Energy Storage for Lunar Surface Exploration

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This paper presents the updated results of a previous NASA study funded under the Advanced Exploration Systems (AES) Modular Power Systems (AMPS) project. This work focuses on generating high-level system sizing relationships for two lunar surface locations that serve as bounding conditions for most other locations. Four critical parameters are considered to provide sizing data: specific energy, energy density, specific power, and power density. Given the energy storage requirements or customer power demand for a lunar mission location, the data presented in this paper provides a method to determine the critical parameter values of a Regenerative Fuel Cell (RFC) system in order to perform high-level mission architecture trades.

I. Nomenclature

AES = Advanced Exploration Systems
AMPS = Advanced Exploration Systems Modular Power Systems
BoP = Balance of Plant
C = Celsius
DRA = Design Reference Architecture
DRM = Design Reference Mission
$E_{storage}$ = Net energy storage required for the mission
ED = Energy Density
GCD = Game Changing Development
GPoD = Global Point of Departure
kg = kilogram
KPP = key performance parameters
kW = Kilowatts
kW•hr = Kilowatt•hours
L = Liter
MJ = MegaJoules
NASA = National Aeronautics and Space Administration
$P_{customer}$ = Nominal power demanded by the customer
PD = Power Density
PEM = Proton Exchange Membrane
psia = pounds per square inch, absolute
PV = Photovoltaic
RFC = Regenerative Fuel Cell
SAWS = Solar arrays with storage
SE = Specific Energy
SP = Specific Power
SOFC = Solid Oxide Fuel Cell
V = Volt
W = Watt
W•hr = Watt•hours

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II. Introduction

The National Aeronautics and Space Administration (NASA) continues to develop technologies to satisfy the persistent need for consistent and reliable power systems that enable large-scale Lunar surface exploration, both manned and robotic. Photovoltaic (PV) solar array power systems are a popular energy source for lunar missions due to the high technical maturity availability of sunlight. When sunlight is not available as a power source, an alternate method of providing power must be used. The traditional power architecture solution sizes the solar array to both power the customer load and charge an energy storage system while sunlight is available. When sunlight is unavailable, the energy storage system discharges to support the customer loads. In the past, batteries have met the energy storage requirements over short charge/discharge durations with the lowest overall mass and fewest system complications compared to other technologies. Progressing surface exploration to include manned missions increases the power demand by at least an order of magnitude. In addition, the lengthy eclipse durations inherent in many lunar surface exploration locations result in longer discharge periods and correspondingly higher energy storage requirements. For such missions, the battery mass quickly becomes prohibitively large, necessitating an alternative energy storage method. One such alternative is the Regenerative Fuel Cell (RFC).

A Proton Exchange Membrane (PEM)-based RFC system integrates a fuel cell, an electrolyzer, and a multi-fluid reactant storage system into an energy storage device. The energy capacity of the RFC is determined by the amount of available hydrogen and oxygen storage. Typically, hydrogen and oxygen are stored as gases at elevated pressure, due to the advantage of decreased system volume and simplified thermal requirements. The need to reduce or eliminate the parasitic power penalty for pressurizing the reactant gases drives electrolysis to operate at high pressures, thereby eliminating the need for compressors in the system. However, the increased line and component masses that are required to contain the elevated pressures must also be considered. Previous system trades suggest that the optimum gaseous storage pressure is in the range of 1000 to 1800 psia, but may vary based on the mission requirements [1].

The RFC discharges power through a fuel cell that converts the stored chemical energy of oxygen and hydrogen into direct-current electricity, heat, and water. This product water is accumulated until it is later consumed in the charging portion of the cycle. Fuel cells are, inherently, a current-producing device with the resulting electrical potential (voltage) indicating the reaction efficiency. Increasing the system pressure and temperature increase the reaction efficiency by increasing the molecular concentration and reaction kinetics. For PEM fuel cells, the standard operational regimes are 40 to 65 psia and 20 to 80°C. A general operation cycle for a PEM-based RFC system is shown in Figure 1.

