The Effectiveness of Power Distribution Systems for Deployment on the Lunar Surface

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Outline

- Define Trade Study to run
- Define Figures of Merit
- Detail Sizing Code
- Results
- Discussion

Study Overview

Power Generation → Necessary power → Power Distribution → Each node (1,3,5,7 total) is connected back to the Power Generation Module via a Power Cable, RF Beaming, or Laser Beaming → Power Consumption → 10 kW, 25 kW, 50 kW per node → Surface Systems

Consumer Node Distances:
1 km, 3 km, 5 km, 8 km, 15 km

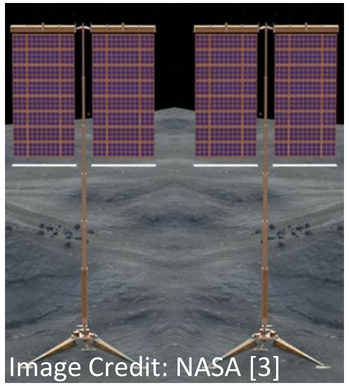


Image Credit: NASA [3]

Power Conditioning (Thermal Control Subsystem) — Power Cable — Power Conditioning (Thermal Control Subsystem)

Power Conditioning (Thermal Control Subsystem) — DC-to-RF Beam — RF Beam-to-DC — Power Conditioning (Thermal Control Subsystem)

Power Conditioning — DC-to-Laser (Thermal Control Subsystem) — Optical Conditioning — Laser-to-DC (Thermal Control Subsystem) — Power Conditioning

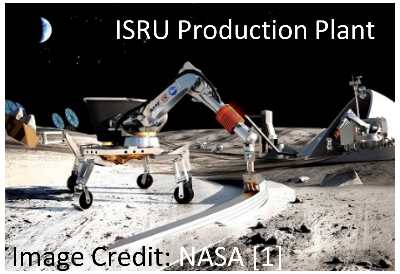


Image Credit: NASA [1]

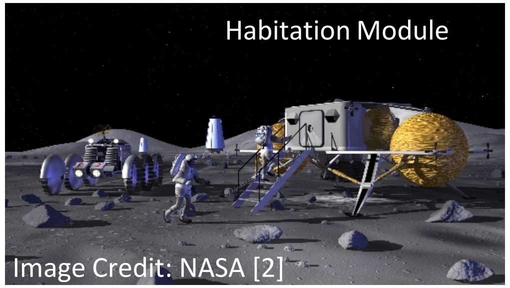


Image Credit: NASA [2]

Power generated by VSAT

- Each array outputs 10 kW @ 120 Vdc, 250 kg mass
- Assume we have enough to meet total power required

[1] "Landing Pad, Berm, Road & Habitat Construction", Published 12/07/2018, Source: https://www.nasa.gov/sites/default/files/atoms/files/nac_tie_december_2018_gsanders_isru.pdf
[2] "Entering a Lunar Outpost", Published 05/15/2006, Source: https://www.nasa.gov/exploration/multimedia/jfa18833.html
[3] Taylor, C., "Lunar Surface Solar Array Design Reference Mission, Concept of Operations, and Requirements," Tech. rep.,NASA Langley Research Center, Hampton, Virginia, April 2020.

Trade Study Overview

- The morphological matrix represents each discrete value that needs to evaluated during this trade study
- Example for 1 Case:
  - Optical Beaming
  - 50 kW delivered
  - 3 Powered Surface Systems
  - 8 km distance
- No intermixing of values
  - i.e. for the case above all power distribution is accomplished via optical beaming

Power Distribution Method	Cables	Optical Beam	RF Beam		
Power provided to each Surface System	10 kW	25 kW	50 kW		
Number of Powered Surface Systems	1	3	5	7	
Distance from VSAT to each Surface Systems	1 km	3 km	5 km	8 km	15 km

