Lunar Microgrid Systems Engineering Methodology for Resilient Design

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Poster created by Sonia Bendre

Introduction

For upcoming lunar missions, NASA aims to establish a long-term sustainable presence on the moon. Initially, with short-term missions, ranging from weeks to months, to a permanent crew presence. This requires significant infrastructure. Various electrical distribution systems could be implemented to support a mission objective. To this end, a design methodology was developed to assist in early design-space exploration of candidate electrical architectures for microgrids on the lunar surface, as shown in Fig. 1.

A case study follows the methodology to find candidate architectures for a long-term crewed lunar presence on the south pole, which is likely to be an upcoming goal for an Artemis III or Artemis IV mission. These architectures are shown in Fig. 2. As indicated by NASA, a long-term lunar presence would require four nanogrids within the larger lunar microgrid.: a lunar habitat, two grids for in-situ resource production and excavation, and a grid to house nuclear fission power generation.

This presentation contains a high-level overview of the methodology, as well as its application on three power distribution architectures– radial, ring, and meshed– including developing state diagrams for fault detection in each and finding their differences in mass.

Methodology

After identifying the main goals of the mission and specific microgrid functions, as described by the methodology, initiating fault events could be defined, fault trees could be developed, and in-depth trade-offs could be calculated.

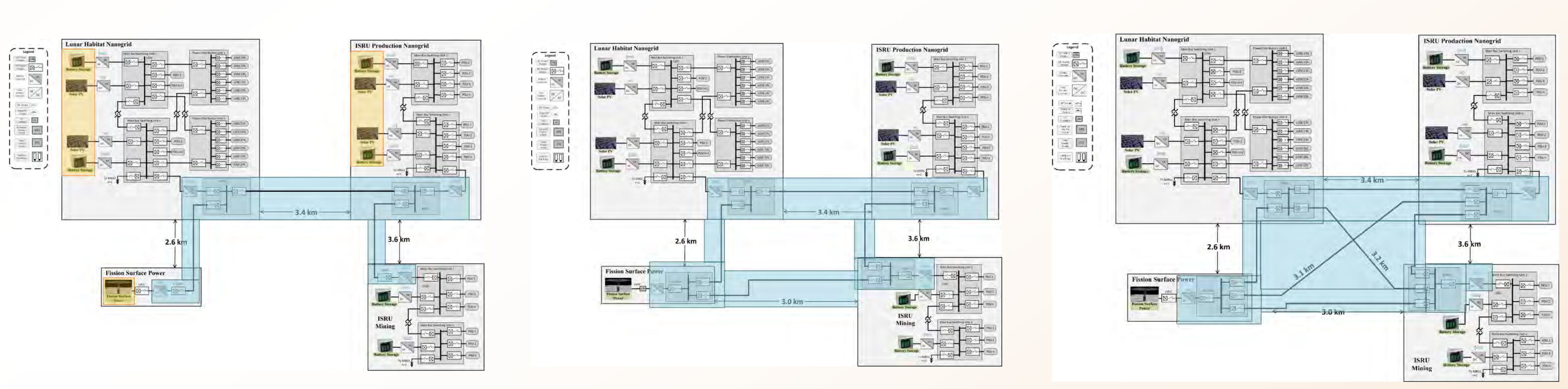
The main missions of our case study operation are to further scientific development, which requires hardware including a long-range rover, its charging station, and developed communications systems, establish autonomous operability of microgrids, and explore craters for signs of water-ice.
However, before being able to assess various network configurations and DER locations, the networks had to perform fault detection, isolation, and recovery (FDIR). Designing a meshed network to successfully perform FDIR is a challenge as protective functionality must be correctly distributed between power conversion and power distribution equipment. This task is more complex than conventional power distribution protection design as it combines domain knowledge between power distribution and power electronic engineers in new form. SAPHIRE 8, a program that generates dynamic event trees, can be used used to accomplish this.