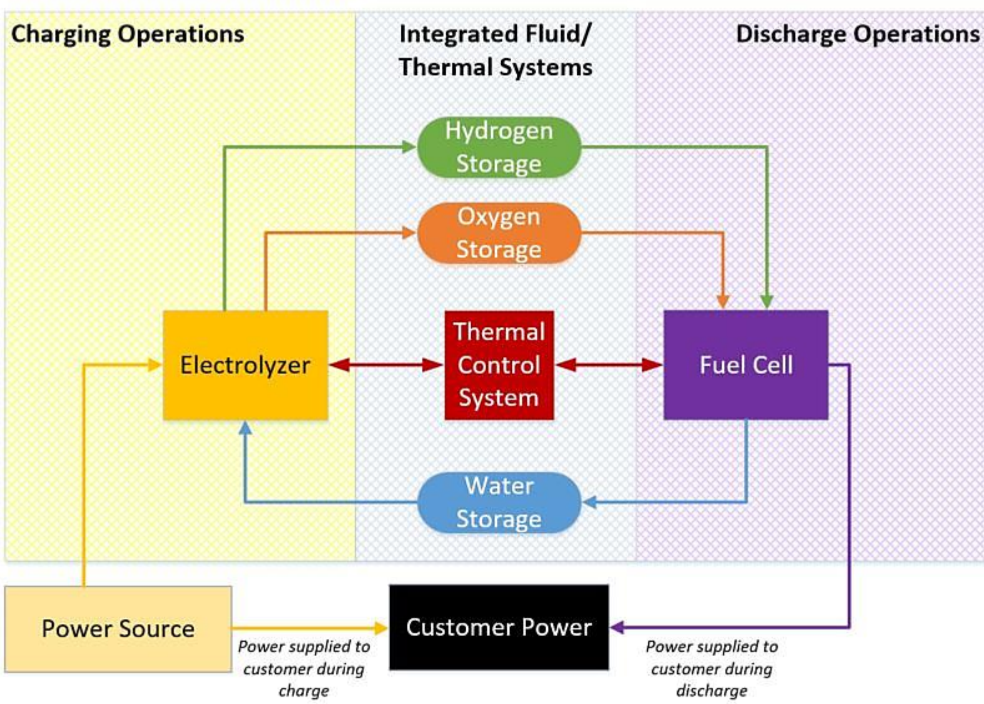

Figure 1. Simplified schematic depicting the charge/discharge operations for a PEM-based RFC energy storage system

Unlike RFC systems, batteries incorporate energy conversion (power) and energy capacity (storage) into one package that encompasses both the energy storage mass and the power production mass. An RFC dissociates the two masses, thereby enabling independent sizing of each. Because an RFC stores chemical energy as gases, it is able to store energy in large quantities with a relatively low mass penalty. This advantage becomes more pronounced as energy storage levels increase. NASA continues to evaluate RFC systems for lunar surface exploration as the sub-systems and individual technology elements mature. Current studies corroborate the findings of previous studies to show that the solar-based lunar surface power architecture requires RFC energy storage as an enabling technology for human exploration missions [2-6].

This paper presents the updated results of a recent NASA study funded under the Advanced Exploration Systems (AES) Modular Power Systems (AMPS) project using an analysis method previously developed under the AMPS project [1, 7]. Multiple studies have been performed in the past two decades to evaluate and optimize surface power systems for lunar exploration [8-13]. This AMPS study evaluates multiple surface locations on the Moon, with the goal of establishing a common approach towards technology development and system design for surface power systems that use RFC energy storage methods. Since individual elements of an RFC system can be scaled to meet particular mission requirements, one RFC design may not be applicable to all surface locations. However, enough commonality exists to suggest a single preliminary development approach to answer the technology development needs for RFC systems. For this study, Proton Exchange Membrane (PEM) fuel cell and electrolysis stacks were selected due to a relatively high technical readiness and an ability to operate over a variety of pressures and flow conditions, as determined in recent NASA studies [1]. This paper focuses on the definition of preliminary RFC energy storage system sizing relationships to help in high-level studies evaluating energy storage solutions for lunar applications.

III. Regenerative Fuel Cell Modeling Tool Development Overview

NASA has investigated RFC energy storage options for lunar missions since the late 1960s [14]. A string of Design Reference Architectures (DRA) and Design Reference Missions (DRM) supplied Key Performance Parameters (KPP) as development targets. The latest assessment of potential mission KPP values was published in December 2017 [15]. In parallel, the AMPS program and the NASA Game Changing Development (GCD) office collaborated to study the latest incarnation of RFC energy storage technologies and evaluate the feasibility for use in lunar or Martian missions. Using identical analysis tools of the same RFC technologies, the AMPS team focused on lunar applications while the GCD team focused on Martian missions powered by deployable solar arrays with storage (SAWS).

