IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Microgrids for Extraterrestrial Habitats: A Review of Technologies, Needs, and Challenges

Leila Chebbo[1], Graduate Student Member, IEEE, Muhammed Ali Gultekin[1], Graduate student Member, IEEE, Ali Bazzi[1], Senior Member, IEEE, Sean A. Q. Young[2], Joseph P. Kozak[2], Member, IEEE
[1]Electrical and Computer Engineering Department, University of Connecticut, Storrs, CT 06269 USA
[2]Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723 USA

Corresponding author: Leila Chebbo (Leila.chebbo@uconn.edu).

This work was partially supported by a Space Technology Research Institute Grant (80NSSC19K1076) from NASA's Space Technology Research Grants Program.

ABSTRACT The National Aeronautics and Space Administration (NASA) and other space organizations are preparing for new space exploration and habitation initiatives. These include human return to the Moon through the Artemis mission, human exploration of Mars and deeper space habitats, and the establishment of permanent human bases on the Moon, Mars, and beyond. Such installations demand a highly reliable, resilient, safe, and autonomous power system to support the habitats' different functions, systems, and electrical loads. This paper presents a review of the different power sources, energy storage options, microgrid architectures, in addition to challenges and needs for future extraterrestrial habitat microgrids. In addition, this paper reviews the economic challenges and life cycle costs of future extraterrestrial microgrids. Of special focus in this paper are the degradation causes and mechanisms of space microgrid components due to harsh environments in which such microgrids will operate. With the information presented in this paper, which accurately compares different technologies' performance for the same function, researchers in the space community will be able to make better decisions regarding the requirements and technology development of an extraterrestrial power system.

INDEX TERMS Extraterrestrial power system, environmental challenges, microgrids, space exploration, space habitat.

NOMENCLATURE

NASA	National Aeronautics and Space Agency.
ESA	European Space Agency.
JAXA	Japan Aerospace Exploration Agency.
ISRO	Indian Space Research Organization.
CNSA	China National Space Administration.
EV	Electric vehicles.
ECLSS	Environmental control life support system.
LCC	Life cycle cost
FDD	Fault detection and diagnosis.
PV	Photovoltaic.
PMR	Power-to-mass ratio.
VSAT	Vertical Solar Array Technology.
LILT	Low intensity, low temperature.
RTG	Radioisotope thermoelectric generator.
SNAP	System nuclear auxiliary power.
RORSAT	Radar ocean reconnaissance satellite.
FSP	Fission surface power.
KRUSTY	Kilopower reactor using stirling technology.
HEU	Highly enriched uranium.
HALEU	High-assay low-enriched uranium.
DRACO	Demonstration rocket for agile cislunar operations.
NTP	Nuclear thermal propulsion.
TRISO	Tri-structural isotropic.
TOPEX	Topography Experiment.
Li-ion	Lithium-ion.
Ni-H$_2$	Nickel-Hydrogen.
LATP	Lithium Aluminum Titanium Phosphate.
LiPON	Lithium phosphorus oxynitride.
LLZO	Lithium lanthanum zirconium oxide.
LCO	Lithium Cobalt Oxide.
LiS	Lithium-Sulfur.
NCA	Lithium Nickel-Cobalt-Aluminum Oxide.
LFP	Lithium iron Phosphate.
LTO	Lithium-Titanium-Oxide.
NMC	Lithium-Nickel-Manganese-Cobalt-Oxide.

ATCS	Active thermal control system.
RHU	Radioisotope heater units.
PEM	Proton exchange membrane.
SO	Solid oxide.
AFC	Alkaline fuel cell.
ISS	International space station.
AO	Atomic oxygen.
UV	Solar ultraviolet.
LEO	Low earth orbit.
AU	Astronomical unit.
SPE	Solar proton event.

I. INTRODUCTION

Establishing long-term human presence in space for scientific discovery, economic benefits, finding a backup home, and inspiring the new generation of explorers has been the main interest of several space organizations. These include the National Aeronautics and Space Administration (NASA), European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), Indian Space Research Organization (ISRO), and China National Space Administration (CNSA) [1]-[7]. With Artemis missions, the primary goal of NASA and their international partners is human return to the moon using innovative technologies to discover more of the lunar surface, which is considered the steppingstone to space exploration [4].

