Homer J. Fincannon

NASA Glenn Research Center

Solar Power Generation

For lunar polar bases, the lightest power generation available is from solar arrays. Solar arrays can take advantage of long sunlight periods (up to 6 continuous months a year) in favorable locations to generate power. At polar locations, the solar array need only track very slowly (12 degrees per day) around one axis to follow the Sun as it makes its way around the horizon once every month. Due to solar array's excellent power per unit mass, they have the potential to be deployed in large numbers to attain very high power levels to enable a variety of lunar base activities, particularly for production level In Situ Resource Utilization (ISRU). Each landed lunar base hardware will carry their own independent solar arrays such as on landers, rovers or other mobility assets, stationary habitats, laboratories and ISRU equipment. However, it is also possible and beneficial to have a dedicated, centralized base power system which can power a variety of the other base hardware by way of power transmission cables and/or recharge stations. Solar power must be incorporated with some energy storage system to enable night or winter survival. Solar arrays are relatively simple including solar cell surface, harness, mechanical/structural parts and gimbals. These considerations will be discussed further in this section.

Solar Array

A solar array is composed of solar cell components mounted on a substrate which are in turn supported by various mechanical/structural elements. This substrate is not the same as "solar cell substrate". Here, it is a surface onto which components are attached. This substrate may be rigid, flexible or thin film. In the past, rigid substrates were used exclusively. It was made with two facesheets sandwiching a light honeycomb core. Structural design was used to assess the rigid substrate (especially to handle launch loads) and, in fact, its mass was bookkept under the structures subsystem. A rigid panel solar array (an example is shown in Figure 1), while light, is at least double the mass of flexible substrate solar arrays and takes a lot of volume to stow for launch. For the lunar surface, they are usually practical for lower power levels or when available outer surface area on the spacecraft can be used to mount them. On the opposite extreme, thin film substrates are essentially thin plastic or metal which solar cells are printed on. While very light, these currently have lower efficiencies (half that of triple junction cells) so are not considered for lunar base applications at this time. The so-called flexible substrate option is either some sort of fabric or film. Examples of typical flexible solar arrays include the Ultraflex and Roll Out Solar Array (ROSA). Figure 2 and 3 shows the Ultraflex type of solar array, which has been used on the Cygnus ISS Cargo Module and on the Mars Insight lander as well as the Mars Phoenix lander (not shown). Figure 4 shows a ROSA type demonstration solar array which has been flown on the International Space Station and been selected for use on the Gateway. Other development work is currently funded for rectangular flexible lunar solar arrays such as for the Lunar Surface Solar Array (LSSA) project. Other similar concepts exist such as the Compact Telescoping Array (CTA) (Ref. 1).

Figure 1: Typical rigid panel solar array as shown for the Juno spacecraft (Credit: NASA)

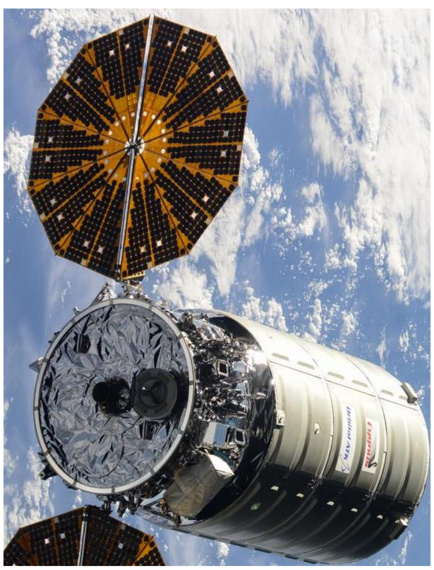

Figure 2: Ultraflex solar array in Earth orbit on an ISS Cygnus cargo module (Credit: NASA)

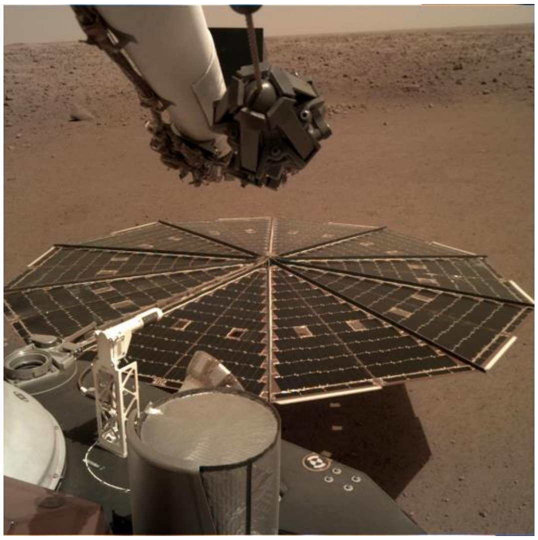

Figure 3: Ultraflex solar array on the Mars surface on the Insight lander (Credit: NASA)