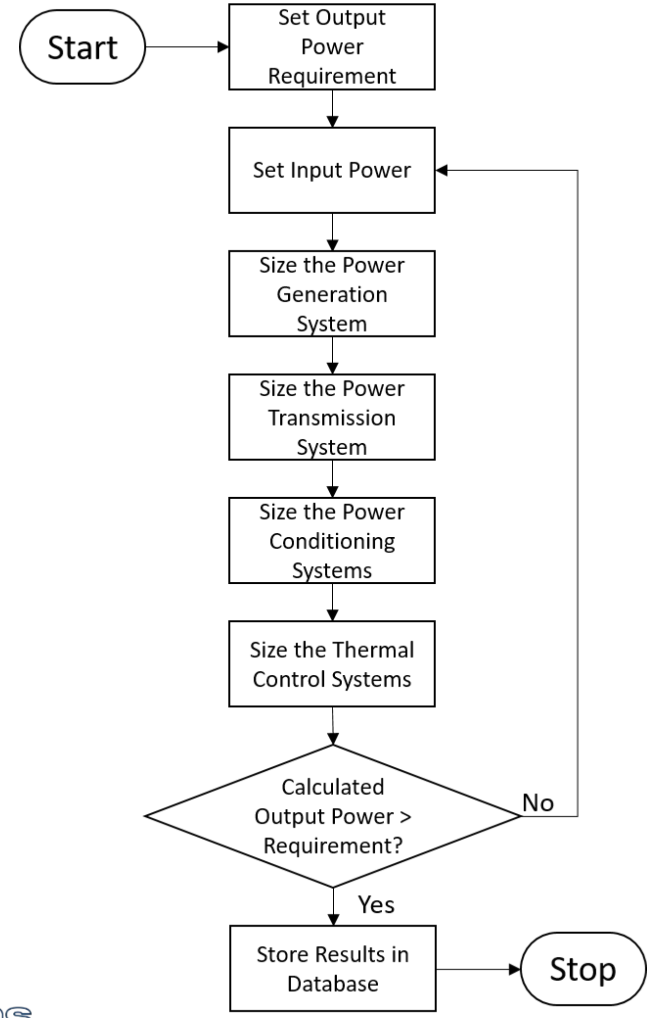
Trade Study Figures of Merit

- For each case, the three FOMs will be evaluated based on the technical details provided in the table to the right
- Landed mass will serve as the main discriminator
- System Reliability and Maintainability along with Operational Flexibility will serve as secondary and tertiary discriminators, respectively
- All results will be stored in a common file to enable ease of data visualization

Figure of Merit	Description	Priority Level	Type	Technical Details
Landed Mass	The mass of the system required to be landed on the lunar surface to operate	1	Quantitative	$mass_{landed} = mass_{power\ conditioning} + mass_{transmission\ equipment} + mass_{thermal\ system} + mass_{deployment\ solutions} + mass_{control\ systems} + mass_{LSSA}$
Reliability and Maintainability	The availability of the power distribution system to provide power across operational conditions	2	Qualitative	The overall system availability, ease of maintenance, required spares, etc. to maintain the operability of the power distribution systems. Low/Moderate/High Scale
Operational Flexibility	The ability for the system to provide power over a wide range of different operations for the end user(s)	3	Qualitative	The range of new operations enabled by each system and compare to baseline system. Low/Moderate/High Scale

Sizing Code Overview

- Sizing Code is a looped, iterative solver
- Begins by setting output power required equal to the input power
- Sizes each sub-system and calculates performance
- Calculates the output power after it has traversed the system
- Performs a convergence check:
  - Is the calculated output power greater then or equal to the requirement?
    - Yes – Store the results and move onto the next case
    - No – Increase the input power and redo the sizing loop



Sizing Code Overview – Power Electronics

- Sizing Algorithms are derived from Metcalf's Report: "Power Management and Distribution (PMAD) Model Development"
- Common Power Electronics capable of being sized:
  - DDCU
  - SAVOR
- Contains the coded models for the various power electronic components
- Power electronics are sized as the sum of the masses of their subcomponents

Power Electronics Sizing Algorithm – DDCU Sizing

Inputs: Voltage In, Voltage Out, Power Level,

Outputs: Mass of DDCU, Heat Generated by DDCU

- Define Component Efficiencies, redundancy factor
- Size 1st DC Filter
- Calculate 1st Filter Power Loss
- Size DC-AC Inverter
- Calculate Inverter Power Loss
- Size AC Transformer
- Calculate Transformer Power Loss
- Size Rectifier
- Calculate Rectifier Power Loss
- Size 2nd DC Filter
- Calculate 2nd DC Filter Power Loss
- Size Control, Monitoring Systems
- Size Internal Conductors
- Size Enclosure
- $mass_{DDCU} = mass_{dc\ filters} + mass_{inverter} + mass_{transformer} + mass_{recitifer} + mass_{CMS} + mass_{conductors} + mass_{enclosure}$
- $heat_{generated} = \sum sub\ component\ power\ losses$
- Return $\text{Mass}_{\text{DDUC}}$, Heat Generated

