Modeling of Spacecraft Power Systems: Thermal and Electrical Optimization for Space Exploration

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I. Introduction

Achieving a 45-day human Mars transit may seem a farfetched idea in the future, however the recent research in using Wave Rotor Enhanced Nuclear (**WREN**) propulsion architecture begs to differ. A fast transit time requires stringent mass optimization. Because electrical wiring contributes to **approximately 6%** of a spacecraft's total dry mass, minimizing this weight without compromising thermal stability is essential.

To solve this, this research is focused on creating mathematical models to create a virtual replica (**Digital Twin**) of the spacecraft that can automatically modify and optimize its own components. To help reach this goal, the models in this poster serve as an example of how to design a digital twin. There are two Power Management and Distribution (**PMAD**) systems examples that we will be modeling in this research poster, a high-voltage DC distribution system with wire and a solar panel system.

This project develops physics-based thermodynamic models in Python for spacecraft transmission wires and solar array panels. By simulating thermal limitations and electrical performance, these models identify design "sweet spots" where mass is minimized and efficiency is maintained. Ultimately, these baseline component models can be integrated as OpenUSD assets to construct a comprehensive Digital Twin spacecraft's electrical subsystem.

II. Methods

Subject of Study
- Primary Subjects: Individual components of a spacecraft's electrical power system, specifically Power Transmission Wires and Solar Array Panels.

Materials
- Solar Cells: **Gallium Arsenide (GaAs), Perovskite, Silicon**
- Transmission Wires: **Copper, Aluminum**

Measures
- Solar Arrays: Quantified incident solar flux, radiative heat dissipation, and temperature-dependent photoconversion efficiency.
- Transmission Wires: Calculated the required wire mass needed to safely dissipate Joule heating while maintaining a target of 97% efficiency.

Procedures
- Mathematical Formulation: Derived governing thermodynamic equations to mathematically describe the energy balance of solar cells and transmission wires in a vacuum. Example wire equation is shown below:

Transmission Wire Equation: $\frac{I^2 \cdot (\rho_{20}[1+\gamma(T-20)])}{\pi r^2} + 2r\alpha_{opt}I_{sun} = 2\pi r\epsilon\sigma T^4$

- Digital Twin Simulation: Developed an object-oriented Python script to act as the foundational Digital Twin, essentially simulating their behavior under different environmental conditions.

Data Analysis
- Thermal Solvers: Utilized Python numerical solvers to calculate exact thermal equilibrium points.
- Orbital Simulation: Ran solvers across a range of heliocentric orbital distances to generate comparative performance curves.
- Performance Limits: Identified and visualized thermal limits and "no-go" zones for each material model using generated graphs.