Three main considerations were taken into account when calculating mass:
1. Sizing of Distributed Energy Resources (DERs)
2. Sizing of cabling
3. Sizing of other power distribution (DC/DC converters, RBI)

DERs include photovoltaic arrays, fission surface power, and the Battery Energy Storage System (BESS). The cabling connecting the architectures is assumed to be made of aluminum wiring. Fig. 3 shows the decision-making flowchart used to determine the size of the ESS. Because each full day on the lunar surface is equivalent to around 28 days on Earth, batteries will have to contain enough power to sustain the lunar base over a 14-day period of darkness.

The cable length is dependent on the selection of architecture, as shown in Fig. 2.

Mass estimates were produced for a DC-DC converter and RBI. The blue-highlighted connections in Fig. 2 show the power distribution equipment whose mass can be directly calculated. Highlighted in yellow in Fig. 2(a) are the energy production and storage units. A meshed architecture, which is designed to optimize for redundancy and resiliency, weighs considerably more than a radial or ring design.



(a) (b) (c)

Fig. 2. Power distribution equipment in (a) Radial, (b) Ring, and (c) Meshed Lunar Architectures.

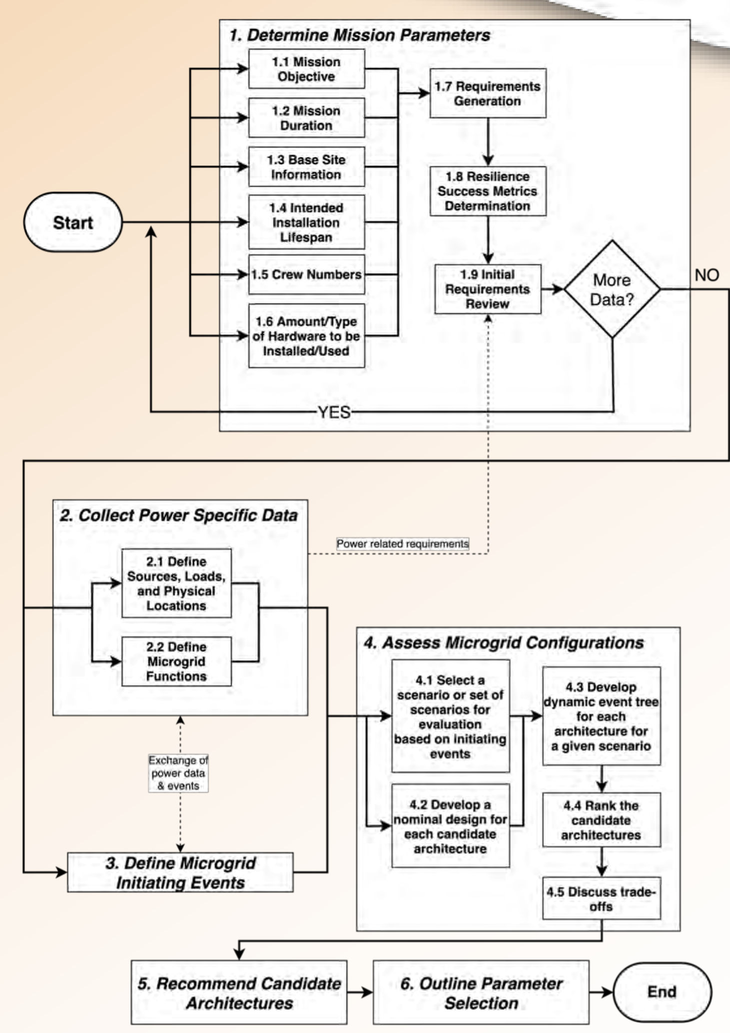


Fig. 1. Outline of steps in the resilient lunar microgrid design methodology.

