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Assessment of architectural options for surface power generation and energy storage on human Mars missions

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A R T I C L E I N F O

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A B S T R A C T

The provision of power for human Mars surface exploration is generally assumed to be achieved using nuclear fission power systems, particularly if in-situ production of part or all of the Earth return propellant is considered. This paper provides a comprehensive analysis of surface power generation and energy storage architectures for human Mars surface missions, including tracking and non-tracking photovoltaic power generation, nuclear fission power generation, dynamic radioisotope power generation, and battery and regenerative fuel cell energy storage. The quantitative analysis is carried out on the basis of equal energy provision to the power system user over the course of one Martian day (including day and night periods); this means that the total amount of energy available to the user will be the same in all cases, but the power profile over the course of the day may be different from concept to concept. The analysis results indicate that photovoltaic power systems based on non-tracking, thin-film roll-out arrays with either secondary batteries or regenerative fuel cells for nighttime energy storage achieve comparable levels of performance as systems based on nuclear fission power across the entire range of average power levels investigated (up to 100 kW of average usable power over the course of the Martian day). Given the significant policy and sustainability advantages of solar power compared to nuclear fission power generation, as well as the significant development and performance increase for thin-film photovoltaic arrays and energy storage technologies that is anticipated over the coming decades, solar power as the primary source for human Mars surface power generation should be seriously considered as an alternative to traditional nuclear fission based power generation approaches.

1. Introduction and motivation

The human exploration of Mars is generally considered as the ultimate goal of human spaceflight endeavors in the foreseeable future. Power generation for use on the surface of Mars for habitation and communications, as well as for surface mobility and potentially in-situ propellant production is a key enabling component of human Mars surface exploration.

Past mission architectures and reference designs have predominantly relied on nuclear fission power generation, especially if they relied on in-situ production of propellant for Mars ascent and/or TEI [1,2,4,5]. Some design studies have considered photovoltaic power generation as an alternative or secondary option for surface power generation [1,3,8], although usually not for approaches relying on in-situ production of propellants. There have been initial attempts at comprehensive analyses of Mars surface power system architectures [10], but these tend to be limited to parts of the architectural space such as solar

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power only. What is lacking at present is a comprehensive comparative analysis of nuclear, radioisotope, and solar power architectures; the work presented in this paper is a first attempt to close this gap.

Section 2 provides an overview of the architectural space that was analyzed. Section 3 contains descriptions and assumptions for the different power and energy generation technologies included in the analysis. Section 4 introduces the quantitative modeling approach, and Section 5 contains a discussion of associated results. Section 6 provides a summary of the work presented and important conclusions.

2. Surface power architecture options for human Mars missions

An enumeration of architectural options was carried out based on three architectural variables: the choice of daytime power generation technology, the choice of eclipse power generation technology, and the energy storage technology (if required); constrained enumeration yields the alternatives shown in Fig. 1. Note: for architectures where primary power generation is based on photovoltaic arrays, there is an option for using radioisotope heat sources with thermoelectric or thermodynamic (“dynamic”) power conversion to supply part or all of the nighttime power; these options also may have different characteristics for contingency operations (e.g. during a global Martian dust storm), because RTG-based architectures are to some degree independent of sunlight and the intensity of insolation.

Major metrics considered for the surface power analysis were total power systems mass and volume, captured in normalized form (average power/total system mass [W/kg] or average power/total system volume [W/m^3]). The analysis that was carried out for each architecture was an equal energy analysis which assumes that all systems provide the same energy per Martian day, but not necessarily the same continuous power output i.e. for a nuclear fission based system and a solar-based system, the user receives the same energy per Martian day, but whereas the nuclear system provides a near-constant power output, the solar power system provides the majority of the energy during the day to reduced the amount of energy storage required at night (which is a major contributor to system mass). Note: as the solar-based systems are sized for the worst possible day, i.e. the day with the shortest insolation period/longest eclipse period, the total energy provided by the solar-based system over the course of the surface mission is actually underestimated in the analysis.