Dc Filter Sizing

Inputs: Power In, Redundancy, Efficiencies, Voltage, Ripple Factor

Outputs: Filter Mass, Power Out

- Mass = $22.05\left(\frac{1}{\left(\frac{Ripple}{0.01}\right)^{0.5}}\right)\left(\frac{1-0.998}{1-Eff}\right)(Redundancy\ factor)(Eff * Power\ In)(Voltage^{-0.9} + 0.000015)$
- Power Out = Efficiency*Power In

Sizing Code Overview – Thermal Control System

- Sizing algorithms and parameters are adapted from:
  1. Metcalf's Report: "Power Management and Distribution (PMAD) Model Development"
  2. Goncharov, K., Panin, Y., Balykin, M., & Khmelnitsky, A. (2016, July). High thermal conductive carbon fiber radiators with controlled Loop Heat Pipes. 46th International Conference on Environmental Systems.
  3. Ku, J. (2015). Introduction to Loop Heat Pipes.
  4. Qu, Y., Wang, S., & Tian, Y. (2018). A review of thermal performance in multiple evaporators loop heat pipe. *Applied Thermal Engineering*, *143*, 209-224.
  5. Deng, D., Liang, D., Tang, Y., Peng, J., Han, X., & Pan, M. (2013). Evaluation of capillary performance of sintered porous wicks for loop heat pipe. *Experimental Thermal and Fluid Science*, *50*, 1-9.
  6. Wertz, J. R., Everett, D. F., & Puschell, J. J. (2011). *Space mission engineering: the new SMAD*. Microcosm Press.
  7. Birur, G. C., Siebes, G., Swanson, T. D., & Powers, E. I. (2001). Spacecraft Thermal Control.
- The heat pipe will extract heat from the power electronics and transmission device coldplates

Thermal Control System Sizing Algorithm

Inputs: Heat Generated, Operating Temperature, Component Dimensions

Outputs: Mass of Thermal Control System

- Calculate total heat to be dissipated for hot-case
  - Includes incident and reflected solar radiation
  - $\frac{1}{2}A_{surface} \times \alpha \times irradiance_{solar} \times (1 + albedo)$
- For Each Component:
  - Size the Coldplate: $Mass = 13.6 \times Area$ [1]
  - Size the Heat Pipes
    - Includes: evaporator, wick, transport lines, condenser, compensation chamber, and ammonia
  - Size the Radiator: $Area = \frac{\left(\frac{1.0823E10}{Radiator\ Sides} * Q\right)}{\left(Coldplate\ T - \Delta T_{coldplate-to-radiator}\right)^4 - T_{Sink}^4}$ [1]
    - $Mass = 0.625 \times Radiator\ Sides + 1.25$ [2]
    - Calculate additional heat incident on the radiator
    - Recalculate the necessary radiator size
    - Iterate until converged on the appropriate radiator size
- Calculate Thermal Control system mass: $mass_{TCS} = mass_{coldplates} + mass_{heat\ pipes} + mass_{radiator}$
- Return Mass

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Sizing Code Overview – Power Cables

- Sizing Algorithm is derived from Gordon's Report: "Electrical Transmission on the Lunar Surface Part I—DC Transmission"
- Configuration is 2 solid copper cables: 1 hot-1 return
- Overall cable designed to be 2-fault tolerance – Kerslake assumption
  - Requires 3 set of cable pairs
  - fail-operate with full power, fail-safe with 50 percent power
- Iterative solver that sizes cable to carry the required power with less then 5% voltage drop and passively maintain the operating temperature
  - Determines optimal transmission voltage to reduce overall system mass
- Cable mass is calculated with a 10% routing factor to account for any unexpected obstacles/terrain that have to be routed around