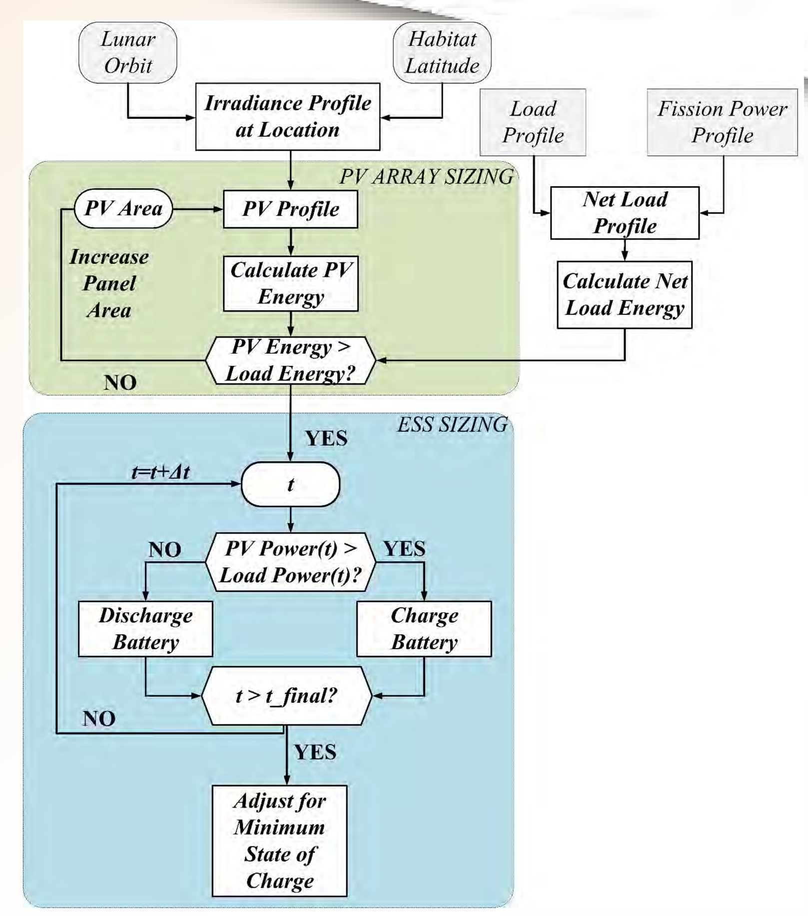


Fig. 3. ESS Sizing Flowchart.