Extraterrestrial human establishment depends on environmental factors such as temperature, atmospheric conditions and composition, radiation, and water availability [8], [9]. The term ‘habitable planet’ is meant to imply a planet with surface conditions naturally suitable for human beings, that is, one that does not require extensive feats of engineering to remodel its atmosphere or its surface so that people in large numbers can live there [8]. Different robotic missions have been exploring the habitability of different planetary bodies [10]. For example, the moon’s lack of atmosphere and liquid water cannot naturally support human life [10]. However, its proximity to Earth makes it the best first choice for a settlement and is considered the stepping stone for deep space exploration. Also, experiments showed that high ionic strength, driven to extremes on Mars by the ubiquitous occurrence of divalent ions, makes the Mars environment inherently uninhabitable despite the presence of water [10], [11]. Table 1 summarizes the habitation characteristics, such as the atmospheric conditions and minimum and maximum temperatures of ten planets and moons. Table 1 presents information about the distance from Earth, which can give an understanding of the possible Earth communication challenges in different missions. Also, it provides data about the distance from the sun and the length of the day, which can help identify a suitable source of power for each mission.

The installation of deep-space habitats or colonies requires a resilient, reliable, and autonomous power system that can sustain the habitats' different functions, systems, and electrical loads. These loads include environmental control and life support systems (ECLSS), monitoring and

TABLE 1. **Habitation characteristic of ten different planets, moons, and small rocky bodies.**

Planets or Moons	Main atmospheric composition	Distance from earth (km)	Distance from sun (km)	Day period (hours)	Annual Radiation (mSv)	Min Temp. (℃)	Max Temp. (℃)	Ref.
Earth	Nitrogen, Oxygen, Argon	0	150×10^6	24	3.11	-89.15	56.85	[12], [13], [14]
Moon	Neon, Helium, Argon	3.84×10^5	150×10^6	655.2	525.6	-248.15	119.85	[12], [15], [16], [17], [18]
Mars	Carbon Dioxide, Nitrogen, Argon	5.46×10^7	228×10^6	24.6	226.3	-140.15	20.85	[12], [19], [20], [21], [22]
Venus	Carbon Dioxide, Nitrogen	6.1×10^7	107×10^6	5832	Unknown	29.85	701.85	[12], [23], [24], [25], [26]
Mercury	Oxygen, Sodium, Hydrogen	8.98×10^7	70×10^6	4224	Unknown	-180.15	429.85	[26], [27], [28]
Europa	Oxygen (tenuous, almost vacuum)	6.28×10^8	780×10^6	86.4	197×10^4	-223.15	-153.15	[29], [30], [31]
Ganymede	Oxygen (tenuous)	7.76×10^8	1.07×10^6	171.8	29.2×10^3	-183.15	-113.15	[32], [33]
Titan	Nitrogen, Methane	1.22×10^9	1.427×10^9	381.6	Unknown	-184.15	-178.15	[34], [35]
Ceres	Water vapor (tenuous)	2.69×10^8	413×10^6	9.1	Unknown	-143.15	-143.15	[36], [37]
Proxima Centauri b	Unknown	3.97×10^{13}	–	Unknown	31.1-186.6	-156.15	33.85	[38], [39]

communication systems, scientific laboratories and instruments, chargers of rovers and electric vehicles, and some hotel or housekeeping loads, such as habitat lighting, food preparation, and other astronauts' activities [40]. Considering the extreme environmental conditions, electrical load criticality, system complexity, and logistics of equipment transportation, having a comprehensive state-of-the-art review of power system components is vital to developing a reliable power system for future extraterrestrial habitats.

The major candidates for primary energy sources for extraterrestrial space habitats currently include solar radiation and nuclear reactors [41]-[43]. Moreover, a reliable energy storage system should be considered in extraterrestrial habitats for power backup purposes during critical situations and failure in their power system components [42], [44], [45]. Primary and secondary fuel cells can also be used for power generation for short-duration missions and energy storage in long-term space exploration missions. Dc, ac, and hybrid dc and ac power distribution architectures are proposed in the literature for deep space applications [44], [46]-[48]. Additionally, a resilient electrical control system that can operate autonomously is required for space applications to manage power generation units, distribution system, and loads, it should also optimally dispatch available generated power. Autonomous operation of the control system is crucial, especially during critical situations where human intervention is challenging. Rapid response time is required in crewed and uncrewed systems despite communication latency [45].