Power Cable Sizing Algorithm

Inputs: Power Delivered, Transmission Length

Outputs: Landed Mass, Power Input Required

- Set efficiency based on Voltage drop requirements
- Set Operating Temp
- For each Transmission Voltage
  - Current (I) = Power Level / Voltage
  - While not Converged do:
    - $Solve\ for\ radius\ using\ Volt\ Drop: r = \sqrt{\frac{2Power_{in}Length_{transmission}\rho}{eff_{Volt\ Drop}\,\pi V^2_{transmission}}}$
    - $R = \frac{resistivity * Length_{Transmission}}{\pi radius^2_{cable}} = \frac{\rho L}{\pi r^2}$
    - $heat_{generated} = I^2R + 274.4rL$
    - Solve for the $T_{operating}$ $heat_{radiated} = constants\frac{\pi r^2}{2}[(T^4_{operating} - T^4_{Space}) + (T^4_{operating} - T^4_{Surface})$
    - Update resistivity: $\rho_{update} = \rho_0[\frac{T_O - T_{material}}{293 - T_{material}}]$
    - Check for convergence
  - Calculate Total cable mass: $mass_{cables} = 6L(density_{conductor}\pi r^2)$ + $Mass_{insulation}$
- Transmission Voltage = argmin($mass_{cables}$)
- Size Deployment Systems
- Size Step up DDCU(Power Level, Transmission Voltage) & ATCS($heat_{required,disapated}$)
- Size Step down DDCU(Power Level, Transmission Voltage) & ATCS($heat_{required,disapated}$)
- Return Landed Mass

Sizing Code Overview – RF Power Beaming

- General Sizing Algorithms were adapted from previous NASA works: “Design Study for a Ground Microwave Power Transmission System for Use with a High-Altitude Powered Platform”, “MICROWAVE POWER TRANSIVSISSION SYSTEM STUDIES Volumes I to IV”
- Based on further research into surrounding work, it was assumed that the antenna array would achieve a Gain of 40
  - Plan to perform a sensitivity study to this assumption next set of design runs
- Assumed each antenna bar could transmit 1 kW while maintain passive cooling
- Assumed 100 W/m2 needed to get correct power draw from Rectenna
- Trade study explored the best transmission frequency
  - Explored 2.45, 5.8, and 10 GHz

RF Power Beaming Sizing Algorithm

Inputs: Power Level, Transmission Length

Outputs: Landed Mass, Power Input Required

- For each Transmission Frequency
  - While not Converged do:
    - Solve for Transmission Power Required: $P_{transmission} = \frac{4\pi d^2 Power_{incident}}{10^{Gain/10}}$
    - Size Microwave Generators to meet power requirement
    - Size the Transmission Antenna to meet power requirement
    - Calculate power needed from rectenna
    - Size the Rectenna
  - Calculate Total system mass: $mass_{RF} = mass_{generators} + mass_{antenna} + mass_{rectenna}$
  - Calculate system power losses
- Required Voltage = f($microwave\ generators$)
- Size Step up DDCU(Power Level, Required Voltage) & ATCS($heat_{required,disapated}$)
- Size Step down DDCU(Power Level, Required Voltage) & ATCS($heat_{required,disapated}$)
- Return Landed Mass

