribution.

Alignment Sensitivity
Testing showed that even small angular misalignments produced measurable differences between sensor readings, reinforcing the importance of precise tracking for sustained energy collection. Maintaining alignment increases cumulative energy capture by extending the duration of effective concentration, rather than relying on increased mirror count or aperture area.

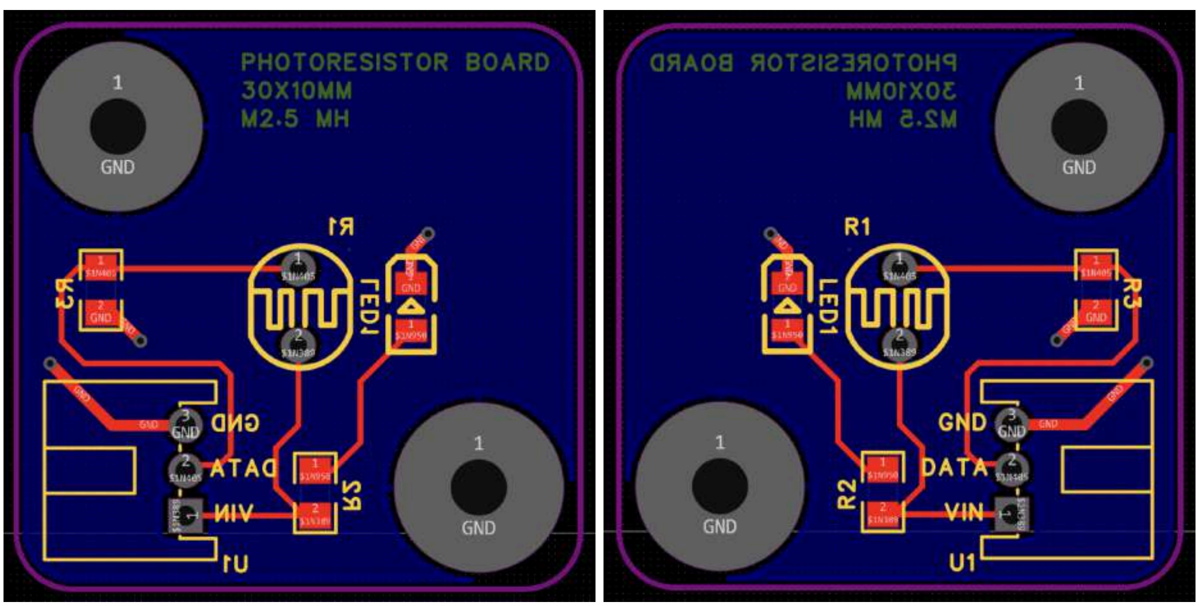


Figure 6.1

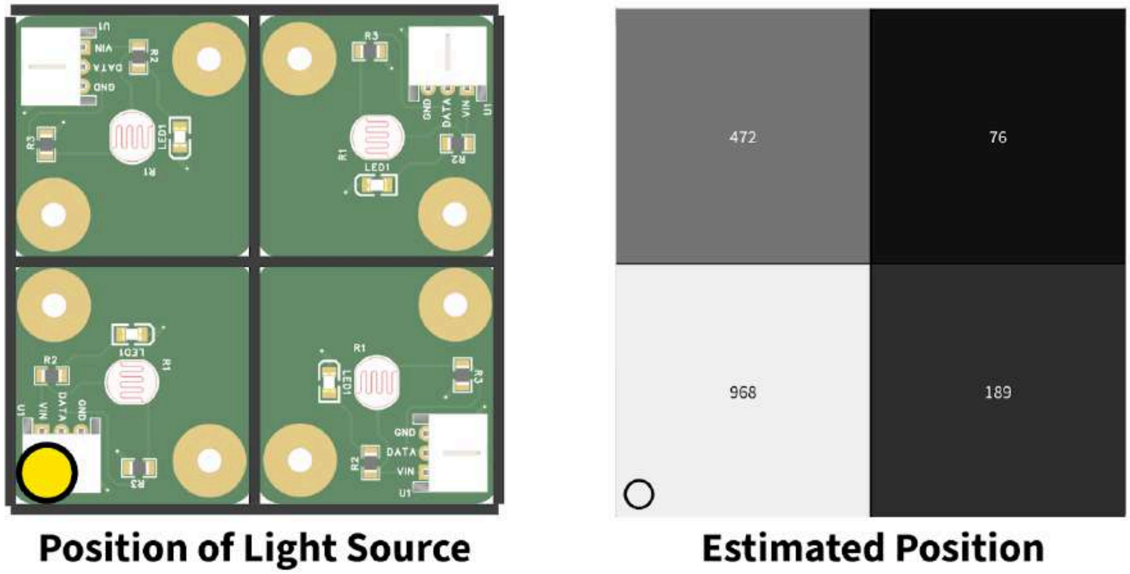


Figure 6.2; Note: This illustration shows what the MCU would perceive as “Not Aligned”.

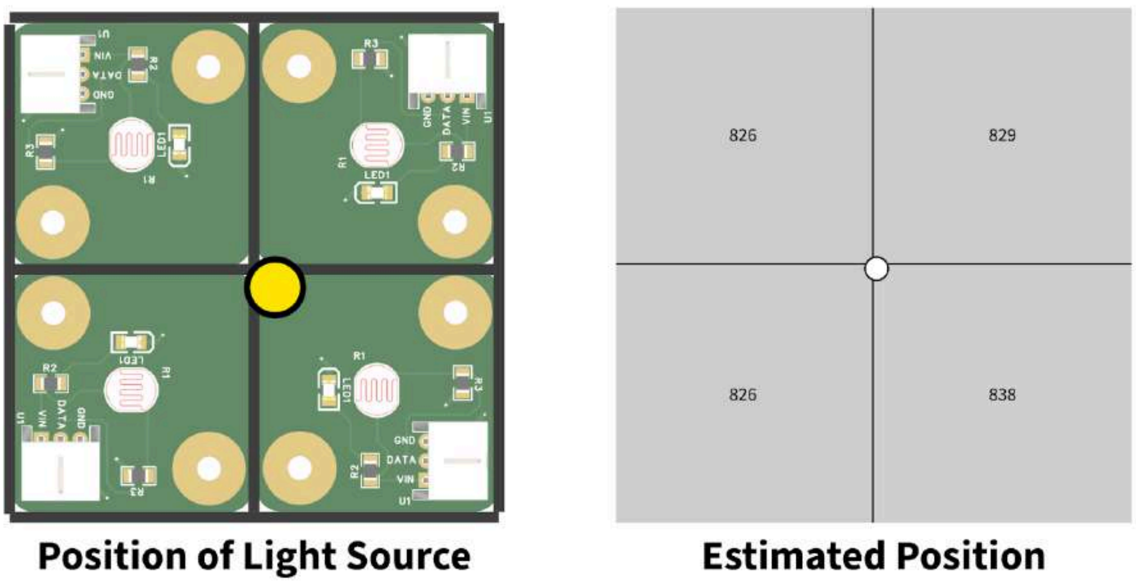


Figure 6.3; Note: This illustration shows what the MCU would perceive as “Aligned”.

Dynamic alignment and optical testing are demonstrated in the accompanying video.

7. Thermal Interface & Energy Flow

Concentrated Flux Interface

Light concentrated by the mirror system is directed onto a central receiver plate, where optical energy is absorbed and converted into heat. Rather than focusing to a single point, the system distributes concentrated flux over a defined surface area, reducing extreme local heating and making convergence behavior easier to observe and control. This receiver serves as the boundary between the optical system and downstream thermal pathways.

Material Considerations
Structural and interface components were fabricated from PETG to reflect fabrication constraints relevant to off-Earth or resource-limited environments. PETG was selected for its higher thermal stability relative to PLA and its ease of fabrication using consumer-grade equipment. For reflective surfaces, aluminum foil was used to approximate thin, lightweight reflective materials commonly employed in spacecraft insulation, allowing low-mass reflectivity using readily available materials.