In 2017, the joint AMPS/GCD team created two regenerative fuel cell models that predict the mass, volume, and efficiency of an integrated RFC system [1, 7]. These models were based on assumed steady state operating conditions, including a constant customer power load and constant power supply to the electrolyzer. One model utilized a PEM fuel cell paired with a PEM electrolyzer, while the second model included a Solid Oxide Fuel Cell (SOFC) paired with the PEM electrolyzer. Solid oxide electrolysis was eliminated from consideration due to limitations on the pressure at which the electrolysis can be performed. A trade study was performed to assess whether a PEM or SOFC system was better suited for various mission locations on the Moon and Mars [1]. This tool excluded any consideration of the source of the initial power (e.g. PV, nuclear, etc.) to focus solely on the energy storage element of a power architecture.

In 2018, this steady state model was modified to account for transient power supply to the electrolyzer from a solar array supply during daylight hours. Realistic solar flux profiles were added to enable accurate characterization of RFC performance throughout multiple charge/discharge cycles at various surface locations. Additionally, the model now includes updated PEM fuel cell and electrolyzer performance data, expanded component level specifications options, means to estimate solar array sizing, more user input options, and improved theoretical and empirical equation correlations. The revisions broaden the range of assessable mission scenarios while simultaneously increasing model automation, accuracy, and precision.

IV. Selection of Critical Parameters for RFC Sizing

The intent of this study is to define critical parameters used in comparing multiple energy storage options, and to develop a tool to aid in RFC energy storage system sizing for a particular location. At various lunar locations, this study will allow for a rapid assessment of RFC performance based on preliminary power requirements through the evaluation of the four-(4) critical parameters shown in Table 1. Each of these critical parameters can be considered when evaluating and quantifying the performance of an RFC energy storage system for high-level mission trades. These parameters are characterized as a function of two independent variables: nominal power demanded by the customer, $P_{customer}$, and net energy storage required for the mission, $E_{storage}$. $E_{storage}$ refers to the total RFC energy storage capacity, while $P_{customer}$ specifically refers to the power that the fuel cell must supply to meet the customer requirement. The total fuel cell output power must account for both the power supplied to the customer as well as the power required to support parasitic RFC system hardware needs.

Table 1. Definition of Critical Parameters for Analysis

Parameter	Concept	Units
Specific Energy, SE	$E_{storage}/Total\ RFC\ System\ Mass$	$\frac{W \cdot hr}{kg}, \frac{MJ}{kg}$
Energy Density, ED	$E_{storage}/Total\ RFC\ System\ Volume$	$\frac{W \cdot hr}{L}, \frac{MJ}{L}$
Specific Power, SP	$P_{customer}/Total\ RFC\ System\ Mass$	$\frac{W}{kg}$
Power Density, PD	$P_{customer}/Total\ RFC\ System\ Volume$	$\frac{W}{L}$

In the current mass sensitive environment, the first and likely most influential critical parameter is specific energy, SE, defined as $E_{storage}$ divided by the total RFC system mass and measured in units of W•hr/kg or MJ/kg. The second parameter is energy density, ED, defined as $E_{storage}$ divided by the total RFC system volume and measured in W•hr/L or MJ/L. Because total energy storage is a function of mission duration and power level, specific energy and energy density are very useful metrics for long duration missions requiring the lowest possible system mass and volume, respectively. These two parameters dominate trade spaces that prioritize the total energy storage capability of a system. For example, a traditional manned surface exploration mission requires the lowest possible mass to maximize both payload and habitat capability during both daylight and eclipse periods. Another example is a lunar rover that requires its power system to have the lowest possible mass and volume for its power system in order to maximize payload capacity while also being capable of providing the required hibernation power to survive the lunar night.

Contrastingly, some mission applications are primarily power-centric, and put more emphasis on power delivered to the customer rather than overall energy storage. Such a mission could include a lunar rover that is required to have a low mass, low volume, rechargeable power system capable of solar-independent operations. The rover may have access to a power source during its charging cycle that does not rely on solar power, such as nuclear power, or it may have the ability to recharge over multiple solar periods with only minimal hibernation power during eclipse periods. In addition, some crewed vehicles and ascent/descent vehicles may place more emphasis on power delivery over energy storage requirements, but retain the need for recharging at some point in the mission cycle. Two additional critical parameters are identified to satisfy these missions. One such parameter is specific power, SP, defined as the $P_{customer}$ divided by the total RFC system mass, and measured in W/kg. The last parameter is power density, PD, defined as the $P_{customer}$ divided by the total RFC system volume, and measured in W/L. These two parameters are based on nominal power values that neglect any substantial variability in load profiles, which causes the reported power density numbers to be lower than what may be observed in a system with variable power loads. Capturing the dynamic load profiles within the mission trade space will require additional analysis beyond the scope of this paper.