Architecture	Primary power generation	Secondary power generation	Energy storage
1	Nuclear fission - Stirling cycle	N / A	N / A
2	Nuclear fission - Brayton cycle	N / A	N / A
3	Photovoltaics - tracking	N / A	Li-Ion batteries
4	Photovoltaics - tracking	N / A	Regen. FC
5	Photovoltaics - tracking	Dynamic RTG	Li-Ion batteries
6	Photovoltaics - tracking	Dynamic RTG	Regen. FC
7	Photovoltaics - tracking	Dynamic RTG	N / A
8	Photovoltaics - non-tracking	N / A	Li-Ion batteries
9	Photovoltaics - non-tracking	N / A	Regen. FC
10	Photovoltaics - non-tracking	Dynamic RTG	Li-Ion batteries
11	Photovoltaics - non-tracking	Dynamic RTG	Regen. FC
12	Photovoltaics - non-tracking	Dynamic RTG	N / A
13	Dynamic RTG	N / A	N / A

Fig. 1. Architecture options for Mars surface power production.

As can be seen in Fig. 1, the work in this paper is focused on nuclear fission and photovoltaic power generation architectures with different options for secondary energy generation and energy storage, if required. Specific technologies were researched before performing analysis on each architecture. The studied technologies are discussed in Section 3 below.

3. Surface power generation and energy storage technologies

Specific technologies for the architectures were researched in order to ascertain their level of readiness. A number of RTG technologies that are currently being developed by the NASA Science Mission Directorate [9] were assessed. Traditional rigid solar arrays (tracking) and newer thin film arrays (non-tracking) were considered for the solar-based options.

This section provides an overview of the different power generation and energy storage technologies considered in the architecture-level analysis. Performance assumptions and references are provided where possible.

3.1. Solar power generation technology

Two technologies were considered here. They included ultra-light amorphous silicon rollout blanket arrays and high efficiency inflexible tracking arrays. The ultra-light arrays have efficiencies of 15% and a mass/area of 0.063 kg/m^2 [6]. These arrays have only been tested as small units, so the TRL for a large system that would be needed for human surface exploration are lower than that for the already existent inflexible array systems. The high efficiency arrays are based on ISS arrays. They have 20% efficiencies and mass/area of 2.5 kg/m^2. The structural overhead is based on ISS. Also, multi-axis tracking was assumed to achieve perpendicular solar flux incidence throughout the Martian day.

An important added consideration for the ultra-light arrays is how to protect the rolled blanket from high winds. It was found that if the blankets are simply laid on the surface without any additional anchoring, a light wind of only 7.35 m/s would lift the arrays. Therefore a concept

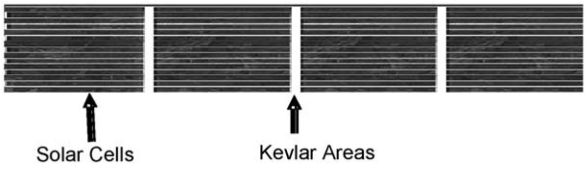

Fig. 2. Ultra-light blanket arrays with Kevlar portions for rock placement.

was developed to weigh down the arrays by adding Kevlar areas equal to 10% or the total array area in which rocks will be placed to weigh down the full array (see Fig. 2). It was found that 9.2 kg/m^2 of rock is needed in the 10% Kevlar regions to secure the array against the top recorded Mars wind of 25 m/s. The major effect of this consideration is increased deployment time which will be discussed below.

3.2. Battery technology

Batteries can be used for both secondary power generation and for energy storage. Li-ion batteries were considered in this study for their high energy density and common use in aerospace systems. To be conservative, current performance numbers were used. The batteries have a mass-specific energy density of 150 Wh/kg and a volume-specific energy density of 270 kWh/m^3.

3.3. Regenerative fuel cell technology

Again regenerative fuel cell can perform both the tasks of secondary power generation and energy storage. Here hydrogen/oxygen regenerative fuel cells were considered. The fuel cells have mass-specific energy density of 250 Wh/kg and volume-specific energy density of 200 kWh/m^3 [7]. It was assumed that the reactants were stored in tanks at 200 atm internal pressure.

3.4. Nuclear surface primary power technology

Two designs were considered for nuclear primary power production in this study. Both are nuclear reactors with dynamic conversion. One design uses a brayton engine for the conversion and the other a Stirling engine. The brayton based design is adapted from the Prometheus design for a lunar based reactor. The radiator was resized for use in the Martian thermal environment. The brayton design must be located 210 m from base and have a 3.5 m effective regolith shield to mitigate radiation effects. The Stirling engine based design comes from the JSC element/systems database [6]. It consists of an SP-100 type reactor and four Sterling engines. The Stirling design must be located 1 km from the base and the reactor itself must be located below the surface for radiation shielding.

