ISRU-Based Thermoelectric Generator and Solar Panel Production and Performance on the Moon and Mars.

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Introduction: Power is the fundamental enabler of sustained human activity beyond Earth. Every ISRU process—from material extraction and metal reduction to habitat construction and life support—demands reliable energy input. As Lordos et al. argue, power availability has historically been the primary driver of industrialization, and this relationship is no different in space: without abundant energy, large-scale extraterrestrial activity cannot progress [1].

Programs such as NASA's Artemis, which aims to establish a long-term human presence at the lunar south pole, exemplify this transition from short-duration exploration to sustained surface operations [5]. Current mission architectures assume that most power-generation hardware is launched from Earth, making surface energy capacity mass-limited and prohibitively expensive to scale. ISRU has been explored primarily as a means of producing consumables such as propellant and oxygen, but its potential role in replicating power infrastructure from local resources has received limited systematic attention.

This work investigates whether two classes of power-generation systems— photovoltaic (PV) solar panels and thermoelectric generators (TEGs)—can be manufactured from locally available regolith on the Moon and Mars, and whether the energy returned over their operational lifetimes exceeds the energy invested in their production. If achievable, this creates a positive-feedback loop: locally produced power enables more energy-intensive ISRU processing, which in turn enables the fabrication of additional power systems, driving progressive growth in surface energy capacity. Together, these technologies form a complementary foundation for ISRU-based power generation on both planetary bodies.

Architecture:

Solar Panel System. The solar panel adopts a layered architecture consisting of a basaltic glass cover with a thin SiO_2 anti-reflective coating deposited by physical vapor deposition, aluminum front and back contacts, and a multicrystalline silicon photovoltaic absorber shown in Figure 1. Silicon recovered as a byproduct of MRE is refined to 5N purity (99.999%) through vacuum-based zone melting, exploiting the natural high vacuum of the lunar surface [2, 6]. The p-type silicon layer is doped with aluminum (locally sourced); the n-type layer is doped with phosphorus, supplied from Earth in trace quantities given its negligible mass contribution. Three panel mounting configurations are evaluated: vertical support, sun-tracking perpendicular, and floor-mounted.

Power output of the solar array is modeled as:

$$P_{\text{array}} = S\cos\theta\, A\,\eta_{\text{ref}}\left[1-\beta(T_{\text{cell}}-T_{\text{ref}})\right]\eta_{\text{sys}}\,\eta_{\text{rad}} \quad (1)$$

where S is the solar constant, θ the incidence angle, η_{ref} the reference cell efficiency at temperature T_{ref}, $\beta =$ temperature coefficient, η_{sys} a system loss factor, and η_{rad} the cumulative radiation degradation factor. Cell operating temperature is determined by radiative equilibrium in the absence of atmospheric convection.

Thermoelectric Generator System. TEGs convert a temperature difference directly into electrical power via the Seebeck effect, with no moving parts, and can operate continuously as long as a thermal gradient is maintained [4]. The device consists of aluminum conductors bridging p-type and n-type semiconductor legs arranged electrically in series and thermally in parallel shown in Figure 2.

From an ISRU perspective, the semiconductor selection is constrained to materials whose constituent elements are confirmed present in lunar and Martian regolith in exploitable quantities. Iron disilicide ($FeSi_2$) is chosen as the p-type material and magnesium silicide (Mg_2Si) as the n-type counterpart. Both are synthesized by reacting the respective metals with silicon under high-temperature processing conditions compatible with proposed ISRU metallurgical techniques. Purity requirements for TEG semiconductors are less stringent than for PV cells, easing the refining burden.

The open-circuit output voltage of the TEG module is:

$$V_{\text{out}} = N\,\alpha_{AB}\,\Delta T \quad (2)$$

where N is the number of thermocouple pairs in series, $\alpha_{AB} = \alpha_p - \alpha_n$ is the differential Seebeck coefficient between the p-type ($FeSi_2$) and n-type (Mg_2Si) legs, and $\Delta T = T_{\text{hot}} - T_{\text{cold}}$ is the applied temperature difference.