Nearly every NASA spaceflight mission focuses on specific energy and specific power due to the need to maximize system output while minimizing system mass. However, some applications require equal or greater emphasis on system volume, due to limitations on the allowable system footprint or packaging. Energy density and power density are often key parameters when considering mobile vehicle systems such as small landers and rovers, where the RFC system must fit into a small, sometimes predetermined volume to allow the vehicle to accommodate other functional systems and payloads. Often, the volume limit provides the most challenging requirement for such systems due to the relatively large volume associated with reactant storage. While the work presented in this paper did not include packaging optimization, it should be noted that an RFC system volume could be distributed by subsystem volume into multiple locations in order to address vehicle center-of-gravity, thermal, or other integration issues.

V. Analysis Inputs and Assumptions

Due to the varying environmental conditions and operational limitations of various mission locations, the data presented can only be considered valid for a specific range of lunar mission locations. In this study, mission locations at the lunar equator and lunar south pole were considered. Both locations were analyzed in a previous study, with the lunar equator representing a mission with the highest energy storage requirement, and the Shackleton Crater at the lunar south pole representing a mission with the lowest energy storage requirements for a lunar location and the longest daylight duration [1]. Figure 2 depicts the landing sites under serious consideration by the Constellation program in

2009 after evaluating many potential lunar landing sites [16]. Under the Global Point of Departure (GPoD) element of the Human Lunar Reference Architecture development, this list was further reduced and divided into three-(3) categories: sortie (7-day) missions, extended stay (≤28 days) missions, and long duration (70-day) missions [17]. There are 13 missions included, with five-(5) sortie missions, seven-(7) extended stay missions, and one long duration mission. Ref. 18 discusses the selection criteria and merits of the selected locations, as summarized in Table 2. This table illustrates that the bulk of the landing locations are in close proximity to either polar or the lunar equator.

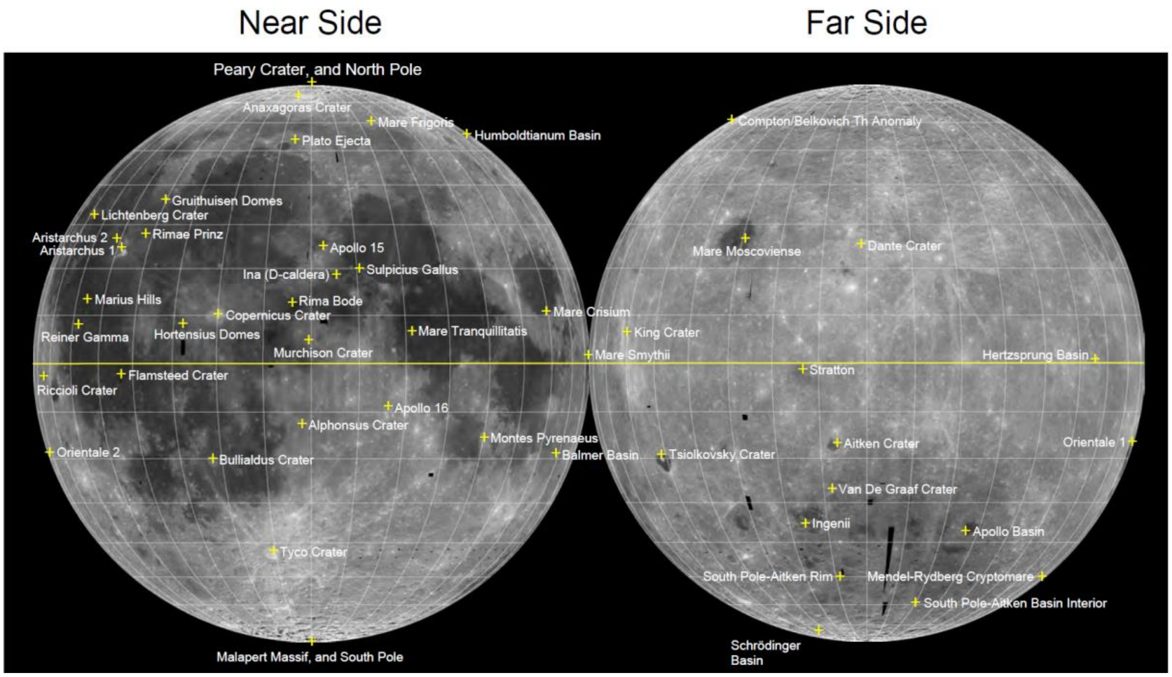

Figure 2. NASA Constellation regions of interest on the Moon, as presented in Ref. 16

