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Authors

Abel, Anthony J
Berliner, Aaron J
Mirkovic, Mia
[et al.](#)

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Photovoltaics-Driven Power Production Can Support Human Exploration on Mars

Anthony J. Abel^{1,2†}, Aaron J. Berliner^{1,3†}, Mia Mirkovic^{1,4}, William D. Collins^{5,6*}, Adam P. Arkin^{1,3,7*} and Douglas S. Clark^{1,2,8*}

¹Center for the Utilization of Biological Engineering in Space (CUBES), Berkeley, CA, United States, ²Department of Chemical and Biomolecular Engineering, University of California, Berkeley, Berkeley, CA, United States, ³Department of Bioengineering, University of California, Berkeley, Berkeley, CA, United States, ⁴Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, Berkeley, CA, United States, ⁵Climate and Ecosystems Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA, United States, ⁶Department of Earth and Planetary Sciences, University of California, Berkeley, Berkeley, CA, United States, ⁷Environmental Genomics and Systems Biology Division, Lawrence Berkeley National Laboratory, Berkeley, CA, United States, ⁸Molecular Biophysics and Integrated Bioimaging Division, Lawrence Berkeley National Laboratory, Berkeley, CA, United States

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*Correspondence:

William D. Collins
wdcollins@lbl.gov
Adam P. Arkin
aparkin@lbl.gov
Douglas S. Clark
dsc@berkeley.edu

†These authors have contributed
equally to this work

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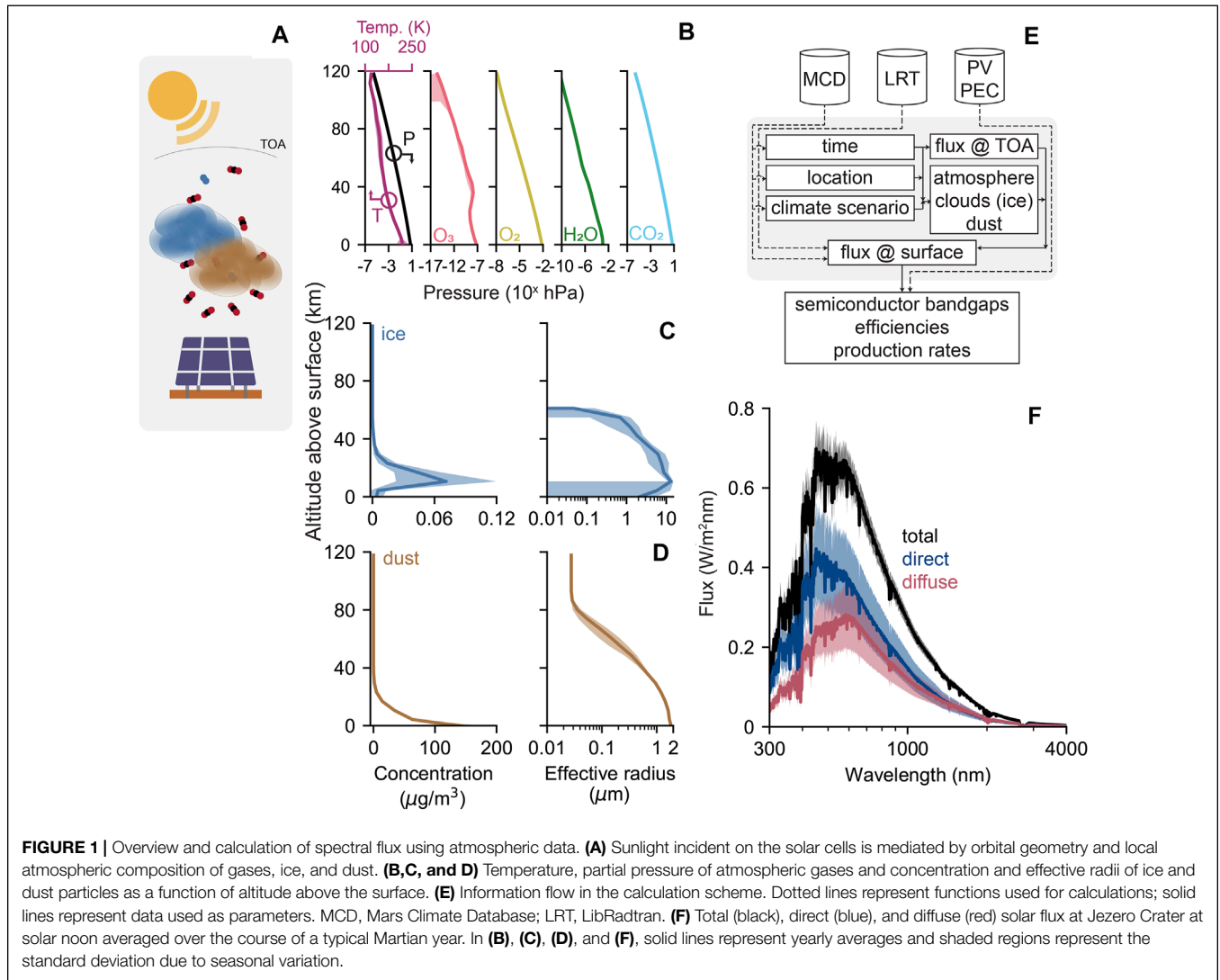
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A central question surrounding possible human exploration of Mars is whether crewed missions can be supported by available technologies using *in situ* resources. Here, we show that photovoltaics-based power systems would be adequate and practical to sustain a crewed outpost for an extended period over a large fraction of the planet's surface. Climate data were integrated into a radiative transfer model to predict spectrally-resolved solar flux across the Martian surface. This informed detailed balance calculations for solar cell devices that identified optimal bandgap combinations for maximizing production capacity over a Martian year. We then quantified power systems, manufacturing, and agricultural demands for a six-person mission, which revealed that photovoltaics-based power generation would require <10 t of carry-along mass, outperforming alternatives over ~50% of Mars' surface.