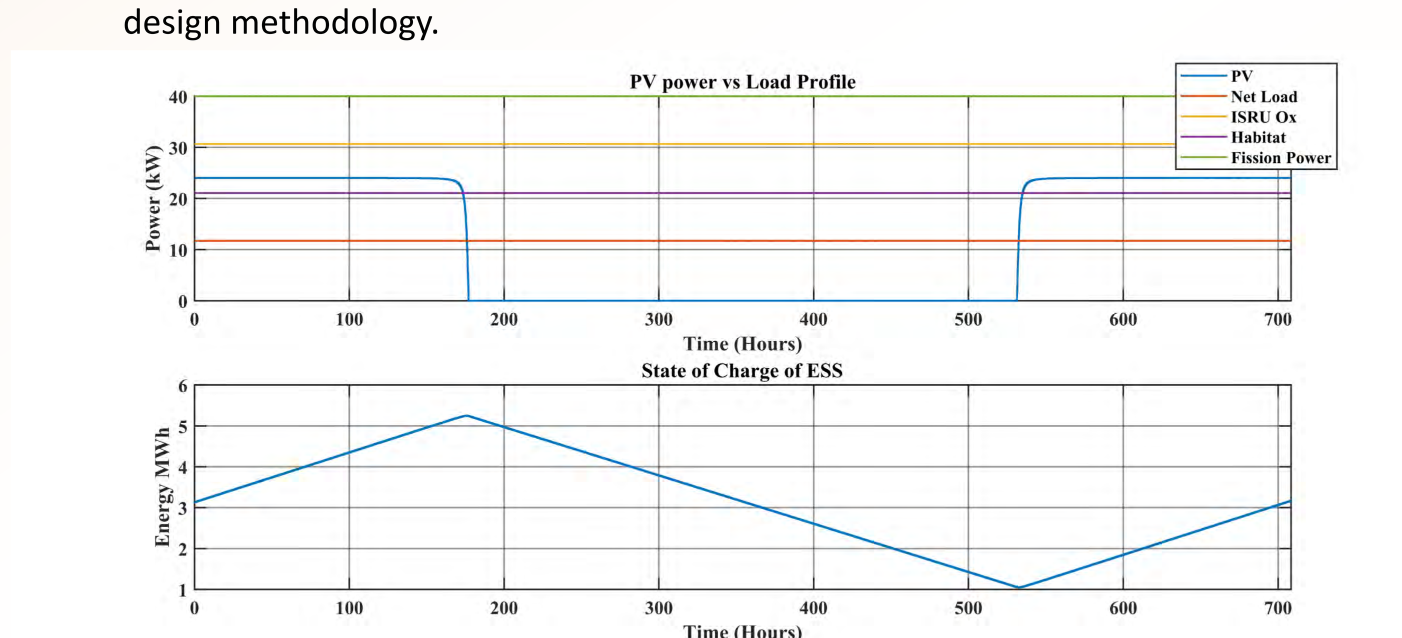


Fig. 4. ESS Charge State Diagram.

The chart generated in Fig. 4 shows the state of charge of the ESS over time, based on the total load from each nanogrid, as well as the additional source of energy provided by fission power. The PV power generated during the light hours provides sufficient energy during the night period.

Fault probabilities were estimated and analyzed for each of the architectures using event trees. The event sequences and probabilities derived provide a baseline for future detailed analysis. Using SAPHIRE 8, dynamic event trees (DETs) were developed for the radial, ring and meshed architectures. Fig. 5 shows an example of a fault tree that could be generated based on a battery failure in one of the internal zones that supplies the ISRU production nanogrid during the lunar night. The trees provide a system of states and events in individual power distributions as well as all possible outcomes allowing future engineers to compare.

Complete sizing of power distribution equipment, based on the architectures, was calculated and is tabulated in Fig. 7. Future systems engineers would be equipped to select a potential architecture from the three developed, in accordance with expense and if resilience to multiple faults is needed.

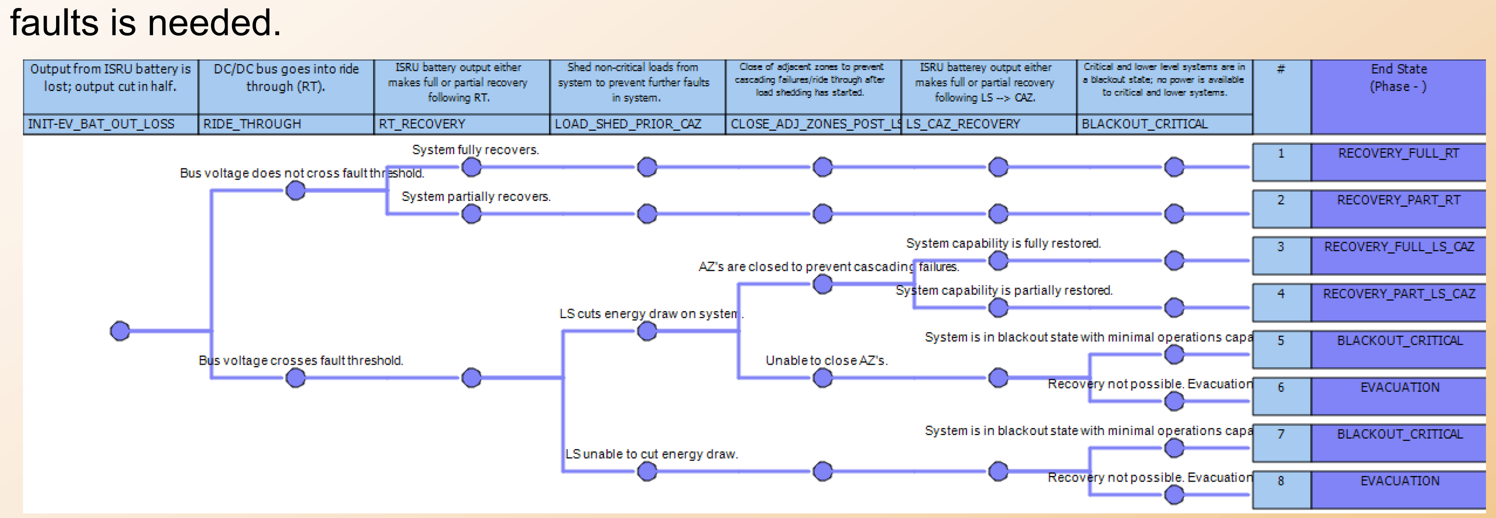


Fig. 5. Fault tree generated based on an electrical fault in a meshed architecture.