Table 2. Lunar Landing Sites identified by Human Lunar Reference Architecture [18]

	Latitude	Longitude	Site Name	GPoD Site Designation	Duration
Polar Sites	90 °N		North Pole	E	Sortie
	85 °S	13 °E	Malapert Massif	D	Extended Stay
	90 °S		South Pole	A	Extended Stay
	90 °S		South Pole	L	Long Duration
Mid-Latitude Sites	57 °N	82 °E	Humboldtianum Basin	M	Sortie
	53 °S	169 °W	South Pole-Aitken Basin Interior	H	Extended Stay
	75 °S	132 °E	Schrödinger Basin	F	Extended Stay
Equatorial Sites	24 °N	47 °W	Aristarchus Plateau	K	Extended Stay
	14 °N	56 °W	Marius Hills	J	Extended Stay
	10 °N	20 °W	Copernicus Crater	I	Extended Stay
	1 °N	88 °E	Mare Smythii	G	Sortie
	13 °S	3 °W	Alphonsus Crater	B	Sortie
	20 °S	129 °E	Tsiolkovsky Crater	C	Sortie

To cover a wide range of potential missions at each location, the average power demanded by the customer, $P_{customer}$, ranged from 100 W to 50 kW. The total energy storage requirement, $E_{storage}$, is then calculated as the nominal power demanded by the customer multiplied by the discharge duration for RFC operations. The full summary of input values being studied is shown in Table 3. Power demand values equal to and less than 1.0 kW were assumed to encompass primarily non-human-rated applications, while power demand values in excess of 1.0 kW were assumed to apply to potential human-rated applications. A 28-V power bus was selected for use in non-human-rated applications, while the larger human-rated mission applications utilized a 120-V power bus.

Table 3. Input Values used for Analysis

$P_{customer}$ *kW*	$E_{storage}$, Lunar Equator *kW•hr*	$E_{storage}$, Lunar South Pole *kW•hr*
0.1	35.6	7.3
0.3	107	21.9
0.5	178	36.5
1	356	73.0
5	1780	365
10	3560	730
25	8900	1825
50	17,800	3650

The updated PEM fuel cell and electrolyzer RFC modeling tool, discussed in Section III, was used to generate the results for this analysis. When using this tool, no redundancy was considered when accounting for the RFC system hardware masses, volumes, and parasitic power. To provide an even comparison, mission duration was set at one year with a best case PV availability for the charge/discharge cyclic assessment. For longer operational durations, additional water mass may be required to account for reactant losses. Additionally, no consideration was given towards integrating the RFC system with potential customers, such as propellant scavenging systems or thermal control systems. Such integration has the potential to reduce the RFC system mass and/or volume extensively, depending on the mission architecture. The power demand to the customer was set at a constant level for both the charging cycle, where power is provided by an external system not included in the RFC system envelope, and the discharging cycle. Some missions, such as small lunar rovers, may require only a smaller subset of the customer power need for discharge operations in order to provide enough power to keep the systems operational in a hibernation mode until solar power and/or heat is again available.

VI. Results

Having selected the two bounding mission locations for the analysis, a series of modeling runs were made based on the assumptions and inputs discussed in Section V. Figure 3 through Figure 7 present the critical parameters of specific energy, specific power, energy density, and power density as a function of customer power demand and net energy storage required. Due to the different assumptions made between mission power demands greater than 1 kW and less than 1 kW, the data must be analyzed separately for those missions.