Keywords: photovoltaics, technoeconomic analysis, human exploration mission, mars, radiative transfer, climate model

INTRODUCTION

Long-duration space missions or continuously-occupied extraterrestrial outposts require Earth-independent power and chemical supply. Mars has an abundance of *in situ* resources, including (sub)surface water ice (Wilson et al., 2018) and carbon and nitrogen in atmospheric CO₂ and N₂ (Webster et al., 2013). Efficient conversion of these resources to reduced forms of hydrogen, nitrogen, and carbon would represent an enabling step towards sustaining a permanent human presence in space. In analogy to the proposed terrestrial "Hydrogen Economy", molecular hydrogen (H₂) can be used as a platform molecule for energy storage, on-demand power supply, and as a reactant driving CO₂ and N₂ (bio)chemical reduction on Mars (Marbán and Valdés-Solís, 2007; Chen et al., 2018; Berliner et al., 2021). Water electrolysis with selective catalysts can drive water reduction to H₂ on cathode surfaces. This technology is attractive for space manufacturing applications since reactions can proceed at high rates at room temperature, enabling the use of low-weight, 3D-printable plastic reactors (Berliner et al., 2021). Commercial electrolyzers



can evolve H_2 from water with up to $\sim 80\%$ energy efficiency (Ursua et al., 2011). Directly solar-powered (i.e., photoelectrochemical (PEC)) devices have also received significant attention, with solar-to-chemical efficiencies reaching $>19\%$ for H_2 production (Cheng et al., 2018). Once generated, H_2 can drive N_2 reduction to ammonia via the Haber-Bosch process for crop fertilizer (Berliner et al., 2021), CO_2 reduction to CH_4 via the Sabatier process or methanogenesis for ascent propellant generation (Menezes et al., 2015), and CO_2 reduction to bioplastics following a variety of metabolic processes for habitat and spare parts manufacturing (Nangle et al., 2020; Berliner et al., 2021).