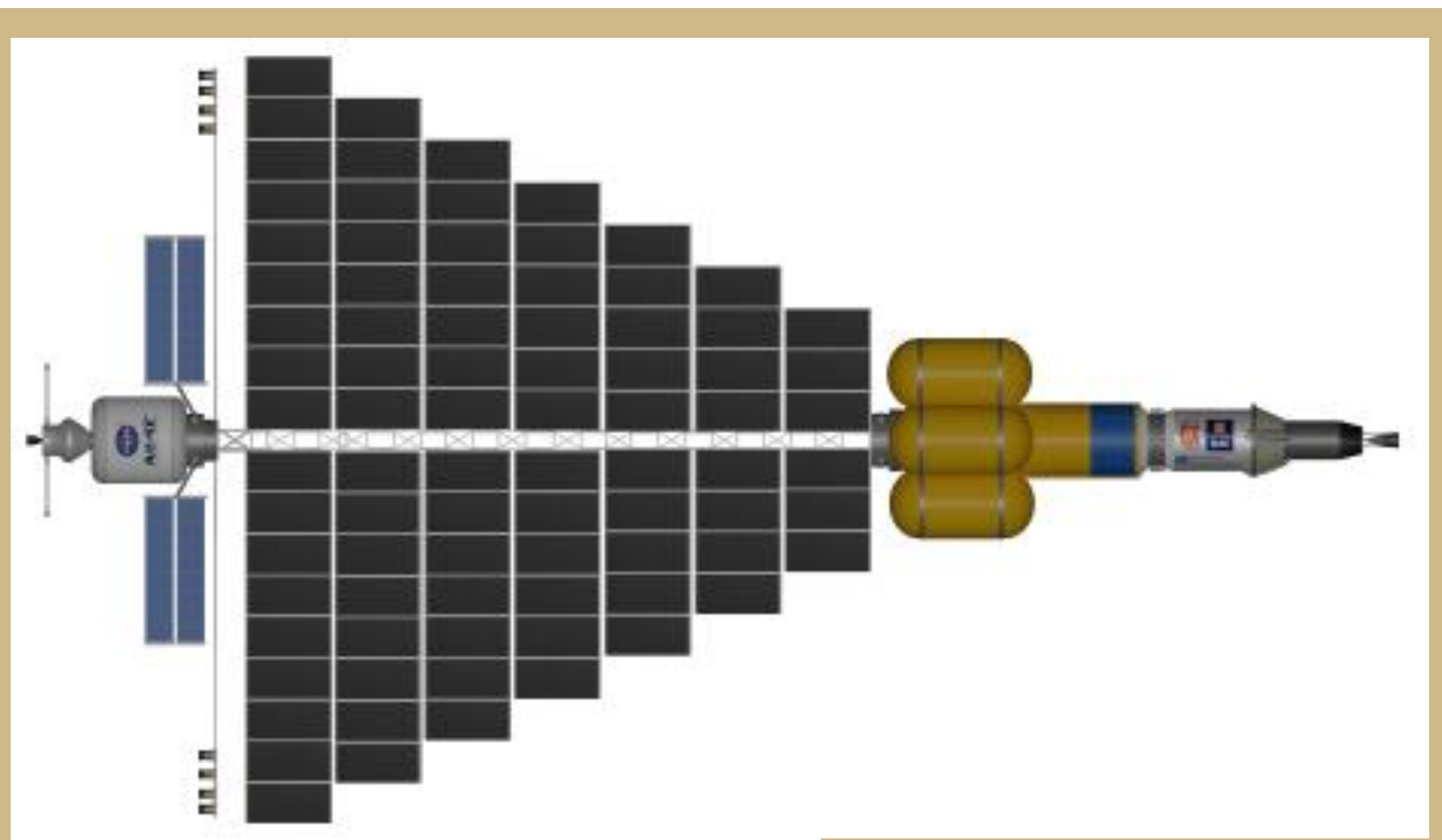

Figure 1. Rendering of the WREN Spacecraft

III. Results