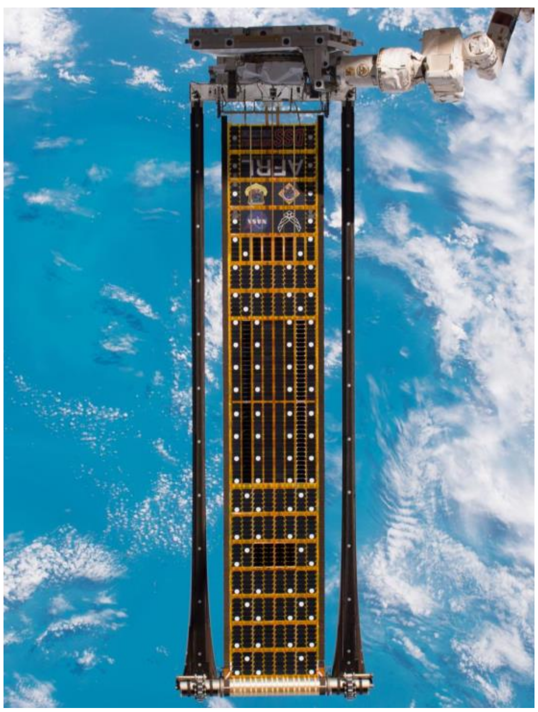

Figure 4: ROSA solar array demonstration on the ISS (Credit: NASA)

Solar Cells

Many varieties of solar cells have been developed for terrestrial use. A small percentage of these have gone through the rigors of space-qualification to assure they can reliably perform in space conditions. Those are discussed here for use in lunar base applications.

In the 1960's, the Lunar Surveyor spacecraft used ~7% silicon solar cells. Advances in solar cell technology has brought the efficiency to as high as 33% (for advanced IMM cells). Typical solar cells such as triple junction types (e.g. ZTJ) are ~30%. Besides being space-qualified, the selection criteria for solar cells for a lunar base are primarily cost and efficiency. Solar cells can cost as much as $700 per watt. More advanced, more efficient solar cells may cost more due to limited production. Despite the benefits of higher efficiency and possible lower mass for a solar array made of the more advanced cells, the cost may be prohibitive. State of the art solar cells have the benefits of large scale production facilities, well established radiation properties, as well as extensive production statistics. For this reason, it is reasonable to assume the use standard triple junction cells for the lunar surface. There might be some desire to use lower efficiency and lower cost cells (e.g. Silicon cells, thin film). Although possible, but the resulting mass increase for high power solar arrays is generally not acceptable.

An examination of solar cell datasheets illustrate the various key properties in defining their performance. These include both the voltage and current as functions of temperature, radiation degradation and solar intensity. Solar cell efficiency is highly affected by temperature. The hotter the cell the less efficient it is. For instance, going from 50 deg C to 120 deg C would reduce cell efficiency from 28% to 22%, an 18% power loss. Cooling the solar cell, typically by way of thermal radiation from off the back of the cell or array, helps to reduce its temperature. This is a function of the emissivity of the surfaces. It is also possible to place thermally emissive surfaces on the front of the solar array to help reduce the solar cell temperature in special cases. If necessary, the back face of the solar array can be connected to a thermal control system to carry away heat. The goal is to keep the solar cell at a temperature less than 120 C as a trade of reducing degradation for adhesives and other non-solar cell components and efficiency drop-off. A typical operating temperature of a bare cell at the lunar pole with perfect sun pointing and free view to space of its backside would be ~40-50C.

Radiation affects both the basic solar cell performance as well as its temperature characteristics. The radiation degradation is based on the solar cell alone (no coverglass). Some solar cells have thinner substrates. For applications where the solar cell backside is generally not Sun facing and where the solar array does not pass through a radiation belt (with omnidirectional radiation), thinner, lighter cell substrates can be considered. The drawback, however, is reduced mechanical properties (e.g. strength). The radiation fluence on the solar cell must be determined using computer analysis from tools such as SPENVIS (Ref. 2) with the assumed protective coverglass material and thickness for the front as well as the cell substrate and thickness and any additional cell back side shielding.