Sizing Code Overview – Optical Power Beaming

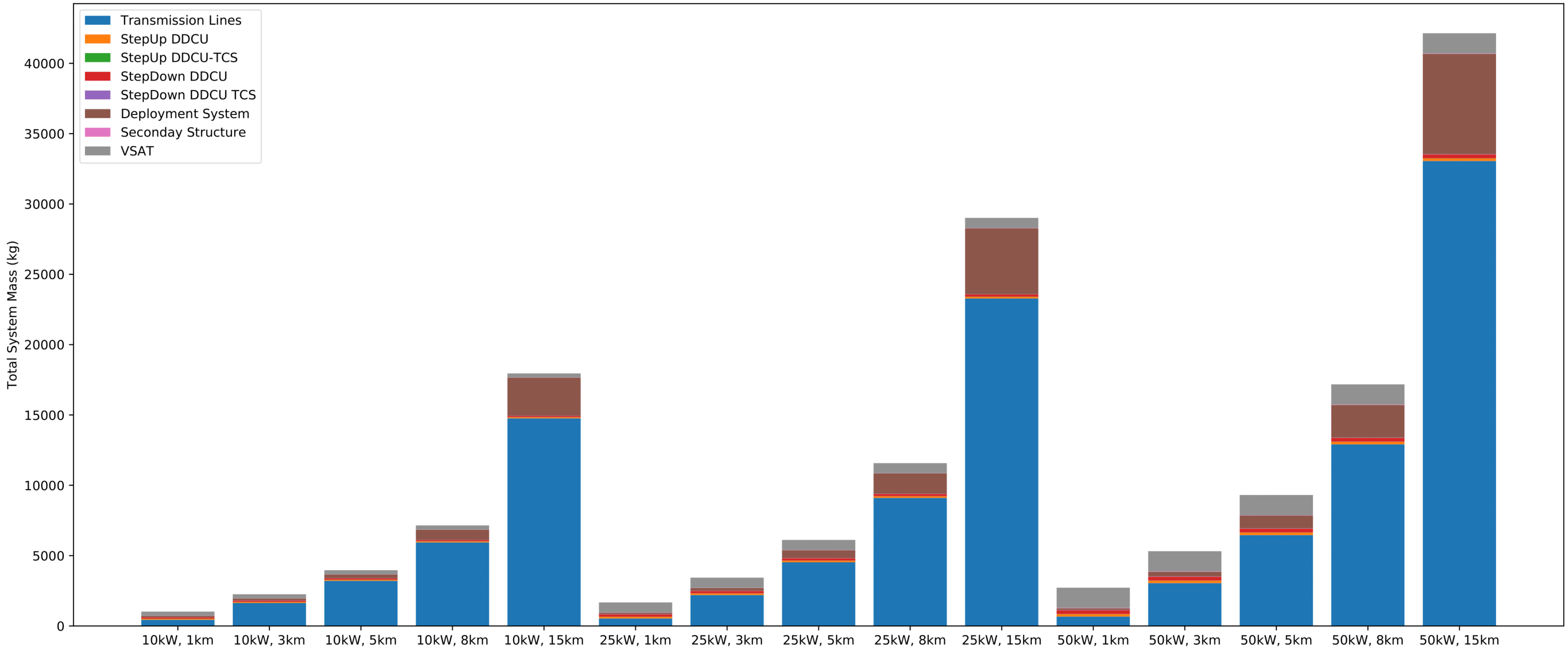
- General Sizing Algorithms adapted from parameters of commercially available products
- Components to be sized
  - Laser – laser head and control unit
  - Lenses
  - Receiver
- Iterative solver to size all components to meet required output power
- Calculate masses for diode and fiber-based lasers
  - Diode has better efficiency and lower mass
  - Fiber has smaller beam -> less lens and receiver mass

Optical Power Beaming Sizing Algorithm
Inputs: Power Level, Transmission Length
Outputs: Landed Mass, Power Input Required

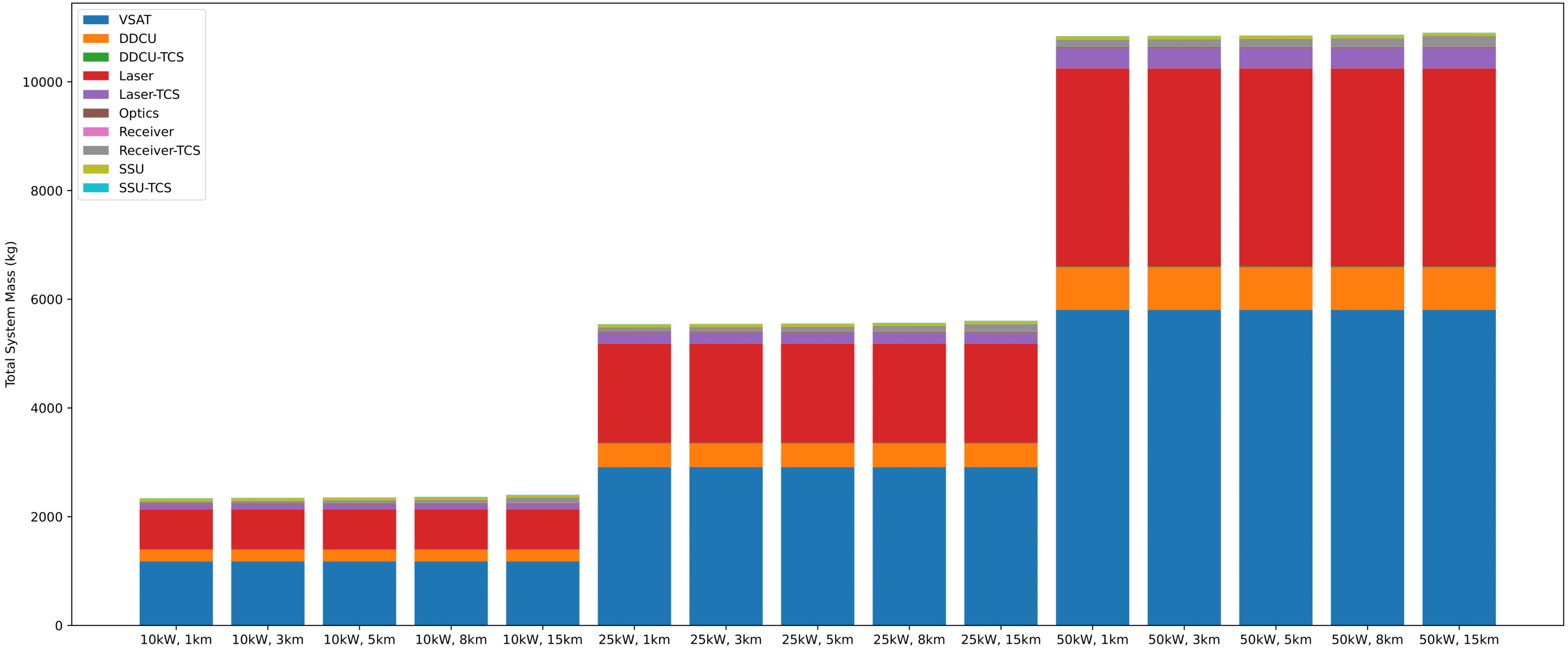
- For diode and fiber laser:
  - Iterate until output power is met:
    - Size Step up DDCU and TCS
      - Return efficiency and mass
    - Size laser and TCS
      - Return efficiency, area, and mass
    - Size the optical conditioners
      - Return mass and beam diameter
    - Size the receiver and TCS
      - Return efficiency, area, mass
    - Size SSU and TCS
      - Return efficiency and mass