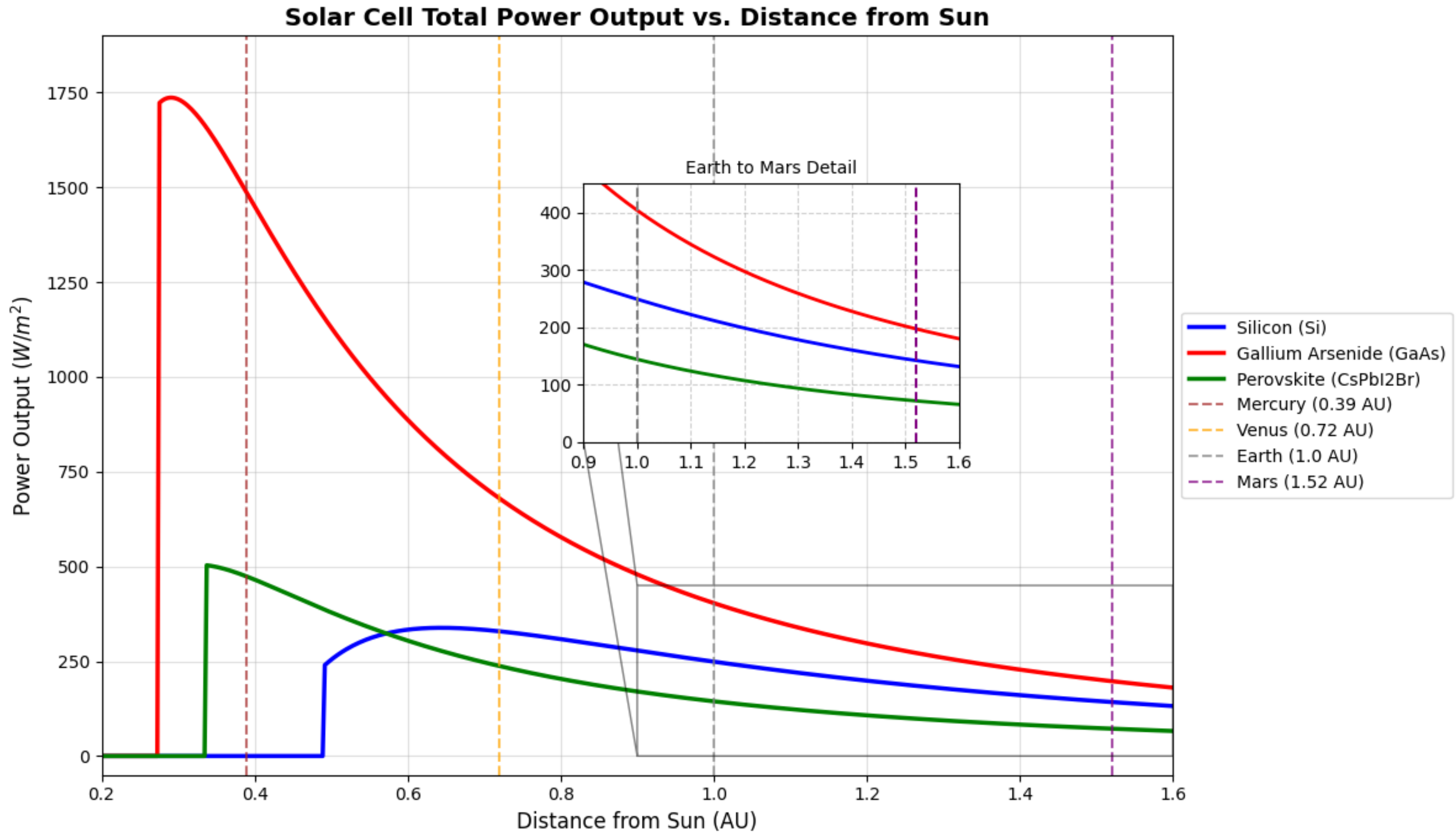

Figure 2. Calculating Power Generation Across All Cell Materials and Distance