3.5. Radioisotope power generation technology

Dynamic conversion RTG systems can act as secondary power generation elements as well as provide a redundant constant power source for added safety in the power system. Here we considered a design for modular general purpose heat sources (GPHS) coupled to Stirling conversion engines. This design has a mass specific power of 13.75 W/kg and volume specific power of 27 500 W/m^3 [6]. These units use PuO_2 for fuel and a 5 kW unit would require 62.5 kg of fuel. A positive feature of this design is that they primarily have alpha-radiation emissions that can be relatively easily shielded against; thus these units could be located close to base without harming the crew or the need for long transmission lines.

4. Quantitative analysis models

In order to compare all the architectures seen in Fig. 1, a model was created to assess mass and volume required to prove sufficient power through the Martian day and night. The nuclear options were modeled directly from reference data available. The solar power options, however, required the creation of a new model. The major requirements driving this model are as follows. The arrays must be sized for end-of-mission power requirements. If several missions go to same site, supplementary arrays are brought each mission to make up for degradation. Arrays must also be sized to provide the required power during the year's minimum incident solar energy period.

The model also includes a number of important assumptions. An optical depth of 0.4 is assumed which is equivalent to hazy skies on Mars. Tracking arrays are multi-axis and keep incident flux perpendicular to array over the day. A nighttime power of 12 kW is assumed to be enough to sustain six crews. The daytime power requirement is not enforced until the sun is 12° above the horizon. Also, initial analysis for all architectures was done for an equatorial location which is actually not the optimal location for solar power on Mars. Fig. 3 shows the daily solar incidence levels over time for three different latitudes. It is seen that some northern latitudes actually have a higher minimum solar incidence over the year. In fact 31° north has the highest minimum incident energy compared to the rest of Mars.

After an initial performance analysis was performed on each architecture, the more feasible architectures were then looked at in the context of performance change as a

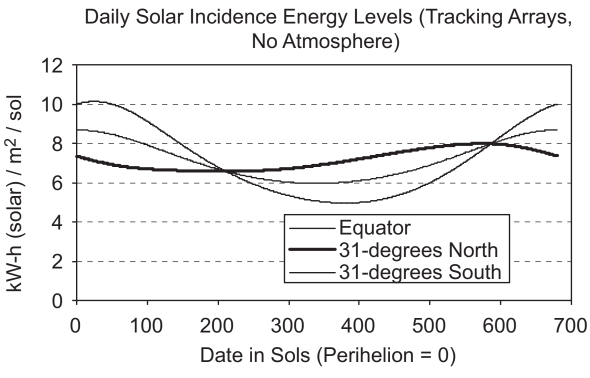

Fig. 3. Mars solar incidence energy levels for three latitudes.

function of latitude location. The steps taken in the modeling process are outlined in Table 1.

5. Discussion of analysis results

Results show that architectures which include thin film rollout solar arrays and either RFCs or Li-ion batteries can be competitive with nuclear based options. Architectures with RFCs come especially close to matching the mass based performance of nuclear reactors with Stirling engines for dynamic conversion at higher power levels (see Fig. 4). This is true at higher power levels because the ultra-light solar arrays begin to dominate the more massive secondary power generation components. Looking at volume based performance it is seen that all thin film solar architectures dominate the nuclear options (see Fig. 5). All tracking array architectures are non-competitive on both a mass and volume basis. All solar based options were also included in architectures where 5 kW RTGs were included. These architectures see a slight performance boost over their non-RTG counterparts, but the performance increase is small and the major benefit of the RTG is still the added safety that a continuous power supply imparts. Fig. 6 gives a 100 kW point design comparison for the competitive architectures.

Table 1
Procedure for modeling primary and secondary power generation components.