- Calculate Total system mass: $mass_{Optical} = mass_{ddcu} + mass_{laser} + mass_{conditioning} + mass_{receiver} + mass_{ssu}$
- Calculate mass of VSAT based on required input power
- Return Landed Mass

Results – Power Cable Sizing



Results – Optical Power Beaming (Diode)



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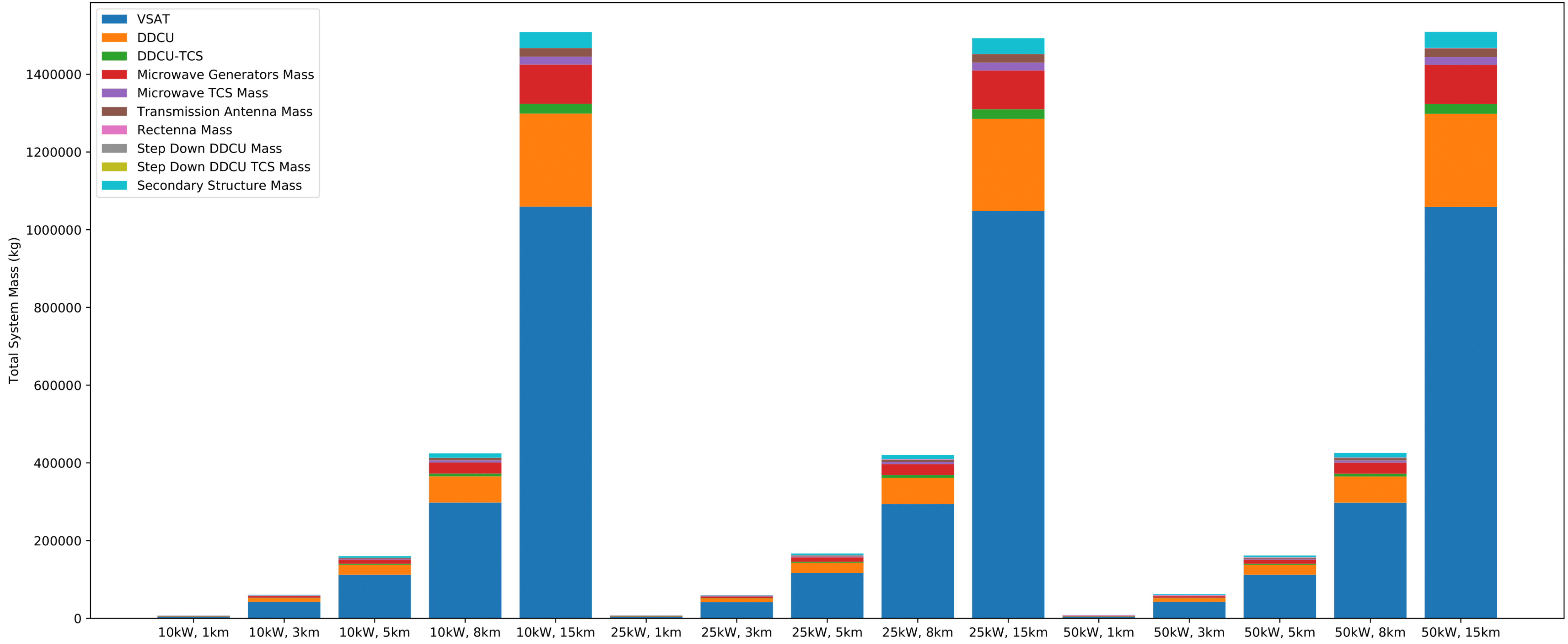
Results – RF Beaming (2.45 GHz)