The solar intensity varies slightly (+-4%) based on the lunar polar site distance from the Sun. A closer, high intensity value is used to determine the hot temperature of the solar array, but for power generation, the further distant solar intensity is used.

Cells are available in a variety of sizes/areas. Larger area (>60 cm^2) solar cells are more desirable due to an improved efficiency of construction/assembly.

Coverglass

To protect solar cells from the assembly process to the operational application, coverglasses are typically used. They are either transparent fused silica or borosilicate material of thicknesses from 2 mil (.05 mm) to 20 mil (.51 mm). As can be expected, for large solar arrays, thick coverglasses can result in considerable mass. Coverglasses are used to protect the delicate solar cells from human or automated handling structural or mechanical impacts, provide an easily cleanable surface (e.g. remove dust), but are mainly used to shield the solar cell from proton and electron particles from the Sun. The backside of the solar cells generally have a thick enough cell substrate to protect the cell in case particles impinge on the back (usually during Earth orbits). The front of the solar cell requires a coverglass of some thickness, dependent on the radiation environment and duration of the mission. Usually for the lunar surface with sun tracking solar arrays, thinner coverglasses (3-5 mil) are acceptable. Thicker coverglass is not needed since lunar surface radiation is not as great as for an Earth orbiting solar array, particularly one that frequently passes through the Earth's radiation belt. Even thinner coverglasses are problematic due to their fragility. The coverglass thickness trade usually results that it is lighter to make the solar array somewhat larger (more solar cells and power) than to try to reduce the radiation degradation effects with a heavier coverglass. Generally, for lunar application, a typical annual degradation of solar power is on the order of 1% for radiation. Radiation analysis using tools (such as in Ref. 2) for assumed coverglass thicknesses helps to perform the trade analysis of mass versus cost. A necessary drawback of coverglass is that is does block part of the incoming power relevant sunlight. This can be up to 4% depending upon the coverglass.

Coverglass Interconnected Cell (CIC)

The CIC brings together the solar cell, coverglass, adhesives, coatings and any required welded interconnects into a structurally reliable assembly for further integration into a solar array. Anti-reflective and conductive coatings are included in the CIC to enhance power generation. The CIC is an approach to standardize the assembly process for space-rated hardware.

Cell submodule

This is an assembly level that is intended to standardize and simplify the solar array assembly/testing process. It is dependent upon solar array type. The method is highly amenable to rectangular solar array designs, although it may be adapted for circular solar arrays made up of triangular parts (e.g. Ultraflex). The concept is to lay out a collection of CICs, typically representing a "string" which is a series connected set of solar cells, to provide a specific desired output voltage. A solar array requires a large number of strings in parallel to provide high power levels for lunar base use.

Dust removal

An assessment must be made of the impact of dust accumulation of the lunar solar array surface. If the solar array is high enough from the lunar surface and the dust accumulation on a vertical solar array is low enough, it may be adequate to oversize the solar array to accommodate long term dust adhesion. If analyses show that higher dust rates are possible, then dust removal techniques are needed. These can involve simple "brushing" to electrodynamic dust removal (Ref. 3). All methods have their complexities, costs and impact on power production.

Gimbals

For a lunar polar base, one axis vertical rotating gimbals are adequate for most solar array concepts. It is possible to have stationary/fixed, non-Suntracking solar arrays, but for constant power generation, this would imply that solar arrays must be deployed in various directions to accommodate the Sun as its azimuthal location on the horizon varies through each month. This is generally not a preferred option since the cost of solar cells and arrays is so expensive. A cylindrical, fixed, non-Suntracking solar array uses roughly 3 times more solar cells than a Suntracking solar array. At ~$1000/W (array level cost, not just cells), this can be a high cost for larger power levels. Other considerations for gimbals are dust resistance, fault tolerance, levelling and thermal. Lunar dust gets into everything on the Moon and all moving parts or mechanisms will have dust as a nemesis. Fortunately, there are methods to reduce this impact, namely by proper design and dust shielding. Fault tolerance are an important aspect in that the solar array can be considered a critical element for human survival at the lunar base. For this reason, it is necessary to include at least one extra gimbal in the design in case of a fault. A locked gimbal would cause a gradual drop-off of power to zero. When the solar array power system is landed on the lunar surface, if only one axis gimbal tracking is used, then a one-time levelling mechanism is required for either the lander or the solar array since the lander may have landed on a slope or a rock, thus limiting the Suntracking accuracy of the solar array through the month. Finally, the gimbal must be heated especially during the cold winter darkness periods. Well insulated gimbals might use the power from operation during darkness to heat them. Another consideration is whether it is needed to use a slip ring or cable wrap to transfer the power across the gimbal(s). Cable wrap is a coiled cable around the gimbal which allows direct power transfer without losses. At some point (typically 360 degrees) in the gimbal rotation, the gimbal must backtrack because the travel is not continuous. This is a lower cost option than the slip ring approach. However, there are concerns about the very low temperatures during darkness periods and how they may affect the cable flexibility (requires heaters) and the amount of power (high currents) such an approach can handle since it requires thicker wires and adds stiffness to the coil. A slip ring provides continuous travel but has losses due to brushes that transfer power across the rotation joint. Usually, these are acceptable for lunar surface designs.