Different environmental disturbances such as dust accumulation, severe temperature variation, radiation, and meteorite strikes affect the functionality, performance, and efficiency of power system components in space. Then, the effect of all external disruptions, as well as the size, weight, and other operational requirements, should be considered in the selection of power system components. The described extraterrestrial power system represents an interconnection between different generation units, electrical loads, energy storage units, and a control system; and can be defined as a space microgrid. Considering the resemblances between space microgrids and islanded terrestrial microgrids, different operation, control, stability, and protection solutions developed for terrestrial microgrids can be adapted to overcome extraterrestrial challenges.

II. PAPER ORGANIZATION AND CONTRIBUTION

This paper presents a review of the available technologies that can be used in extraterrestrial microgrids required for future human establishment on extraterrestrial surfaces, and long-term space exploration. Subsequently, the paper also reviews space microgrid requirements, challenges, characteristics, and technologies available in the technical literature. It describes technologies for power generation, energy storage, power distribution and management, and associated components. Also, this paper highlights the degradation causes and effects of power system components in space. In addition, an economic evaluation and life cycle cost (LCC) of future extraterrestrial microgrids is discussed. The main contributions of this paper include:

- A description of electrical requirements for future human establishment in space and long-term space exploration.
- A representation of the state-of-the-art of extraterrestrial microgrids.
- A review of power system technologies for space applications, including an overview of their performance in space environment.
- A discussion of the challenges in designing and operating extraterrestrial microgrids, emphasizing how technologies from islanded terrestrial microgrids can be adapted to mitigate these challenges.

The paper is organized as follows. Section III describes electrical loads in deep-space habitats. Section IV presents power generation technologies in space, their advantages, disadvantages, and failure modes. Sections V discusses energy storage technologies. The proposed power distribution architectures for space microgrids, as well as their advantages and disadvantages, are described in Section VI. Section VII shows the main requirements of a space microgrid control system. Section VIII presents the causes and effects of the degradation of power system components in space. Section IX presents extraterrestrial microgrids' design, operation, and cost challenges; it also discusses solutions developed for terrestrial isolated microgrids and their applicability in mitigating space microgrid challenges. Section X summarizes the paper and discusses the possibilities of future work needed to improve the reliability of extraterrestrial microgrids.

III. ELECTRICAL LOADS IN EXTRATERRESTRIAL HABITATS

The space environment provides a number of challenges for both crewed and uncrewed missions. A key aspect to successfully operating in extraterrestrial environments is the availability of a reliable power source that can meet mission requirements for the duration of the mission. Power system requirements will vary considerably depending upon the type of mission as well as the individual power requirements of the components or devices associated with that particular mission or activity [49], [50], [51]. A space habitat involves various types of power-consuming units, as illustrated in Fig. 1, and can be categorized into the following areas:

- **Life support systems:** considered as the most critical load type, contributing to human habitation and life support in space. They include ECLSS, such as heating, cooling, water filtration and reclamation, regenerating the habitable atmosphere, and pressure control. Additionally, ECLSS equipment may include loads for biomass composting and waste processing units.