On the Moon, the hot junction is thermally coupled to a sunlit surface while the cold junction is embedded in or contacts a permanently shadowed region (PSR), exploiting temperature differences that can exceed 250 K near the poles [7]. On Mars, the usable thermal gradient is derived from the surface-to-subsurface temperature differential, supplemented in some regions by subsurface ice deposits that stabilize cold-side temperature.

Material Extraction. Both lunar and Martian regolith are rich in silicon, aluminum, iron, and magnesium oxides. Metals are extracted via molten regolith electrolysis

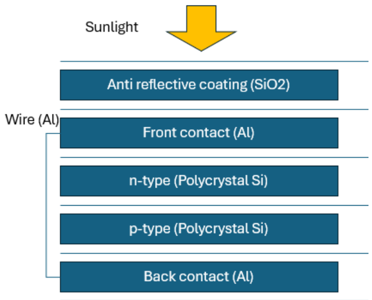

Figure 1: Overall Solar Panel Structure

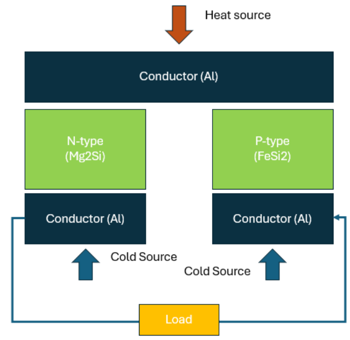

Figure 2: Overall Thermoelectric Generator

(MRE), which simultaneously produces oxygen and reduces metallic oxides at 1500–1600 °C [3]. Aluminum is selected as the primary conductor material for wiring and contacts in both device types. As a byproduct of MRE targeting aluminum, silicon, iron, and magnesium are also co-produced, supplying the feedstock for both the PV absorber layer and the TEG semiconductor legs. Production energy costs for both systems are estimated using Schreiner's parametric MRE model [3], yielding approximately 1×10^{12} J per kilogram of silicon at an operating temperature of 2000 K and an annual oxygen production rate of 1000 kg—the largest modeled case, chosen to minimize per-unit heat losses. Martian regolith requires less energy compare to the lunar regolith as it contains less aluminum which requires more energy. The energy break-even point is defined as the operational time at which cumulative energy output equals total production energy investment, after which the system contributes net positive energy to the bootstrapping cycle.

Results:

Lunar and Mars Solar Panel Performance. On the Moon, three panel mounting configurations are evaluated—perpendicular (sun-tracking), horizontal support, and floor-mounted—with the perpendicular configuration achieving the highest instantaneous output but incurring a significant thermal penalty that nearly doubles its break-even period. Radiation degradation reduces performance by approximately 20% over five years, and the energy break-even period is found to be dominated by glass cover mass rather than wafer thickness: reducing glass thickness from 5 mm to 1 mm shortens break-even from ∼900 days to under 100 days (Figures 3–5 [INSERT Figures 5.2–5.4]). At minimal glass thickness, break-even periods of 100–200 days are achievable, indicating that a positive-feedback power-bootstrapping cycle is technically feasible on the lunar surface. On Mars, solar irradiance is reduced to ∼586 W m^{-2} and is further attenuated by periodic global dust storms; equatorial placements offer the most favorable annual yield, while mid-latitude sites present trade-offs between solar access and proximity to near-surface water ice.

Lunar and Mars Solar Thermoelectric Performance. On the Moon, due to huge tempearture difference, theoretically possible power generation is large that can reduce the breakeven point into around 200 days. However, the performane of TEG at low temperature as the PSR is not well understood and maynot lead to this result. On Mars, as there are no region like PSR that can be used, the power generation is more moderate. Additionally, due to low solar iiradiance, the high temperature is also lower compare to lunar surface. Those two factors makes the break even point quite long more than 1000 days.

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