The primary alternatives for powering life support systems and chemical production facilities on Mars are miniaturized nuclear fission reactors (Drake et al., 2010) and photovoltaic (PV) arrays. While fission reactors are expected to behave similarly regardless of their location, the productivity limits of PV and photoelectrochemical devices are not well-characterized for the Martian surface mainly due to differences in the surface

temperature and solar intensity and spectrum from typical conditions on Earth or in space.

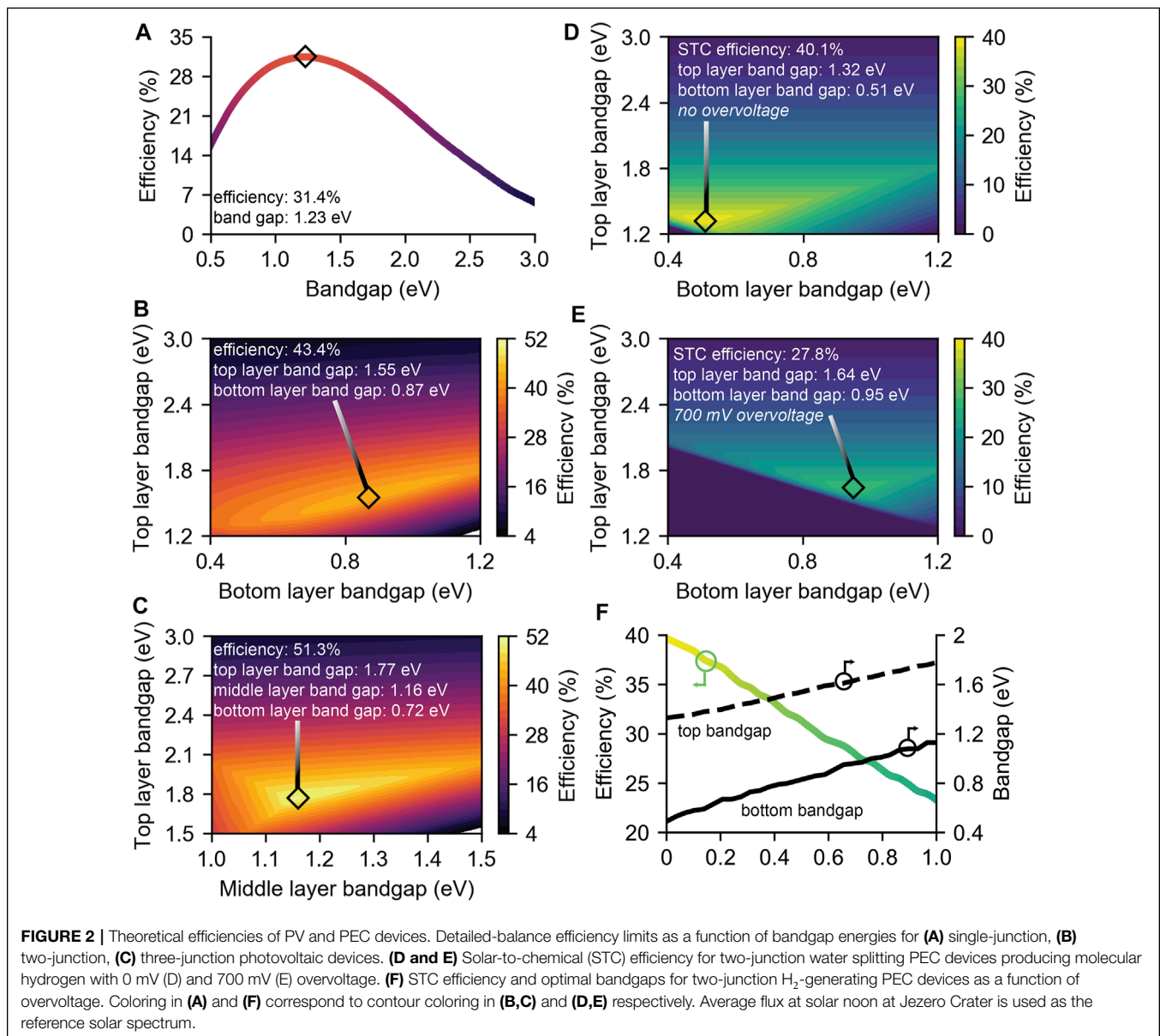
In an effort to determine the potential of PV and PEC devices to support a crewed mission to Mars, we integrated relevant climate data from the Mars Climate Database (Read et al., 1997) into a radiative transfer model, libRadtran (Mayer and Kylling, 2005), to predict spectrally-resolved solar flux across the Martian surface over the course of a year. The modeling overview and sample calculations for Jezero Crater are provided in **Figure 1**. Sunlight incident on the surface originating from the top of the atmosphere (TOA) is mediated by orbital geometry and local atmospheric composition of gases, ice, and dust for a given location (**Figure 1A**). We determined the partial pressures of constituent gases (**Figure 1B**) and the concentrations and effective radii of ice (**Figure 1C**) and dust (**Figure 1D**) particles as a function of altitude above the surface and provided these data as inputs to a downstream radiative transfer model (diagrammed in **Figure 1E**). We then calculated the spectrally-resolved solar flux (**Figure 1F**). At short wavelengths (<400 nm), light