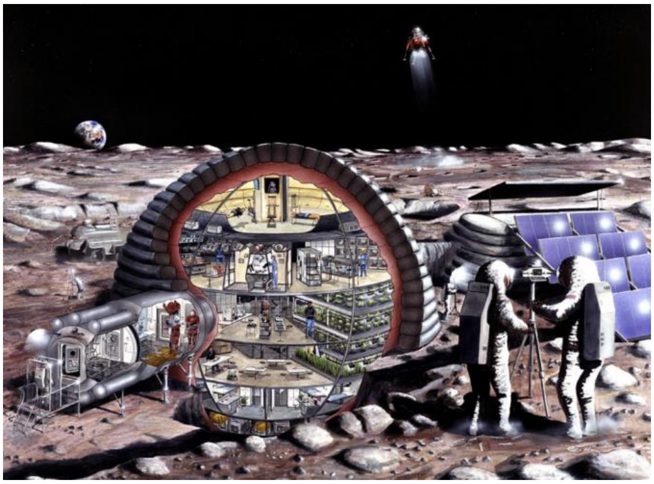


FIGURE 1. Inflatable habitat that could accommodate the needs of astronauts living and working on the surface of the Moon. Depicted are astronauts exercising, a base operations center, a pressurized lunar rover, a small clean room, a fully equipped life sciences lab, a lunar lander, selenological (lunar geology) work, hydroponic gardens, a wardroom, private crew quarters, dust-removing devices for lunar surface work, and an airlock. The top-level shows joggers required to run with their bodies almost parallel to the floor because of the low gravity [52]. Image courtesy of NASA.

- **Communication systems:** are one of the other vital loads for extraterrestrial habitats. The habitat should constantly be in communication with the ground station on Earth, which can be established through communication systems in the direct line of sight or through an orbiter spacecraft. Moreover, communication is needed among different establishments and units on the surface. This electric load type involves all equipment and displays for communications to and from Earth, and to and from personnel in the habitat.
- **Scientific instruments laboratories:** would be included within the space habitat. These require power for conducting experiments in addition to power categorized for communicating results.
- **Habitat systems health monitoring loads:** include various sensors and fault detection and diagnosis (FDD) equipment. These are necessary for space habitats to detect anomalies at an early stage, prevent catastrophic failures, and maintain high resiliency.
- **Exploration and transportation equipment:** EVs are expected to be used for transportation, maintenance tasks, and traversing between key locations. Autonomous or remotely controlled electrical rovers may also be used to explore the surface and environment and collect samples. Therefore, charging stations are needed to charge these rovers and vehicles.
- **Hotel or housekeeping loads:** Those include lighting, food preparation, packaging, and storage, in addition to many other astronauts' activities.

The power required by an extraterrestrial habitat depends on the crew size. For a lunar base, it is estimated to be 35 kW on average for six crew members [43], [53]. The low end estimated power levels for a small six-person base camp and some potential mission devices and vehicles are listed in Table 2. These loads and assumptions do not incorporate heavy industrial activities, like in-situ resource utilization (ISRU) plants, which have been estimated to have power draws that are on the order of, or exceeding, habitat designs [43].

Life support, communication, and monitoring loads require continuous power to maintain life support and safety in the habitat during crewed missions. Though, other intermittent load types, such as housekeeping loads, water reclamation, scientific instruments, and vehicle chargers, fluctuate depending on daily human needs and activities. According to astronaut activities schedule in ISS and like many full-time workers on Earth, the peak demand of astronauts' housekeeping loads in a crewed system is after work hours and during the weekends [54], [55]. Vehicle chargers' peak demand in a crewed system is during astronauts' night hours when no human transportation is performed. However, the peak demand for scientific instruments is during the day's working hours. Power demand and electric load profiles vary depending on the mission type and phase of operation. In crewed missions, the habitats' different functions, systems, and electrical loads operate at full loads. However, in robotic or uncrewed missions, only monitoring loads and the autonomous rovers' chargers operate at full loads. Thermal, pressure, and scientific instruments loads operate at partial load. Housekeeping, air quality equipment, and water reclamation are turned off in an uncrewed system [46], [56].

The location of the extraterrestrial habitat will also change what the power demands will look like. While most scientific instrumentation may remain constant for local operations, different environmental impacts such as temperature and distance from the sun and earth will change the power demand of the other power drawing systems. If the habitat is

TABLE 2. Estimated average and peak power demand in a six-crew Lunar base camp [43], [51], [53]. Note that these are at the lower end of the estimated range of 5-10 kW of power per crew member [43].

Load Type		Average Power (kW)	Peak power (kW)
Hotel or housekeeping loads:	Astronauts' activities	2.5	5
	Habitat lighting	0.5	0.5
Life support systems:	ECLSS	16	16
	Crew support	2.5	17.9
	In situ resource utilization (ISRU) testing	1	10
Exploration/ transportation equipment:	Extravehicular activity (EVA) floodlights	0.5	2
	Rovers and EV chargers	0.5	3
Communications system		1	1
Monitoring loads including FDD and sensors		6	6
Scientific instruments		1	2

further from Earth, the communication system required may require a more powerful transmitter and receiver to be able to reach mission command. Additionally, with different thermal environments, especially colder environments, the necessary insulation and life-support equipment would require more power to enable livable conditions for crewmembers.