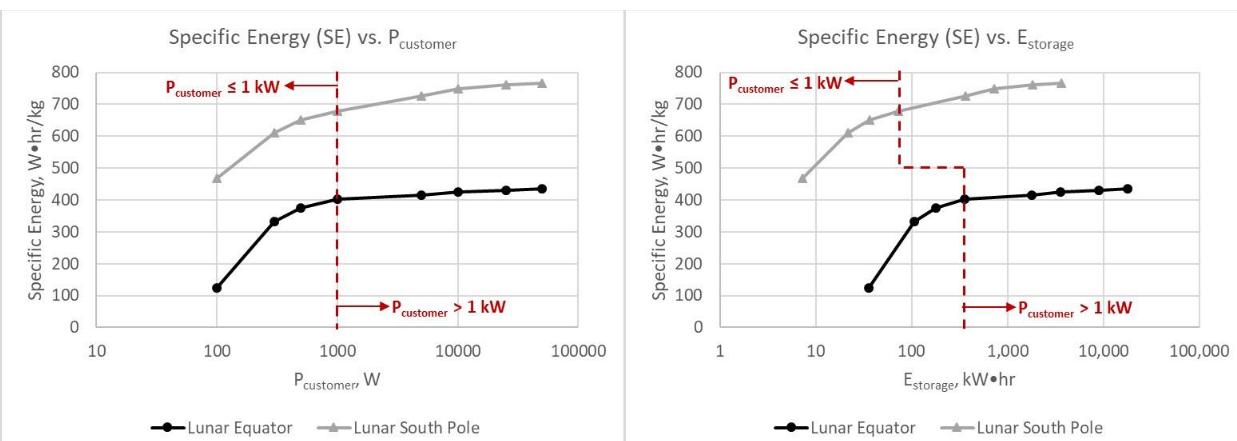

Figure 3. Characterization of the critical parameter Specific Energy relative to power demanded by the customer, $P_{customer}$ (left), and net energy storage required for the mission, $E_{storage}$ (right)

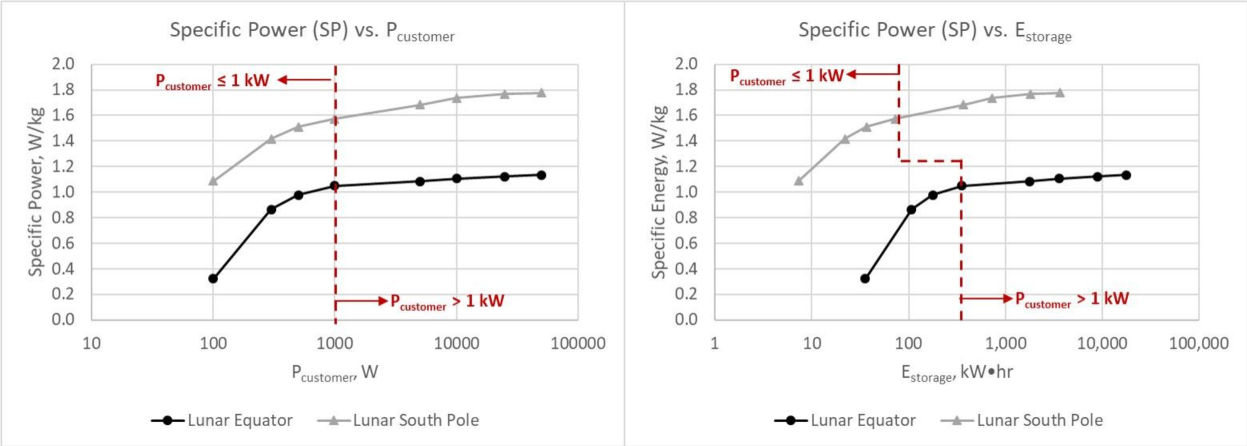

Figure 4. Characterization of the critical parameter Specific Power relative to power demanded by the customer, $P_{customer}$ (left), and net energy storage required for the mission, $E_{storage}$ (right)

As shown in Figure 3, the specific energy of an RFC system is greater at the lunar south pole than at the lunar equator by roughly 40% at most conditions. There is a sharp change in slope when the curve shifts at a customer power demand of 1 kW, which corresponds to the change in assumptions associated with a small surface application that is not human rated compared to the assumptions made for larger, potentially human rated missions. The point at which assumptions shift is noted by the dashed red line in Figures Figure 3 through Figure 7. As the energy storage and power demand requirements increase, the specific energy increases, with the relative gain in specific energy leveling off as requirements exceed 1 kW. Notably, this slope is shallower for the lunar equator case than for the less aggressive lunar south pole case. This is likely due to the lengthy eclipse period that must be survived at the equator, which is longer than that of the south pole. The specific power, characterized in Figure 4, shows a similar trend to specific energy curve, allowing similar conclusions to be drawn for each of the two parameters.