Other mechanisms

Solar arrays include motors, hinges, and various other devices to deploy and support the solar array. These are typically inherent to a specific design and cannot be generalized. Another factor is retraction and redeployment. It is preferred for safety to deploy the solar arrays once. However, it may be necessary to infrequently retract and redeploy solar arrays to ameliorate effects of blast ejecta from landings or possible relocation of solar array assets. In this case, mechanisms must be designed to resist the effects of dust.

Structures/Gravity

Lunar gravity is 1/6 that of Earth. Thus, solar array structures may be less than for Earth and more than for in space. However, there are various considerations that may require stronger solar arrays on the lunar surface. If a lander is landing with deployed solar arrays, then it is necessary to have arrays that can withstand up to 2 g. Also, if a rover has solar arrays that are deployed and operational while mobile, then similarly high accelerations/loads must be designed for to deal with driving over rough terrain at reasonable speeds. Stronger arrays have a drawback of being heavier which places extra requirements on the supporting structure and gimbal. Some solar array designs have been designed to accommodate higher acceleration loads. Ultraflex solar array designs can vary from 0.1 g (in space) to 4.7 g (Cygnus).

Voltage

Solar arrays can be designed for a variety of voltages by adjusting the number of cells in a string. Some research is being done to enable reprogramming of solar array voltages for various user needs. For present solar arrays, their design must account for the acceptable voltage range dictated by the temperature range and a variety of degradation factors. The fundamental voltage selection for a lunar base is based on a combined consideration of harness mass, commonality with other power electronics and user needs. Layouts and spacing of cell submodules (as well as cells) on a solar array need to consider voltages between adjacent strings in order to prevent arcing for higher voltage solar arrays (>100V). Another aspect that affects solar array voltage is that of transmission voltage. For a solar power station at a distance of 1 kilometer away from its user, high voltages (~1000V) are required to minimize transmission line mass. However, such high solar array voltages are challenging and likely presently unreasonable since space-rated components such as diodes are not currently available to handle these voltages under galactic cosmic ray (GCR) bombardment. While the burden could be placed on power electronics to up and down convert voltage from a >100V solar array, if the solar power station could be relocated to closer to the user, a lower power transmission voltage is feasible and the solar array voltage can match it making the transmission electronics unnecessary.

Diodes

Two kinds of diodes exist on solar arrays: cell bypass diodes and string blocking diodes. Cell bypass diodes are usually built into the CICs to avoid loss of a string due to the failure of one cell because of damage or shadowing. The string blocking diodes are used to prevent the reverse flow of electricity into a string from the main power bus (i.e. battery or energy storage) especially during a non-illumination period with no power from the solar array. In addition, in case of a short circuit of a string, the blocking diode prevents the power from the other strings from feeding through the short circuit string. For lower voltage solar arrays (~<120V), diodes exist that are space-rated and can endure GCR hits. However, it is necessary to carefully investigate available diodes for much higher voltages since there is a sensitivity of component endurance under GCR irradiation.

Design Factors

The sizing of a lunar solar array starts with 1366.1 W/m^2 which is the amount of solar power that covers one square meter at 1 AU from the Sun (Ref. 4). This is reduced by any blockage of the sunlight by terrain (based on detailed topographical analysis) and shadowing caused by any local hardware.

Then we use the bare cell characteristics at its listed reference solar intensity and temperature. At this point, a variety of other factors come into determining the required size of the solar array.

In designing a solar array, the voltage, power level, temperature range, degradation rates are needed. The amount of power needed is based on user power needs, power system conversion and transmission losses (efficiencies), power growth margin, and the amount of power that is needed to recharge energy storage (highly dependent upon solar array shadowing by terrain and other hardware). The number of strings determine how much current (or power) is produced. The number of cells in a string determine the voltage produced. Extra cells and strings are based on reliability/redundancy requirements.