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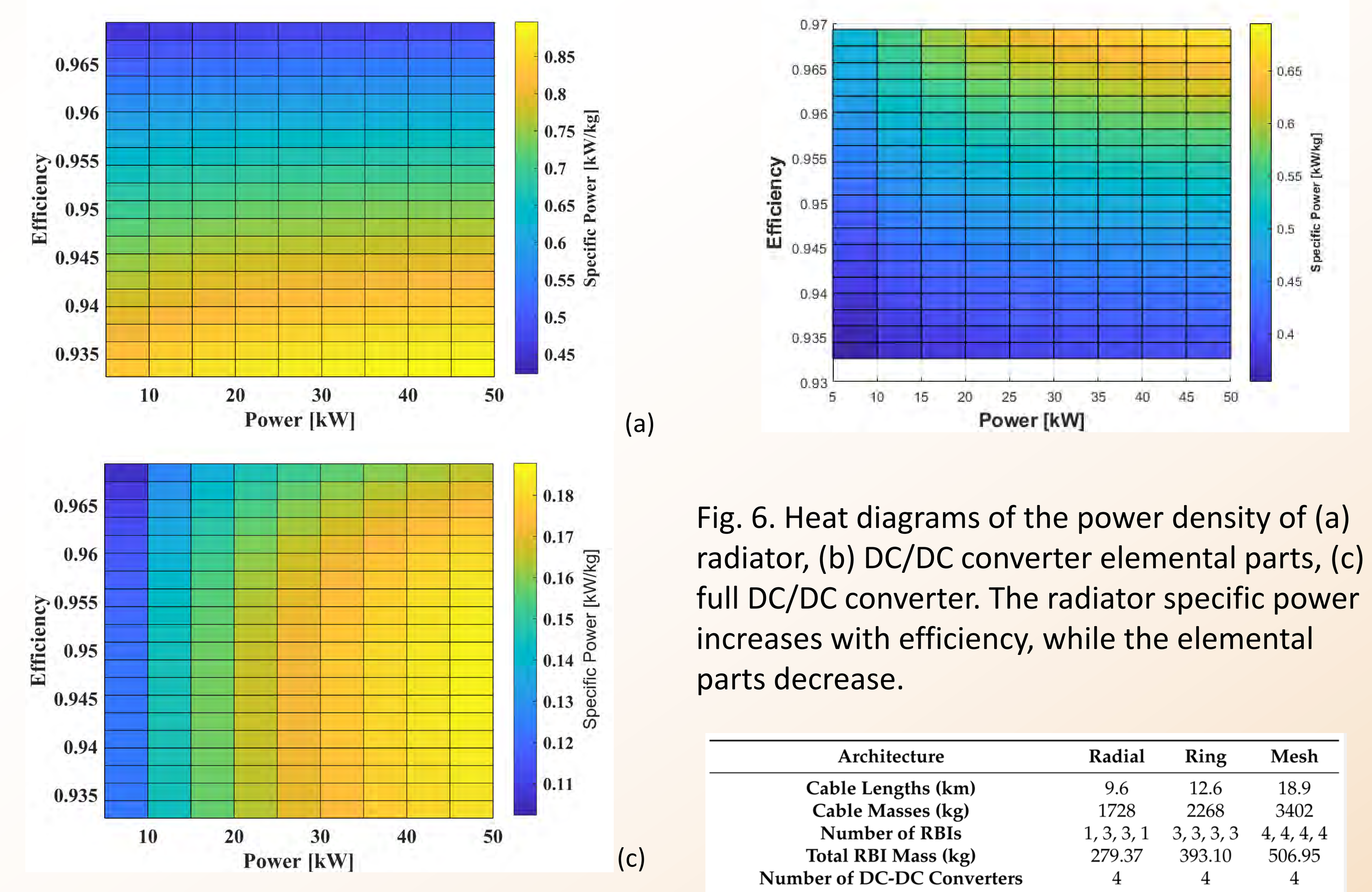

(a) (b) (c)

Fig. 6. Heat diagrams of the power density of (a) radiator, (b) DC/DC converter elemental parts, (c) full DC/DC converter. The radiator specific power increases with efficiency, while the elemental parts decrease.