The trade study runs show that the subsystem hardware that operates the fuel cell and electrolyzer stacks, also known as the Balance of Plant (BoP), has a larger ratio of total system mass at very low power levels, as shown in Figure 5. This shows that there is a minimum effective power level for RFC energy storage. This power level may change based on the mission architecture and requirements. Missions with very low power demands should consider all available options prior to selecting an energy storage architecture.

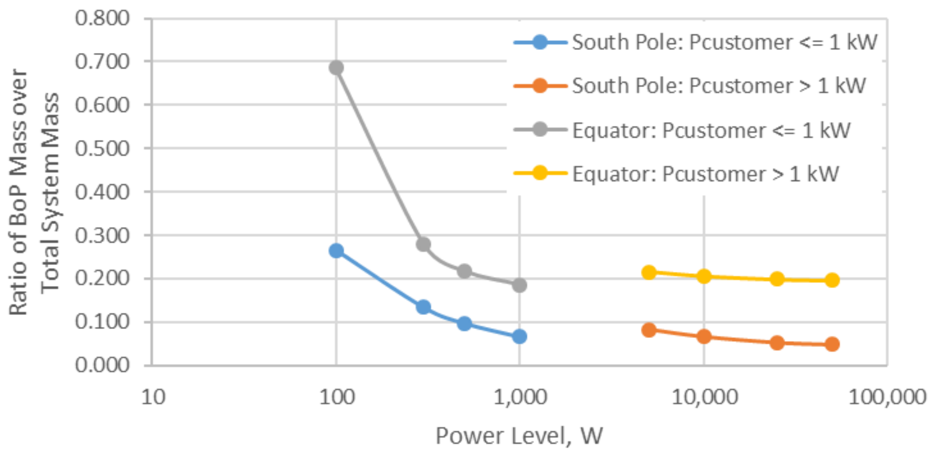

Figure 5. Plot of the ratio of fuel cell and electrolyzer balance of plant mass over the total RFC system mass as a function of customer power demand

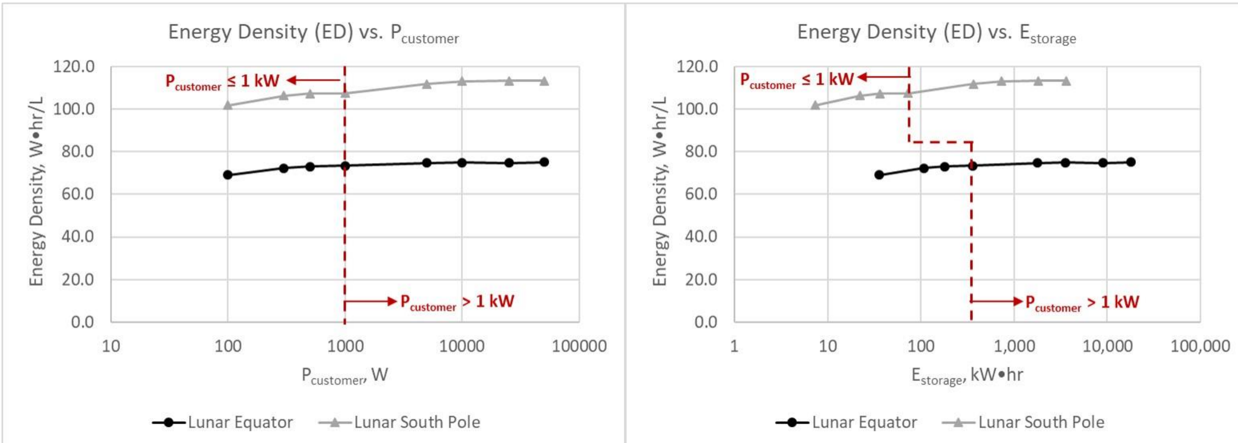

Figure 6. Characterization of the critical parameter Energy Density relative to power demanded by the customer, $P_{customer}$ (left), and net energy storage required for the mission, $E_{storage}$ (right)