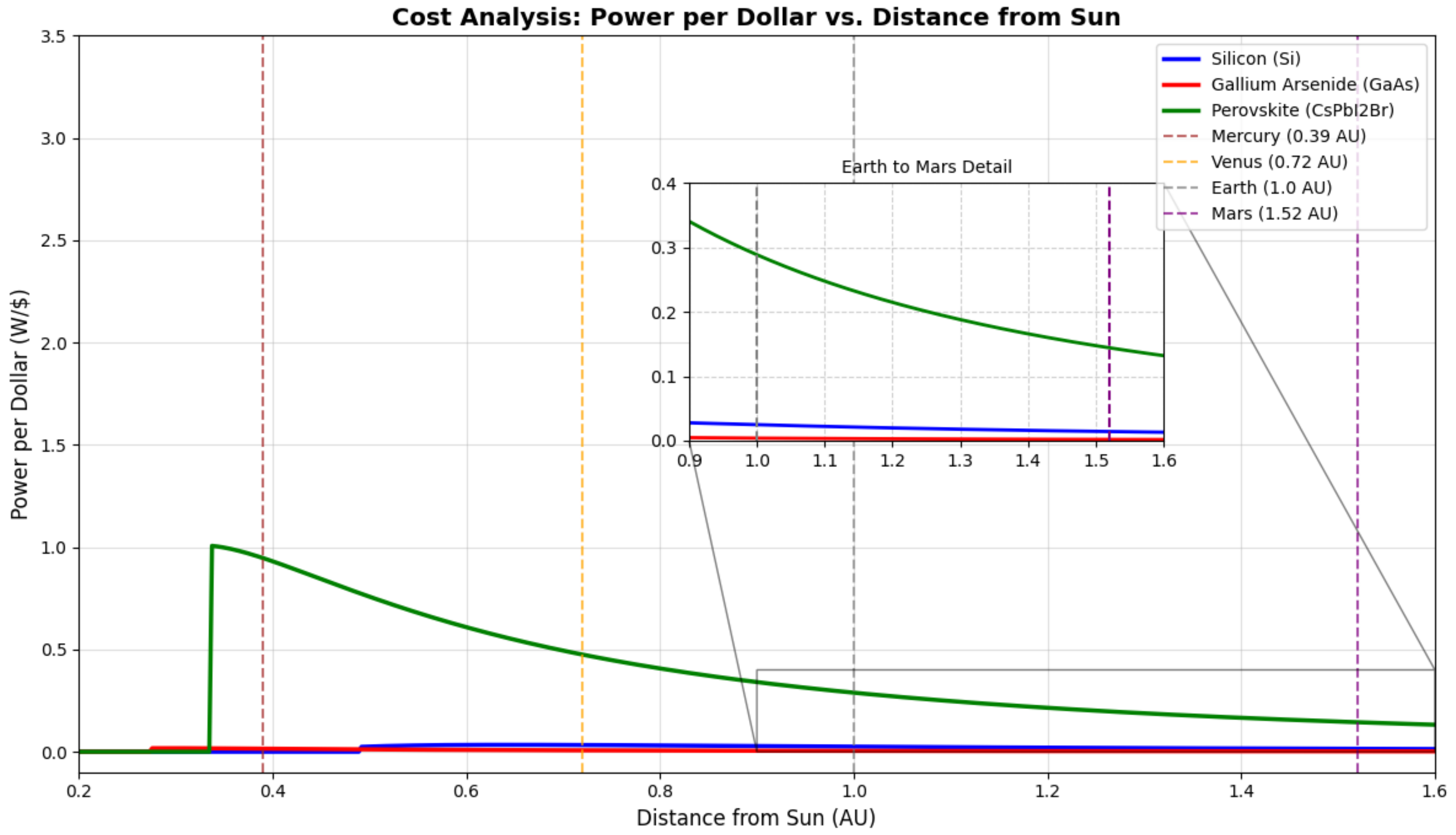

Figure 3. Power per Dollar of All Cell Materials Vs. Distance from Sun