Step no.	Description
1	Calculate total energy in Joules that must be produced by the solar arrays in a day based on the days power requirement
2	Calculate the power per unit area being produced by the solar array as the sun sweeps the sky on the given latitudes minimum solar energy day based on the array's end of life characteristics
3	Integrate to find the total energy that a square meter array can produced over the day
4	Comparing the energy produced by a square meter and the total energy required find the needed array area for the system
5	Calculate the mass and volume for this array area
6	Based on night time energy requirements calculate the mass and volume of the secondary energy production components

Now that thin film solar architectures with RFCs or Li-ion batteries have been singled out as the interesting competitive architectures with nuclear options, it is interesting to look at the effect of latitude location on the power systems' performance. This way, more suitable locations for solar based architectures can be assessed. Taking in the planet's axial tilt and orbital elements about the sun, the minimum solar energy flux based on latitude can be found. Figs. 7 and 8 then present the mass and volume based performance of the power architectures for a range of Mars latitudes. The results show that there is an optimum location for solar architectures around 30° north latitude. The results also show that northern latitudes are always better then their southern counterparts.

Aside from mass- and volume-based performance, deployment time for the very large array area (25,000 m^2 for a 100 kW average daily power system located at the Martian equator) is very important. Deployment time includes time for off-loading of the arrays from the Mars surface landing vehicles, time for unrolling the arrays, and finally time for placing rocks on the above-described Kevlar-patches between the photovoltaically active areas to weigh down the arrays and protect against dislocation by surface winds.

For this analysis we considered the 100 kW average power system located at the Mars equator in order to get an estimate for worst-case deployment time. This requires a 25,000 m^2 rollout array field which includes the addition of the Kevlar areas for wind mitigation. It was assumed that array blankets are 2 m wide and weigh ~40 kg for easy storage and handling by two astronauts. With 0.07 kg/m^2 as the expected array density, only 18 blankets are required. If we assume astronauts can unroll arrays at a walking speed of 1 m/s, the unrolling requires only 7 h. Time will also be needed for unloading, positioning, and connection of the arrays to the power grid or with each

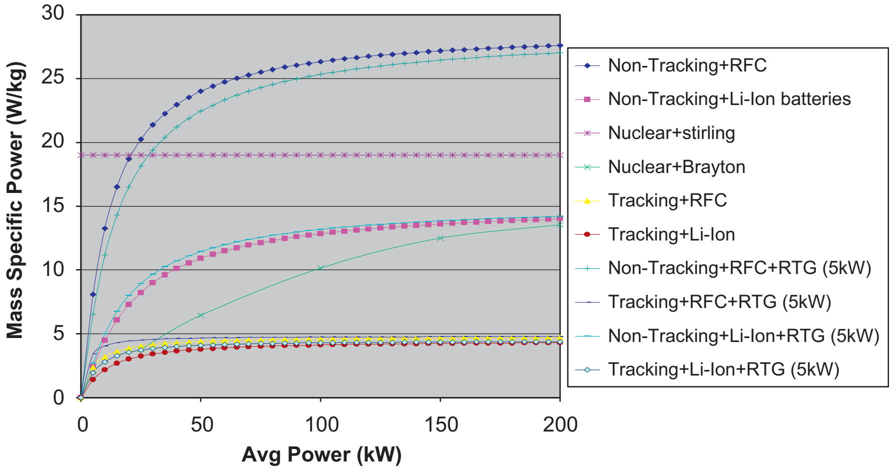

Fig. 4. Mass specific power performance versus average power level for all architectures.

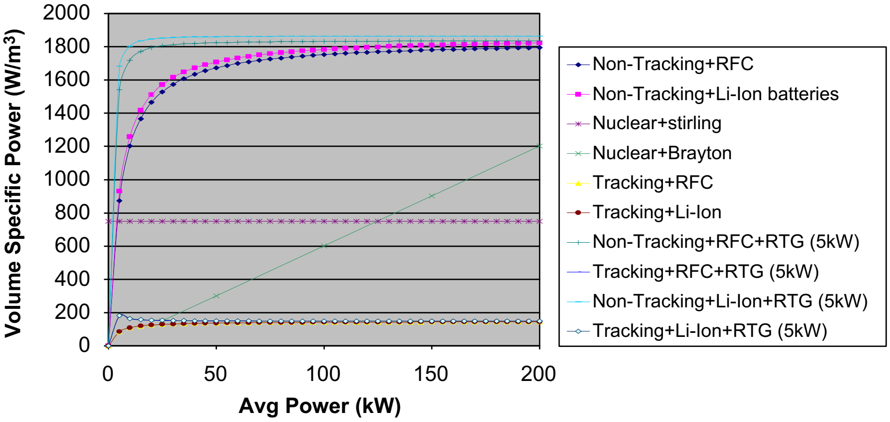

Fig. 5. Volume specific power performance versus average power level for all architectures.