IV. POWER GENERATION TECHNOLOGIES IN SPACE MICROGRIDS

It is critical to have reliable sources of electrical power to support the habitats' different electrical loads in a hostile space or planetary environment [40], [53]. Although the literature proposed solar power as the main source of energy for low-atmosphere environments, small nuclear fission reactors based on Stirling or Brayton converters are also possible candidates for electrical power generation in space. Furthermore, even though fuel cells have been commonly considered for energy storage in extraterrestrial applications [53], they can also be classified as primary power generation units in a more classical context.Table 3 summarizes the advantages and disadvantages of all proposed generation technologies for space applications.

A. SOLAR PHOTOVOLTAIC POWER

Photovoltaic (PV) technology has been the main source of energy for space missions since the beginning of the space age in the 1950s [57]. Advancements in PV technologies have enabled most of the electrical power required by satellites and space missions [58]-[60]. Multi-junction PV cells based on III-V semiconductors are commonly used due to their higher efficiency (around 30%), mature manufacturing processes, long lifetime, and temperature and radiation hardness [61]. Under concentrated sunlight, the efficiency of the triple-junction GaInP/GaAs/Ge architecture reaches 40% [62]. This architecture is widely used for space applications [53], and the most notable advantage of this PV technology is its high specific power - known as the power-to-mass ratio (PMR). Current space PV cells have a PMR as high as 350 W/kg (although proper engineering of the metal contacts can lead to values up to 3 kW/kg) [59], [63]. Table 4 compares different PV technologies.

The amount of power generated by PV panels is heavily influenced by their orientation and angle of inclination. The angle of solar incidence on the panel's surface also changes the panel's output power [64]. In 1993, NASA proposed the fixed tent-shaped array with a 60-degree angle, which can maintain a consistent power output throughout the day [65]. However, it only generates 42% of the output power compared to a solar tracking array [66]. Another proposal is a triangular configuration of three arrays on a tower, which can harness more solar irradiation throughout the year [67]. The suggested PV configuration involves three PV modules, consisting of three PV panels each, forming an equilateral triangle, placed vertically to the ground to maximize PV generation [67]. Different space agencies are supporting the development of vertical solar arrays for long-term space exploration of the Lunar South Pole, including NASA’s Vertical Solar Array Technology (VSAT) program. This technology can autonomously deploy up to 20 meters high, track the sun, and retract for relocation if necessary [68]. Fig. 2 illustrates a few different proposals for solar array configurations. Extreme distances from the sun, as listed in Table 1, and long nights on some moons and planets present the most significant limitation of a solar-based power system. Solar arrays will need to be sized based on the solar illumination available. With intensity scaling with $1/r^2$, where r is the distance from the sun, as the distance increases by a factor of two, the solar array system size would increase four fold. Habitats at Jupiter, for example, are five times further from the sun than Earth and require a solar array 25 times the size of one on Earth to harvest an equivalent amount of energy. Low intensity, low temperature (LILT) effects can reduce performance further. Although low temperatures increase open circuit voltage, low intensities decrease the short circuit current, resulting in an overall decrease in efficiency [69].

TABLE 3. Advantages and disadvantages of power generation technologies for space habitat applications.

Generation Technology	Advantages	Disadvantages	Ref.
Solar PV	• Higher technology readiness level • Higher specific power (power-to-mass ratio) • Safe technology and can be installed near the human base • Long lifetime	• Limited to daytime operation • Larger size to achieve high power levels • May require frequent cleaning due to dust accumulation • Higher degradation factors due to space environmental conditions	[45], [53], [59], [70], [71], [72]
Nuclear fission reactor based on Stirling converter	• Smaller physical size • Highly reliable, resilient, and stable • Capable of continuous operation (location and time independent)	• Radiation concerns require physical separation between the reactor and base camp • Lower power-to-mass ratio • Lower technology readiness level • Lower designed operational lifetime (≈ 10 years)	[45], [53], [59], [71], [72], [73]
Primary fuel cells	• Lower power-to-mass ratio	• Lower technology readiness level • Lower designed operational lifetime	[45], [53], [59], [71], [72], [74]