When sizing a solar array, it is necessary to include all relevant assembly and degradation factors. The designer should carefully consider the various impacts on the solar array. A list of these factors with typical values is shown in Table 1. Each solar array location/environment affects these data. This table is intended for the lunar surface location. Many of these data are estimates or assumptions and should be further refined by the analyst as well as possible to improve the solar array size determination.

Table 1: Solar Array design factors with typical, estimated and assumed values for a lunar surface application.

Design Factor	Affects	BOL Factor	EOL Factor	Explanatory Note
Maximum sun offpointing	Current	0.999	0.999	Based on combined angles for two axis planes. Assume 2 deg for one plane, 1 deg for the other.
Array flatness	Current	0.999	0.999	Array surface not completely flat when deployed. Assumed 2 deg
CIC measurement uncertainty	Current	0.980	0.980	Caused by standard solar cell calibration accuracy to AM0 spectrum, simulator spatial non-uniformity/drift, current/voltage measurement error
CIC assembly	Current	0.995	0.995	Impact of coverglass/adhesives/antireflective coatings on amount of solar flux to reach cell
CIC assembly	Voltage	0.995	0.995	Conversion from bare cell to package of welded leads, coverglass, etc.
Cell Mismatch	Current	0.995	0.995	Based on variation of cell properties between cells
Cell Mismatch	Voltage	0.990	0.990	Based on variation of cell properties between cells
Temperature	Current	0.950	0.950	Cell temperature affected by array design. Assumed value.
Temperature	Voltage	0.930	0.930	Cell temperature affected by array design. Assumed value.
Distance	Current	0.967	0.967	Worst case distance is 1.0167 AU
Random workmanship	Current	0.990	0.985	Quality of assembly, welds, etc.
Cell Interconnect Voltage Drop	Voltage	0.996	0.996	Based on resistance
Blocking Diode Voltage Drop	Voltage	0.993	0.993	Based on diode
Harness Voltage Drop	Voltage	0.980	0.980	Based on harness resistance
Gimbal Voltage Drop	Voltage	0.990	0.990	Slip ring resistance
UV	Current	1.000	0.985	Degradation/darkening of adhesive
UV	Voltage	1.000	0.995	Degradation/darkening of adhesive
Impact	Current	1.000	0.990	Assumed value. Needs analysis based on blast ejecta, micrometeoroid cell damage.
Thermal cycling	Current	1.000	0.980	Assumed value. Needs analysis based on high/low temperatures at poles (day/night cycles) affecting interconnects.
Dust, contaminants	Current	1.000	0.980	Assumed value. Needs analysis based on dust, volatiles, contaminants from regolith or spacecraft.
Radiation	Current	1.000	0.930	Assumed value. Needs analysis based on coverglass, cell and mission length.
Radiation	Voltage	1.000	0.900	Assumed value. Needs analysis based on coverglass, cell and mission length.
Total Reduction of Solar Cell Power		**0.775**	**0.601**	Reduction from base solar cell power. Based on assumed values.

Most of these factors are dependent of the solar array design and require analysis to determine appropriate values. Here, they illustrate that merely using the solar cell properties from the datasheet is inadequate. Rather, careful analysis of temperature, radiation and many other factors will provide a robust, properly sized solar array design.

Note that some factors are not included in this list. These include power conversion efficiencies (solar array regulation, power distribution regulation and power transmission outside of the solar array itself) and how well the power from the solar array can be controlled. These are part of power electronics and are not considered in this section, yet are factors in solar array design.

Temperature

During illuminated periods, the solar array design with its front and back surface thermal characteristics (such as emissivity and absorptivity), lunar surface albedo, infrared emissions, the amount of power removed from the solar array for power generation, and amount of sunlight will determine the solar array and solar cell temperature for purposes of power analysis and solar array design.

During polar darkness periods, the temperature of exposed surfaces with no heaters can get very low. For highly illuminated candidate South Pole base sites, the range of temperatures is from a high of 295 K in the summer to a low of 54 K (below the temperature of liquid Nitrogen) in the darkness of winter. The number of periods of cold is ~10 per year. Thus, this indicates free standing solar arrays and their supporting structures need to be designed and tested for low temperatures. Testing is a challenge given the large nature of high power solar arrays. If operation at these low values is an issue, it may be necessary to incorporate heaters into the solar array.