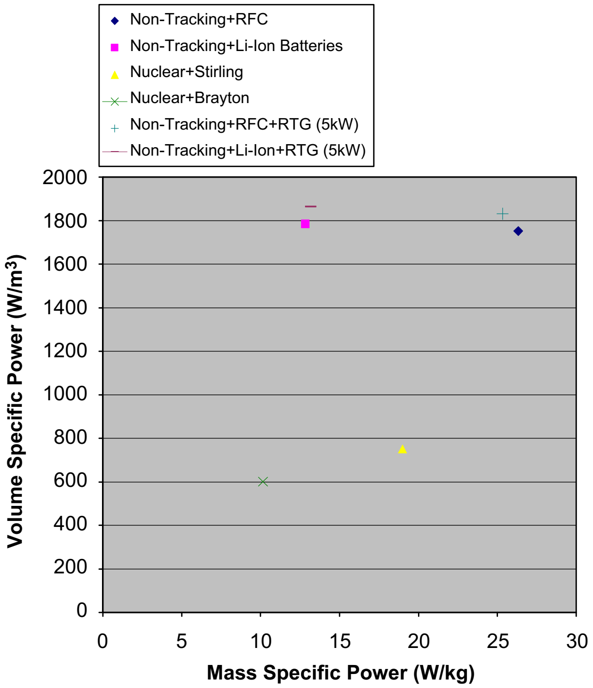

Fig. 6. Mass and volume specific power performance for a 100 kW average power system for the feasible architectures.

other. If it is assumed that 1 h is needed for this for each array, this adds another 18 h. In addition to this, rocks must be placed in the Kevlar areas. Assuming Kevlar areas are 0.3 m in length and the complete 2 m in width, 5.6 kg of rock in each area is needed. There are 225 of these Kevlar areas per array so a total of 4050 of these areas. Assuming two rocks are needed per area to secure the two sides of the array this requires 8100 rocks to be placed. If 30 s is needed to pick and place a rock this will take 33.75 h for two crew members. All of these result in a total requirement of 66 h to deploy the solar array field by two crew members. With six crew members, this could be reduced to 22 h, equivalent to three full extravehicular activities.

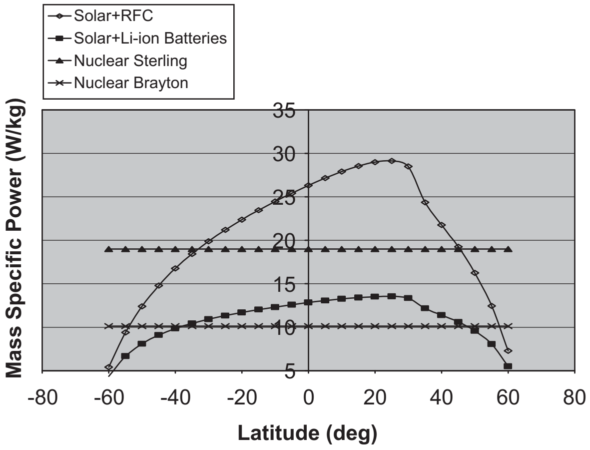

Fig. 7. Mass specific power performance for interesting architectures as a function of latitude.

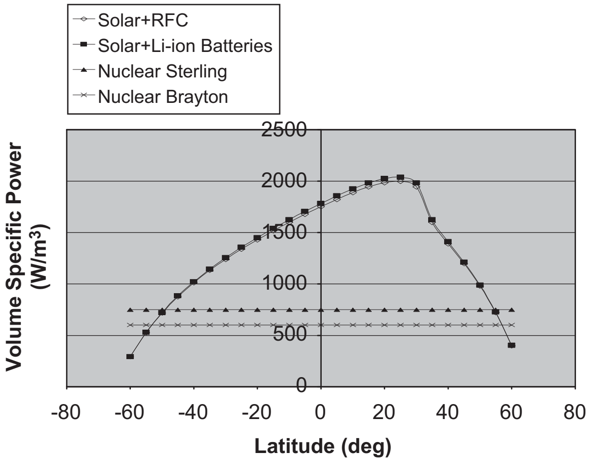

Fig. 8. Volume specific power performance for interesting architectures as a function of latitude.