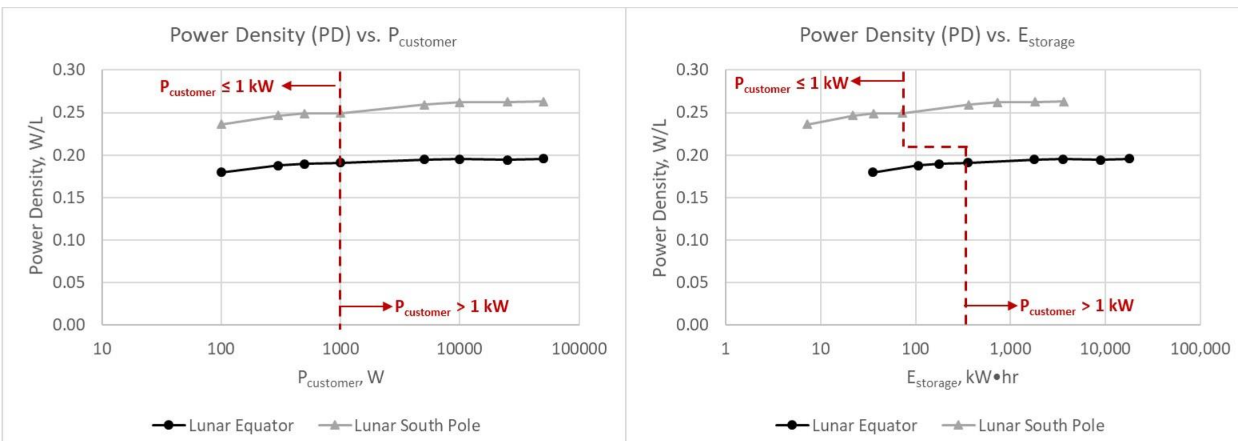

Figure 7. Characterization of the critical parameter Power Density relative to power demanded by the customer, $P_{customer}$ (left), and net energy storage required for the mission, $E_{storage}$ (right)

Figure 6 shows a relatively shallow increase in energy density as the power and energy storage requirements grow, especially compared to specific energy. This is also true of power density, depicted in Figure 7. However, there is still a notable difference of approximately 25 – 30% in the power and energy densities associated with the lunar equator as compared to the lunar south pole. When defining power and energy density, the volume of the RFC system is determined by the energy storage required for the mission. The reactant storage volume is the primary element that dictates the total RFC system volume. For example, an RFC system on the lunar south pole with a customer power demand of 5 kW would have a reactant storage volume that accounts for as much as 93.5% of the total system volume, as shown in Figure 8. This percentage is within a range similar to most RFC systems for lunar locations. For systems where power density or energy density is of particular concern, the reactant storage volume could become a primary focus for more detailed study considerations.

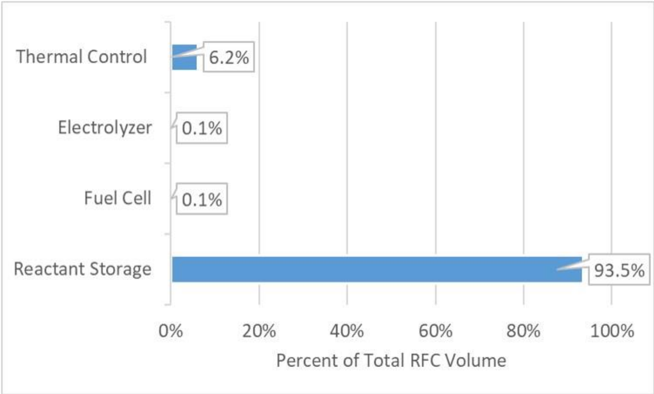

Figure 8. RFC system volume breakdown for a lunar south pole location with 5 kW customer power, sorted by its subcomponents: reactant storage, thermal control system, fuel cell system, and electrolyzer system

By using these charts to generate the critical parameters with a known customer power demand, mission location, and energy storage requirement, a general approximation of the size and scope of an RFC energy storage system for a given mission application can be generated. Once an RFC system is selected as a viable technology solution for a given mission, further analysis can be performed to optimize the system and identify further areas of mass and volume savings.

VII. Conclusions

Both manned and robotic exploration of the lunar surface will require optimized energy storage solutions that minimize system mass and volume. Each mission has a unique set of requirements based on the location and application that may result in different technology solutions. Performing high-level analysis of the available energy storage options may allow mission designers to converge on a technology solution early in the architecture definition process, allowing for more effective optimization of the final system design. The data presented in this paper intended to provide boundary values that encompass nearly every lunar surface exploration location and mission demand. Using the charts presented, high-level system sizing of an RFC energy storage system for a given lunar mission can be performed to aid in architecture trade studies. Following the selection of an RFC system as a viable solution for a given mission, the detailed models used to generate the data in this paper can be used for system optimization and further efficiency gains.

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