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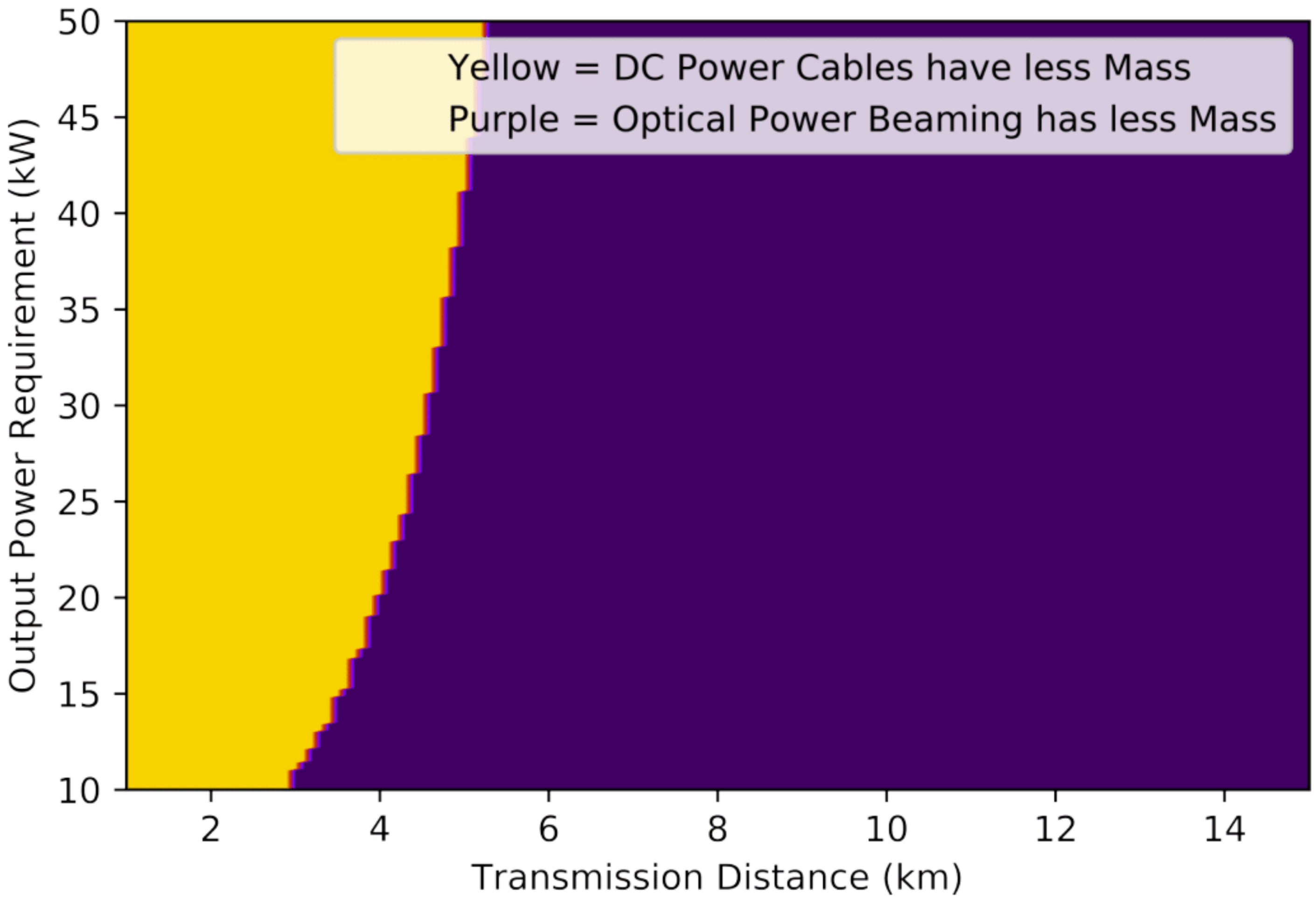
Results – Total System Mass Comparison