transmission through the atmosphere is limited by molecular scattering (primarily by CO_2) and scattering from dust particles (Vicente-Retortillo et al., 2015). Scattering and absorption by gas molecules is significant at wavelengths below 300 nm, but this region is not considered here because it represents a very small fraction of the available solar flux (<0.5%). Above 400 nm, most transmission loss is due to scattering from dust particles. This is markedly different from the case on Earth, where significant molecular absorption by water molecules limits the transmission of near-infrared light.

RESULTS

The modeling results were used to inform efficiency calculations for PV and PEC devices producing electricity and H_2 . Detailed

balance calculations (section 4 in the Supplementary Information) (Döscher et al., 2014; Hanna and Nozik, 2006) revealed ideal current-voltage characteristics for optically-thick devices consisting of 1-, 2-, and 3- junction PV and 1- and 2- junction PEC absorbers dependent on the bandgaps associated with each absorber (Figure 2). Absorber numbers were selected to represent historical choices for PV devices on Martian rovers (Landis, 2005; Stella et al., 2005) and state-of-the-art PEC devices (Jia et al., 2016; Young et al., 2017; Cheng et al., 2018). For PEC devices, we assumed an electrical load consisting of the thermodynamic redox potential and a variable overvoltage term that incorporates loss mechanisms inevitable to a practical PEC device beyond radiative recombination already considered in the detailed balance (Hanna and Nozik, 2006; Döscher et al., 2014).