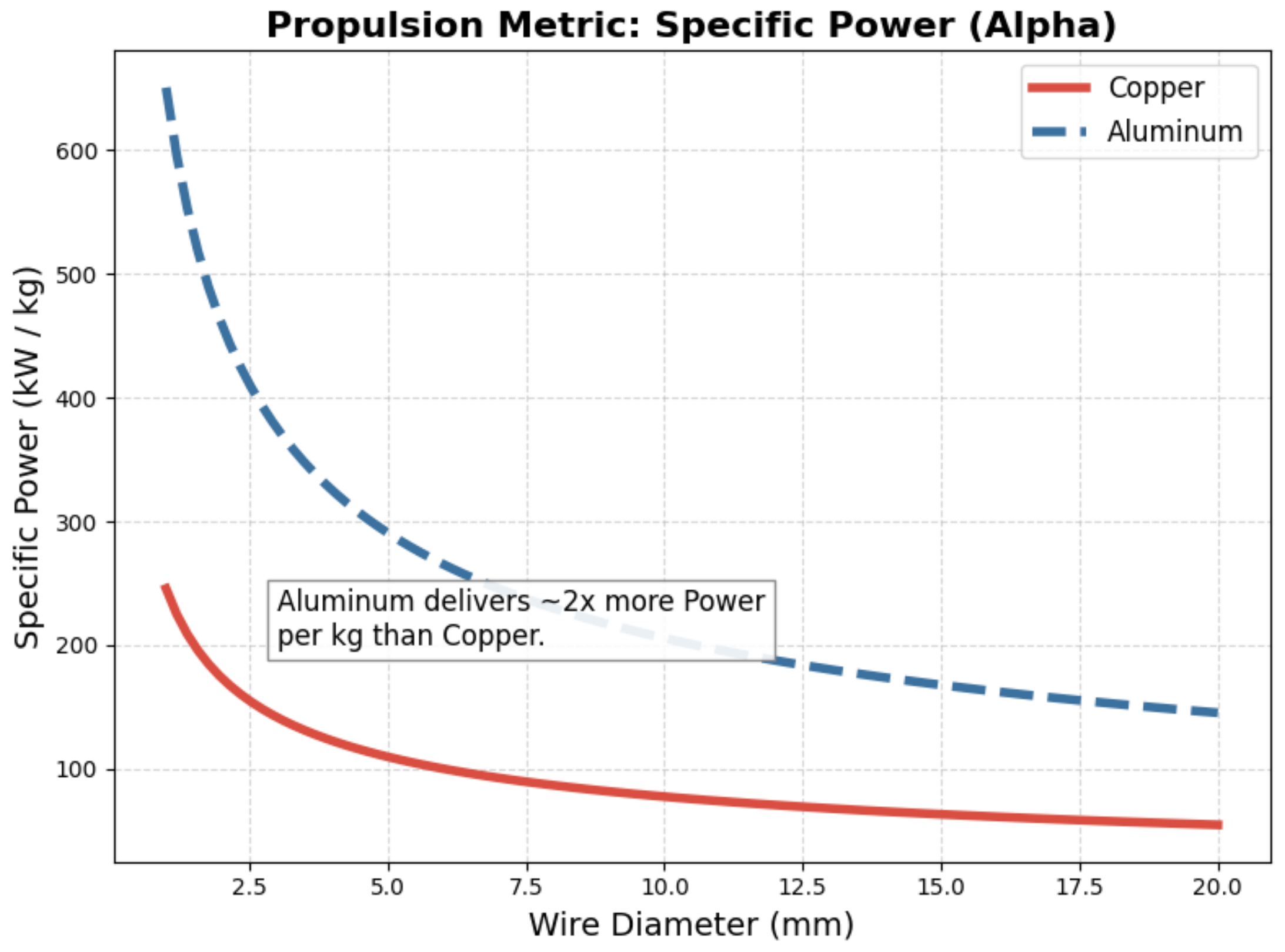

Figure 4. Calculating Specific Power (Power/Mass)