Power must also be provided during the deployment process. It is interesting to note however, that deployment gives 0.76 kW per person hour; therefore we only need

13.2 person hours to reach a capability of 10 kW which is enough for minimal stay-alive power. To be very conservative, we can neglect this and find out what additional fuel cells or batteries are needed to get through the deployment period. If you say full deployment and initial usefulness takes one week, we need either a 10 kW dynamic RTG or fuel cell system to provide 10 kW of continuous power over the week. The RTG system would be approximately 1200 kg and 0.6 m^3 (stored volume). A RFC system would need 2400 kg system with volume 8.4 m^3. This is overly conservative however, and in fact little more than fully charged night-time power generation would be required as two crew members could achieve deployment of the required 10 kW in less than 7 h, i.e. during a single extravehicular activity.

Robotic deployment of the array areas was also considered, although not analyzed in detail. Robotic array deployment would be desirable in case in-situ production of propellants for Mars ascent and potentially also trans-Earth injection is required. In this case, for safety reasons, these propellants must be produced before the crew leaves Earth and commits to the mission, i.e. before the crew can participate in deployment of the arrays. Given recent advances in autonomous robotics as evidenced by the performance and endurance of the Mars Exploration Rovers Spirit and Opportunity, it stands to reason that robotic deployment of large array areas is realistic, especially given that in this case time is not a driving concern: deployment could take weeks or even months without significantly affecting the ability to produce the desired amount of propellants.

6. Summary and conclusions

A systematic comparative analysis of surface power systems for human Mars mission was carried out, including nuclear fission, dynamic radioisotope, and photovoltaic power generation technologies. The metrics considered for comparing architectures were mass-specific average system power and volume-specific average system power; both were calculated based on an equal-energy analysis for each of the architecture options. In addition, deployment time with human crew was estimated for a representative solar array area.

A number of major conclusions can be drawn from the analysis results:

- The performance of photovoltaic power systems is strongly dependent on deployment latitude. There seems to be a performance optimum around 31° of northern latitude; this corresponds to the latitude which receives the most solar energy during the shortest day of the Martian year (this is due to the eccentricity of the heloicentric orbit of Mars which provides a second variation to insolation in addition to seasonal effects).
- For latitudes close to this optimum latitude, photovoltaic power systems exhibit mass- and volume-based performance that is comparable to that of nuclear fission power systems.
- For global access for human Mars surface missions, nuclear power is required either in the form of fission reactors or radioisotope generators.
- Regenerative fuel cells provide better performance than Li-ion secondary batteries. However, there may be development cost differences.
- Deployment time for large-scale photovoltaic arrays is on the order of a few extravehicular activies for deployment with six crew members (as is commonly envisioned for human Mars surface missions). This may be on the same order as the deployment effort required for nuclear surface fission systems.
- For immediate post-landing power generation when using a photovoltaic system, the secondary batteries or regenerative fuell cells intended for surface energy storage can be used (they would be charged in Mars orbit or on the Earth–Mars cruise). This would enable the povision of post-landing power without any significant mass or volume overhead. In addition, deployment of a sufficient array area to provide stay-alive power (estimated to be on the order of 10 kW average power over the course of the day) could be accomplished during a signle extravehicular activity.
- Based on the experience with the MER rovers, Mars global dust storms do not present a significant challenge to photovoltaic power systems because even during these storms scattered sunlight still provides in excess of 10% of the insolation per surface area as during a clear Martian day. This means that the crew can operate in stay-alive mode during the dust storm using a 100 kW-class photovoltaic power system. The use of dynamic RTGs for part or all of the eclipse power generation can provide added robustness for the dust storm season.

It is important to note that significant development of thin-film photovoltaic power generation and energy storage technologies (secondary batteries, regenerative fuel cells, super-capacitors, superconductor energy storage) can be expected in the next decades for Earth energy applications, which would be available virtually “free” of investment for the human Mars surface exploration community. The associated performance gains will make photovoltaic surface power even more competitive with nuclear fission systems for near-equatorial northern latitudes and may perhaps extend the region of feasible latitudes for photovoltaic power systems even further. This indicates that solar-based Mars surface power systems should be seriously considered as an alternative to nuclear fission surface power; the opportunity cost for doing so is very low and the potential pay-off in terms of program political robustness and perhaps also development cost reduction for Mars surface power systems could be quite significant.

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