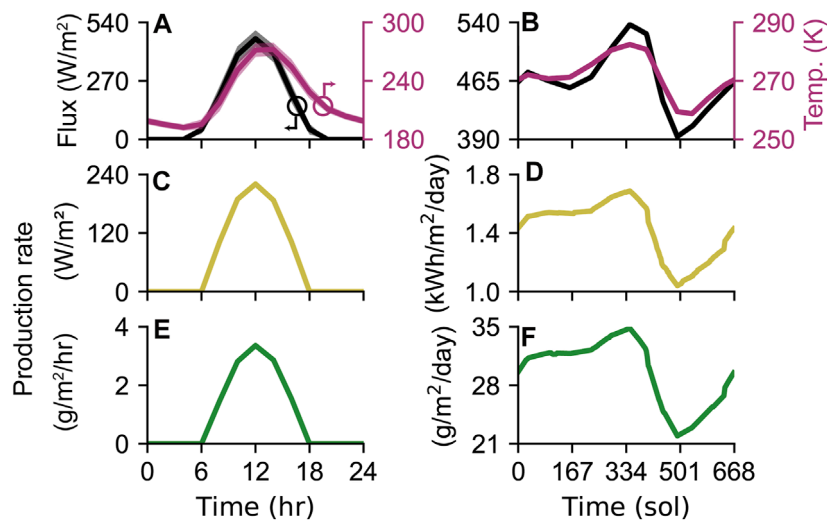


FIGURE 3 | PV and PEC production rates. **(A)** Average and **(B)** daily maximum solar flux (black, left axis) and surface temperature (purple, right axis) as function of **(A)** time of day and **(B)** time of year. **(C,E)** average and **(D,F)** daily maximum production capacity of power **(C,D)** and H₂ **(E,F)** using 3-junction PV and 2-junction PEC cells as described in the main text. Solid lines in **(A,C,E)** correspond to averages; shaded areas represent the standard deviation due to seasonal variation. Jezero Crater is used as the location for plots.

The maximum efficiency for PV devices increases from 31.4% (1-junction; $E_g = 1.23$ eV) to 51.3% (3-junction; $E_{g,1} = 1.77$ eV, $E_{g,2} = 1.16$ eV, $E_{g,3} = 0.72$ eV) with judicious choice of bandgaps (Figures 2A–C). For PEC devices, optimal bandgap choice and efficiency are strongly dependent on system losses (Figures 2D–F), reflecting the importance of careful device construction and catalyst selection (Hu et al., 2013). For a realistic overvoltage loss of 700 mV (Hanna and Nozik, 2006; Hu et al., 2013; Döschner et al., 2014), a maximum solar-to-chemical conversion (SCC) efficiency of 27.8% is feasible for H₂ production.