Loss Mechanisms
Several loss mechanisms were observed throughout testing. Optical losses arose from imperfect reflectivity of the aluminum foil, surface scattering due to handling damage, and sensitivity to mirror misalignment. Additional losses occurred at the receiver through convection and radiative heat dissipation. While these effects reduced overall thermal capture, they provided direct insight into how surface quality and alignment dominate system performance at this scale.

8. Experimental Testing & Observations

Testing Setup (shown in video aswell)
A 1:5 scale prototype of the concentrator was constructed to enable rapid iteration and controlled testing. The system used four custom LDR sensor modules arranged in a 2×2 quadrant configuration, two servo motors for actuation, and an Arduino Nano for control. Testing was performed indoors using a handheld flashlight as a controllable light source, allowing repeatable evaluation of tracking response and alignment behavior without dependence on outdoor conditions.

Observed Behavior

The differential LDR-based control system consistently drove the mirrors toward balanced illumination across all four sensor quadrants. Variations in mirror fabrication produced noticeable shifts in the convergence region, making alignment sensitivity immediately apparent. Introducing the offset secondary mirror simplified final targeting by separating coarse mirror alignment from fine positioning at the receiver.

Unexpected Results
Despite the use of a non-collimated light source, the system responded reliably to differential illumination, indicating that the tracking approach does not require perfectly parallel incoming light. At small error angles, sensor-to-sensor variation became more apparent, highlighting the importance of matched sensor geometry and consistent placement when alignment precision is critical.

9. Limitations & Engineering Tradeoffs

The primary limitations observed in this project emerged through three mirror fabrication iterations, revealing consistent tradeoffs between surface quality, print strategy, and assembly complexity.

In the first iteration, hot glue was used to bond aluminum foil to the printed mirror substrate. This introduced localized protrusions at bond points that distorted the reflective surface and reduced uniformity. Trapped air beneath the foil further degraded surface contact, leading to visible ripples and increased scattering.

The second iteration printed mirrors flat with a reduced top-layer count to minimize weight and material usage. However, unsupported regions warped during cooling, particularly near the center of each segment. In shallow areas of the parabolic surface, layer stepping became prominent enough to negate the intended optical geometry.

The third iteration adopted a modular approach, separating reflective surfaces from structural mounting features and printing mirrors on their side to fit all twelve segments on a single build plate. While this reduced print time, large exposed surface areas and ambient air drafts caused edge lifting and print failures. The thin mirror panels also gradually lost their parabolic profile as layers cooled, increasing the need for post-fabrication repairs and manual bonding.

Across all iterations, optical performance was more strongly limited by surface integrity than by nominal geometric design. Minor scratches, warping, or handling damage to the aluminum foil reflective layer produced noticeable degradation in convergence behavior. These results suggest that at this scale, fabrication method, surface protection, and material choice dominate concentrator performance before ideal optical geometry becomes the limiting factor.

10. Forward Integration & Scalability Considerations

- **Scientific sun positioning data collection:** Light-intensity data used for LDR-based sun tracking could also be logged over time to generate high-resolution sun-position and irradiance datasets. Such data could support scientific analysis of atmospheric effects, dust loading, and diurnal solar variability in a Martian environment.
- **Battery back-ups:** Battery integration would allow excess energy collected during peak illumination to be stored and redistributed during transient shading or low-solar periods. This buffering would improve operational continuity without modifying the core optical or thermal architecture.
- **Space-based reflectors for Martian night use:** Orbital reflectors could redirect sunlight toward surface concentrators during Martian night or extended low-sun conditions, potentially as hosted payloads on existing satellites operated by companies such as ***SpaceX***. Dedicated reflector platforms, including those under development by ***Reflect Orbital***, further illustrate the feasibility of orbit-to-surface solar redirection.
- **System scalability:** The concentrator architecture is inherently scalable, allowing a single array to be replicated into a distributed grid of multiple units. At scale, such an arrangement would resemble a wind farm, where many identical modules contribute collectively to surface energy production.