10 kW						
	Power Cables	Laser (Fiber)	Laser (Diode)	RF (2.45 GHz)	RF (5.8 GHz)	RF (10 GHz)
1 km	1,022 kg	2,745 kg	2,340 kg	6,984 kg	8,787 kg	11,622 kg
3 km	2,253 kg	2,746 kg	2,346 kg	59,036 kg	74,979 kg	99,948 kg
5 km	3,964 kg	2,747 kg	2,353 kg	155,964 kg	198,207 kg	264,349 kg
8 km	7,149 kg	2,750 kg	2,366 kg	413,098 kg	525,118 kg	700,493 kg
15 km	17,953 kg	2,762 kg	2,403kg	1,467,667 kg	1,865,886 kg	2,489,297 kg

25 kW						
	Power Cables	Laser (Fiber)	Laser (Diode)	RF (2.45 GHz)	RF (5.8 GHz)	RF (10 GHz)
1 km	1,672 kg	6,605 kg	5,541 kg	6,984 kg	9,239 kg	12,151 kg
3 km	3,432 kg	6,606 kg	5,547 kg	59,036 kg	74,739 kg	99,549 kg
5 km	6,113 kg	6,607 kg	5,554 kg	155,964 kg	206,365 kg	275,179 kg
8 km	11,574 kg	6,610 kg	5,566 kg	413,098 kg	520,040 kg	693,565 kg
15 km	29,011 kg	6,622 kg	5,604 kg	1,467,667 kg	1,846,473 kg	2,463,349 kg

50 kW						
	Power Cables	Laser (Fiber)	Laser (Diode)	RF (2.45 GHz)	RF (5.8 GHz)	RF (10 GHz)
1 km	2,721 kg	13,006 kg	10,839 kg	6,984 kg	10,150 kg	13,268 kg
3 km	5,314 kg	13,007 kg	10,845 kg	59,036 kg	76,309 kg	101,547 kg
5 km	9,308 kg	13,008 kg	10,852 kg	155,964 kg	199,526 kg	265,920 kg
8 km	17,176 kg	13,011 kg	10,864 kg	413,098 kg	526,109 kg	701,667 kg
15 km	42,137 kg	13,023 kg	10,902 kg	1,467,667 kg	1,866,051 kg	2,489,352 kg

Results – Power-Distance Breakdown Plot



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Results – Qualitative FOMs

Key Takeaways

- DC Power Cables
  - Extensive operational history on earth with high reliability
  - No issues noted on ISS or satellites due to power cable failure
  - Cables are heavy and require large trailers to tow them and keep tension on the cable
- RF Power Beaming
  - Untested at this scale
  - Large amount of components
  - Requires large receiving antenna, impossible to mount on a mobile platform
- Optical Beaming
  - Large operational history of industrial lasers
  - Modular Components allow for ease of maintenance
  - Concentrated beam allows for smaller PV receiver that could be mounted on a rover

	Reliability	Maintainability	Operational Flexibility
DC Power Cables	High	Moderate	Low
RF Power Beaming	Low	Low	Low
Optical Power Beaming	Moderate	Moderate	High

Summary

- The prescribed trade study was ran and the initial results were compiled into this document
  - Total run time for all cases ran: 1.853 seconds
- Power cable mass appears to have linear scaling with power but strong quadratic scaling with distance
  - The insulated wires appear to have a higher quadratic coefficient
  - At higher power levels and distance, thickness is a significant mass fraction of total system due to a much higher transmission voltage
- Laser Power beaming mass is nearly invariant with distance but scales quadratically with power level
  - Large initial mass investment but can be scaled over a large range of distances
  - Approximately 40% of the mass is attributed to the VSATs due to an average 21% power efficiency
- RF Power beaming is not a viable option for this configuration due to both distance and power levels required

Avenues for Future Work

- Examine relative masses of power distribution **<u>and storage</u>** systems
- Trade mass of battery/storage systems vs. reliability for each distribution approach
- Incorporate a lunar terrain model to analyze line-of-sight issues for power beaming
- Explore the sensitivity to variations in solar flux due to intermittent and partial illumination
- Explore the sensitivity to the voltage drop requirement
- Incorporate a more detailed operations model to quantify the impacts of different power consumer types and energy storage devices
- Develop an analytical model to quantify the reliability of the power distribution systems using Markov Chains