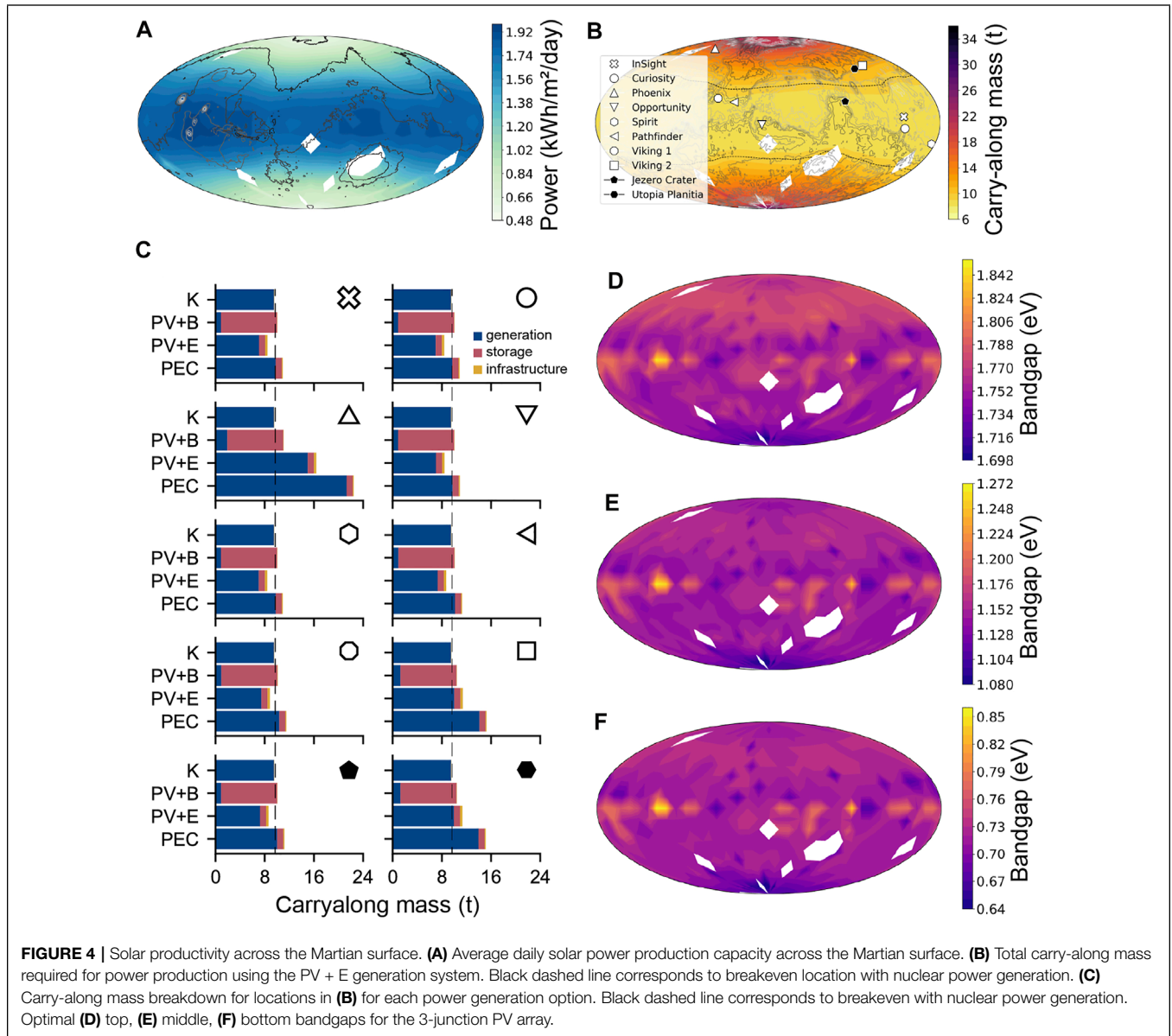
To evaluate the potential for solar cells to supply power and commodity chemicals, we determined the maximum practical production capacity for 3-junction PV (operating at 80% of the detailed balance limit) and 2-junction PEC devices (with a 700-mV overvoltage) over the course of a Martian year (Figure 3). Daily and seasonal variation in solar flux and temperature (Figures 3A,B) cause substantial (~27% deviation from the yearly average) changes in production rates (Figures 3C,D). We defined solar day (sol) 0 at a solar longitude (Ls) of 0° (vernal equinox) and assumed the solar cell operating temperature was equal to the surface temperature at all points. Dust storm season begins at sol ~372 (Ls~180°) and is primarily responsible for the drop in production capacity from a peak of ~1.7 kWh/m²/day at Jezero Crater to a minimum of ~1.0 kWh/m²/day at the height of dust storm intensity around the winter solstice (Ls ~270°, sol ~514).

Bandgap combinations that maximize production over the course of a year are 5–15% different from those that optimize efficiency at solar noon (Supplementary Table S7). For both PV and PEC devices, the top junction bandgap shifted up (for H₂-generating PEC devices, from 1.64 to 1.77 eV), while the bottom junction bandgap shifted down (from 0.95 to

0.83 eV). Hence, the photon absorption window for the bottom junction is broadened (by ~35% for the PEC device). This likely works to maximize productivity during the less dusty season (higher solar flux, Figure 3B) by accounting for the relative blue-shift of surface-incident light (Figure 1F) due to reduced scattering.

DISCUSSION

Production capacity of power and commodity chemicals must compare favorably to the demand necessary to sustain a Martian habitat and depends on the outpost location on the planet surface (Figure 4A). Moreover, energy storage capacity is crucial for solar-powered production systems because the Sun sets daily. We therefore developed a detailed process model to account for power systems demands, including habitat maintenance (for example, habitat temperature control and pressurization), fertilizer production for agriculture, methane production for ascent propellant, and bioplastics production for spare parts manufacturing (Supplementary Figure S12). We considered four different power generation scenarios: 1) nuclear power generation with the miniaturized nuclear fission Kilopower system; 2) PV power generation with battery energy storage (PV + B); 3) PV power generation with compressed H₂ energy storage produced via electrolysis (PV + E); and 4) PEC H₂ generation with compressed H₂ energy storage (PEC). In our calculations, we assumed a capacity factor of 75% to account for the solar flux deviation throughout the Martian year (Figure 3) and sized energy storage systems (batteries or compressed H₂) to enable 1 full day of operations from reserve power. We then calculated the carry-along mass requirements for each of the power generation systems considered.