Architecture	Radial	Ring	Mesh
Cable Lengths (km)	9.6	12.6	18.9
Cable Masses (kg)	1728	2268	3402
Number of RBIs	1, 3, 3, 1	3, 3, 3, 3	4, 4, 4, 4
Total RBI Mass (kg)	279.37	393.10	506.95
Number of DC-DC Converters	4	4	4
Total DC-DC Converter Mass (kg)	908.22	908.22	908.22
Total Distribution Mass (kg)	2,915.6	3,569.3	4,817.2
Total DER Mass (kg)	33,425	33,425	33,425
Total Architecture Mass (kg)	36,341	36,994	38,242

Fig. 7. Architectural Sizing Breakdown

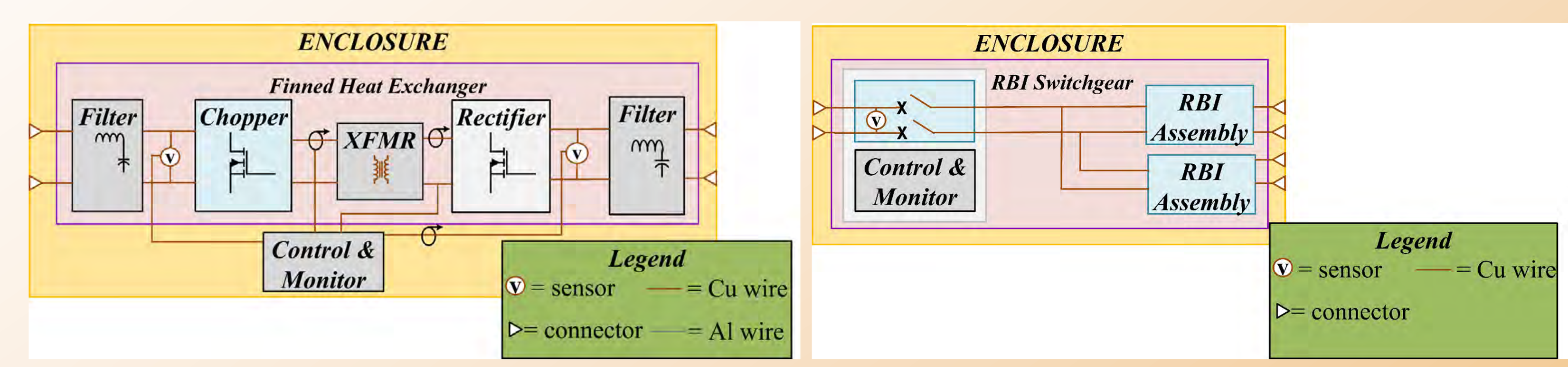

Fig. 8. (left) DC/DC Converter Diagram (right) RBI diagram

Conclusion and Future Work

This methodology can be used for future missions. Our case study gives a specific example, but ideally, the outlined steps provide a detailed walkthrough for systems and power distribution engineers evaluating power distribution architectures on the lunar surface. The results provided a ballpark estimation for the mass of the different lunar architectures and the individual distribution of mass within their parts. The plots shown in Fig.6 depict the relationship between mass and efficiency of the parts used. As well as these mass and energy sizing calculations, the methodology developed can be used to outline reliability and resiliency metrics that must be considered when choosing an architecture.

The paper used to make the mass estimates used technologies from the mid-2000s. Since then, there have been numerous advancements in semiconductor and converter technology. Redesigning the lunar equipment with these new inventions would lead to decreased mass and higher efficiency numbers for power distribution equipment. Developing batteries and continuously complex knowledge of electrical power systems could further improve efficiency.

It should be noted that calculations here assumed no insulation for the cabling. In the future, insulation thickness and material costs should be added to the cost framework developed.

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The MATLAB code used for generating the mass calculations is available on Github at https://github.com/UWM-SEES/ISS-project. For other data/information please contact the authors.