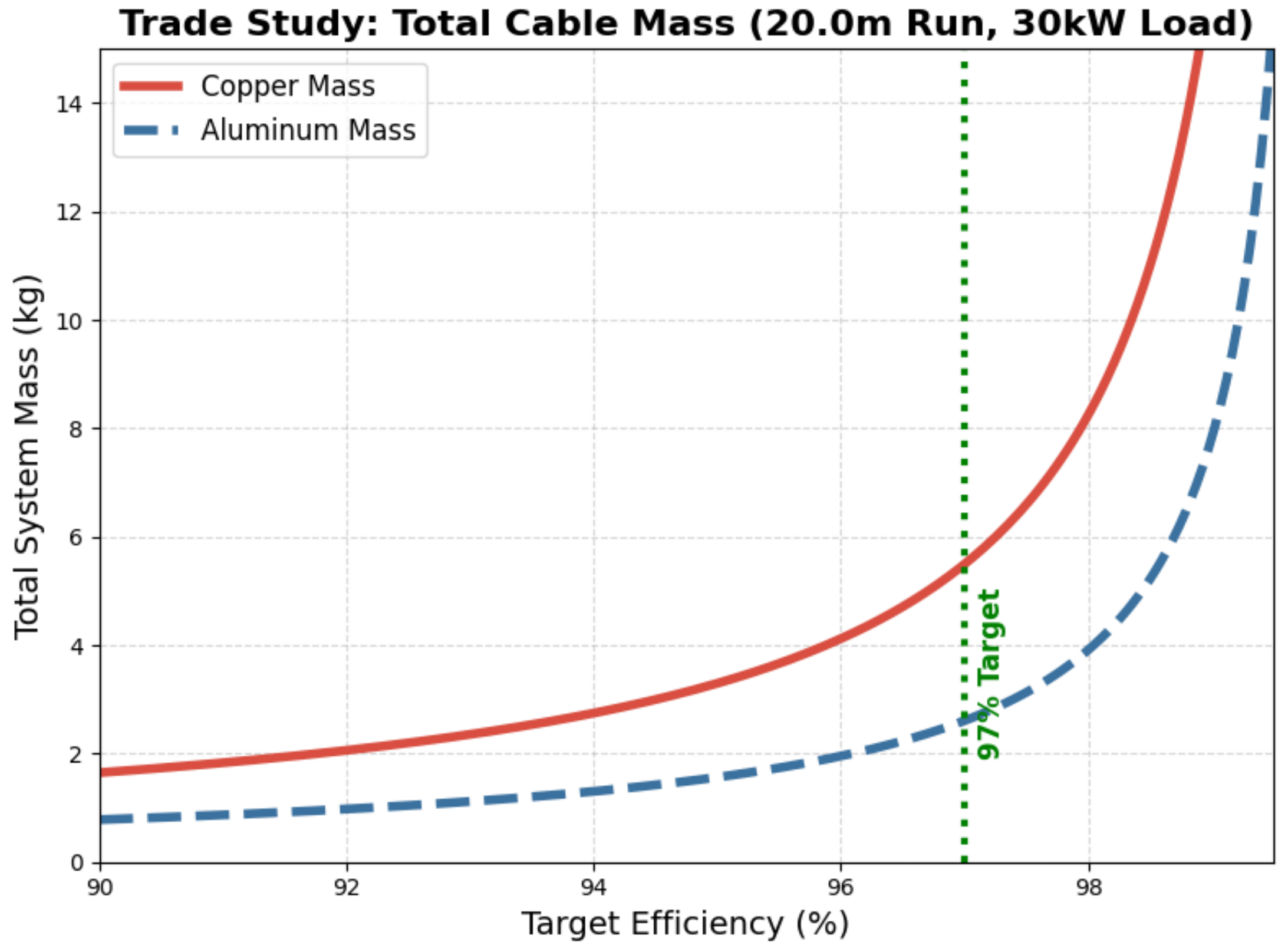

Figure 5. Determining Material Reaching Target Efficiency with Minimal Mass

IV. Discussion

Solar Cell Figure 2 Results:

- As expected, **GaAs demonstrated superior power output** while Perovskite and Silicon provide lower raw power.
- The vertical drops in power output represent catastrophic material failure where operating temperatures exceed structural limits
- All solar cells follows an exponential decay.

Solar Cell Figure 3 Results:

- Although **GaAs create more raw power, Perovskite dominates cost analysis.**
- As distance increases, the cost disparity decreases
- **Perovskite maintains its economic lead** even in lower-light regions. However, if far enough it may not matter.

Transmission Wire Figure 4 Results:

- **Aluminum achieves a significantly higher specific power**.
- Both display exponentially higher specific power at smaller diameters due to higher surface-area-to-volume ratio.
- **Data indicates Aluminum is superior**, capable of exceeding 600Kw/kg compared to Copper's 250kW/kg.

Transmission Wire Figure 5 Results:

- Efficiency gains past 97% target shows diminishing returns.
- **Aluminum scales better** for high performance requirements than Copper.
- 97% efficiency target represents ideal "sweet spot" for WREN project.

V. Conclusion

All in all, this study demonstrates that optimizing a spacecraft's power contains more than just as much power as possible. But also, the consideration of budget and weight constraints. As seen, the power generation of solar cells, **Gallium Arsenide (GaAs)** is still the standard for maximum power density. However, cost analysis showed that **High-Temperature Perovskite** provides a superior return on investment. With almost **60x higher Power per Dollar** for missions that have a tighter budget. Additionally, the transmission wire analysis shows **Aluminum** as the optimal material. Moreover, at a **97% efficiency** point, the Aluminum cabling has a **~54% mass reduction** compared to Copper. This significantly improves the specific power (α) of the Power Management and Distribution (PMAD) system. Collectively, these simulations will be used to create digital twins, helping the future research and development of space exploration.

VI. References

Border, James. *Thermal Model of a Current-Carrying Wire in a Vacuum*. 1 Sept. 2006. *Tech Briefs*,

Casado, Pablo, et al. "Implementation of a 6U CubeSat Electrical Power System Digital Twin." *Aerospace*, 21 Aug. 2024. *MDPI*,

Development of Megawatt-Scale Medium-Voltage High Efficiency High Power Density Power Converters for Aircraft Hybrid-Electric Propulsion Systems . 9 July 2018. *IEEE/AIAA*

Gosse, Ryan. *Wave Rotor Enhanced Nuclear (WREN) Propulsion*.

Longhurst, Glen, et al. "Multi-Megawatt Power System Trade Study." *INEEL*, 15 Mar. 2002, inldigitallibrary.inl.gov/sites/sti/sti/2688773.pdf. Accessed 2 Nov. 2025.

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