Of the three solar-driven power generation options, only the PV + E system outcompetes the nuclear system based on carry-along mass (Figures 4B,C; Supplementary Figure S13). For the PV + E system, the total carry-along mass increases from ~8.3 t near the equator to ~22.4 t near the South Pole (Figure 4B), corresponding to the reduced average daily power generation of the PV array as the latitude is adjusted away from 0° (Figure 4A). The nuclear power system is predicted to require ~9.5 t; hence, the PV + E system out-performs this option across ~50% of the planet’s surface (Figure 4B).

In addition to predicting production capacity and carry-along mass, our model provides design rules for optimal solar cell design. Optimal absorber bandgaps for the PV array are strongly dependent on the location on the surface of Mars (Figures 4D–F). Several factors cause this variation:

the total depth of the air column above a given location (i.e., the difference between the height of the atmosphere and the altitude), gradients in dust and ice concentrations and particle radii, and orbital geometry effects that cause different effective air column thicknesses for locations near the poles. Lower elevations, higher dust and/or ice concentrations, and increasing distance away from the equator (near-polar latitudes) all cause an increase in the optical depth of the air column, which enhances the fraction of light that is scattered. Because the spectrum of scattered light is slightly red-shifted with respect to direct light (Figure 1F), optimal bandgaps decrease to capture more lower-energy photons (Figures 4D–F) in regions where the optical depth is higher. For example, at equivalent latitudes, the optimal bandgaps are wider for regions with higher elevations than for those with lower elevations because

the fraction of light that gets scattered is lower. Regional differences in atmospheric conditions can drive countervailing effects; because the Northern Hemisphere experiences generally lower dust concentrations than the Southern Hemisphere, the lower elevation in the Northern Hemisphere does not result in (on average) narrower optimal bandgaps. Instead, the reduced dust concentration (relative to that of the Southern Hemisphere) results in a reduced optical depth, resulting in wider optimal bandgap combinations (**Figures 4D–F**). In sum, optimal bandgaps for the top absorber range from ~ 1.7 eV to ~ 1.84 eV (**Figure 4D**), from ~ 1.08 eV to ~ 1.27 eV for the middle absorber (**Figure 4E**), and from ~ 0.64 eV to ~ 0.85 eV for the bottom absorber (**Figure 4F**). Optimized triple-junction solar cells could be fabricated from, for example, GaInAsP alloys on Ge substrates with minimal lattice mismatch ($< \sim 1\%$) (Young et al., 2017) or by utilizing compositionally graded buffer layers to minimize threading dislocations (Kidd et al., 1996). These strategies have been deployed previously with success in high-efficiency triple junction device architectures (Geisz et al., 2007).

In conclusion, solar cell arrays with careful attention to semiconductor choice and device construction represent a promising technology for sustaining an Earth-independent crewed habitat on Mars. Our analysis provides design rules for solar cells on the Martian surface and shows that solar cells can offer substantial reduction in carry-along mass requirements compared to alternative technology over a large fraction of the planet's surface.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

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AUTHOR CONTRIBUTIONS

Conceptualization: AJA, AJB. Data curation: AJB, AJA. Funding acquisition: AJB, AJA, APA, DSC. Methodology: AJA, AJB, WDC. Software: AJB, AJA, MM. Supervision: WDC, APA, DSC. Visualization: AJA, AJB. Writing original draft: AJA, AJB. Writing review; editing: AJA, AJB, MM, WDC, APA, DSC.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fspas.2022.868519/full#supplementary-material>

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