Power and Current vs. Voltage

Figure 5 shows typical solar array current versus voltage and power versus voltage curves for an entire solar array. For different operational temperatures, how much power is removed from the solar array and how much is left on the array based on control method and solar array degradation over time, these curves will change in shape. The power versus voltage curve shows that at one voltage, the maximum power can be extracted. Depending upon the solar array voltage control method, this peak power can be utilized.

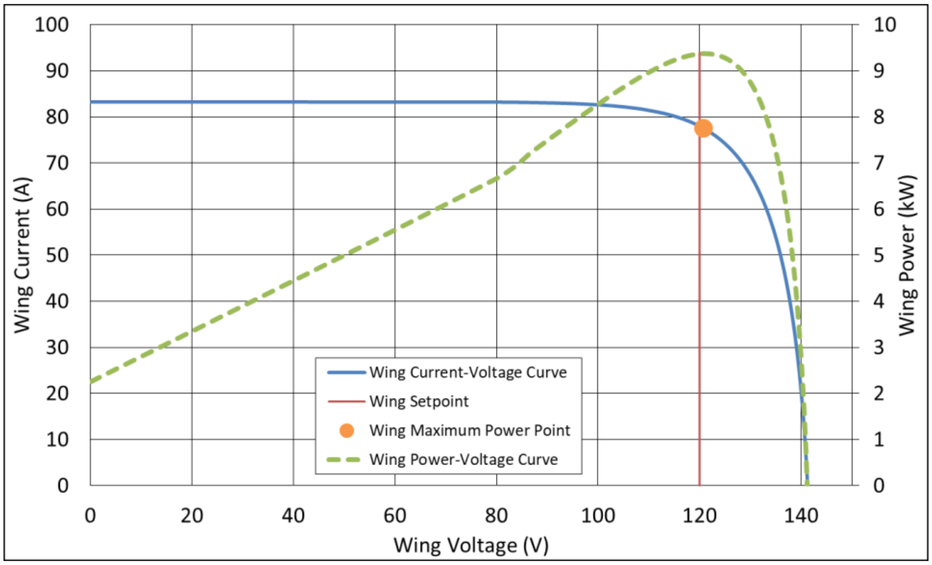

Figure 5: Typical Lunar Surface Solar Array Current and Power versus Voltage curves

Power control

Various approaches to using power from solar arrays exist. One, the "direct energy transfer" (DET) approach, is to have the user draw what power they need and let the solar array provide it as best it can. Thus, the power user (an electrical load or battery) defines the voltage the solar array operates at. This method uses a shunt regulator to shunt away unneeded current from the spacecraft main power bus. This power remains on the solar array, increasing its temperature. Alternatively, "peak power transfer" (PPT) is an approach to maximize the power capability of the solar array by allowing the solar array to operate at its maximum power point at whatever voltage this may be and converting the voltage to the desired user voltage. It is claimed that PPT electronics are more heavy, complex and inefficient than DET using shunt regulators. Each of these are true, but the magnitudes of mass and inefficiency are not large. For instance, a typical PPT card efficiency is 95% versus the DET shunt regulator card of 98%. Mass differences are about a factor of 2, but the mass per watt is low in either case (Ref. 5).

Operation

After landing a stowed solar array on the lunar surface during an illuminated period, the solar array (or lander) needs to be levelled first, then the solar array is deployed using motors that are part of the solar array. After deployment, the gimbal is controlled to allow the solar array to track the Sun. Power is generated, passed through the gimbal to a power regulation/control interface. After the power is processed it passes to the power system, to the energy storage and to the distribution system, which carries it to the users.

References:

1. “Compact Telescoping Array: Advancement from Concept to Reality”, M. E. McEachen, 2018 AIAA Spacecraft Structures Conference, 8–12 January 2018, Kissimmee, Florida, AIAA 2018-1945.
2. “SPENVIS Tutorial: mission concept”, M. Kruglanski, SPENVIS User's Workshop 2010, Mechelen, Belgium, 7 - 9 June 2010. (https://www.spenvis.oma.be)
3. “Current State of the Electrodynamic Dust Shield for Mitigation”, C. R. Buhler, et al, Lunar Dust 2020 (LPI Contrib. No. 2141).
4. ASTM Standard E490-00a: Solar Constant and Zero Air Mass Solar Spectral Irradiance Tables, 2014.
5. “Space Mission Engineering: The new SMAD”, J. Wertz, et al., 2011, pg. 653-654.