TABLE 4. **Characteristics of solar PV cell materials.**

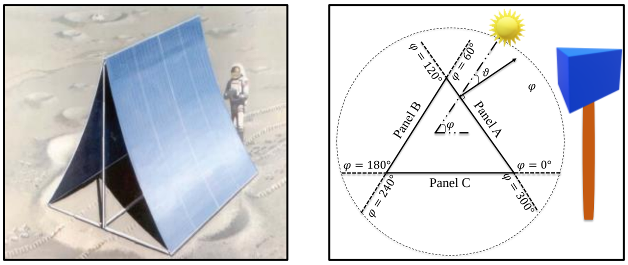
Architecture	Efficiency at $28^\circ C$	Lifetime	PMR (W/kg)	Technical Advantages	Ref.
C-Si	14.80%	Low	Low	• Mature technology • Low fabrication cost	[59], [75], [76]
GaAs	20.00%	Low	Medium	• Mature technology • High temperature resistance	[59], [77], [78], [79], [80]
InP/Si	12.50%	High	High	• High radiation resistance	[59], [75]
InGaP/GaAs	26.90%	Low	High	• High efficiency • High radiation resistance	[59], [77], [78], [80]
GaInP/GaAs/Ge	40%	High	Medium	• Mature technology • High efficiency • High radiation resistance • High temperature resistance	[59], [63], [77], [79], [80], [81], [82], [83]
GaAs/Ge	18.50%	High	High	• Mature technology • High radiation resistance	[59], [77], [80]
Perovskite	26.00%	High	High	• High efficiency • High radiation resistance • High temperature resistance	[59], [74], [84], [85]

Additionally, night time can be a limiting factor for solar arrays; an average lunar cycle lasts 29.531 Earth days [8]. This implies that a solar-powered, extra-terrestrial habitat at mid- or low-latitude must be equipped with an energy storage solution of considerable capacity, which would guarantee the functioning of a base for more than the two-week-long lunar night. However, transporting massive energy storage equipment to space poses payload constraints.

Terrestrial solar cells experience little degradation over time (about 0.5% output power reduction per year) due to exposure to solar ultraviolet radiation [86]. Solar cells in space are susceptible to other extreme environmental conditions such as dust accumulation, space debris and micro-meteorites, extreme temperature variation, and ultraviolet irradiation that affect their performance [57] and can result in degradation in power output of 2-4% per year [87].

B. NUCLEAR POWER

Nuclear power generators use energy from controlled nuclear fission reactions to produce heat, which is then used to generate steam. This steam drives a turbine connected to an electrical generator, converting mechanical energy into electrical energy. Terrestrial nuclear plants involve several key components, including the reactor core, which contains nuclear fuel, typically isotopes of Uranium, a coolant system, a steam generator, a turbine, and a generator. All the components are managed by control and safety systems to ensure efficient and safe operation. Fission reactors adapted to space will require similar components, through significantly miniaturized and hardened for the launch and space environments.



(a) Tent array concept [65] (b) Triangular structure [67]

FIGURE 2. **Illustrations of a subset of PV configuration concepts.**

Nuclear power systems for space applications have primarily been radioisotope-based [88],[89]. Radioisotope power systems utilize the radioactive decay of an isotope to produce heat. Radioisotope thermoelectric generators (RTGs) generate electricity by exploiting a temperature differential between the radioactive material and a cold radiator. For this type of application, plutonium (Pu-238) is an ideal isotope due to its long half-life (87.74 years), high specific power, and safety-favorable decay paths – it is an α emitter which can easily be shielded [90], [91]. Since the early days of space exploration, radioisotope-based power systems have been used extensively on several deep space missions, such as NASA’s Cassini probe and Mars Curiosity rover. In recent years, alternative isotopes have been explored due to the scarcity of Pu-238 in addition to exploiting a Stirling cycle rather than the thermoelectric effect to increase the PMR. Due to the amount of isotope required to produce electrical power, isotope-based power systems are not practical for power requirements greater than approximately 1 kW. Therefore, radioisotope power alone is not viable for base camp applications, though could be used to power rovers and other vehicles [43], [92]-[94].

Alternatively, a nuclear system that utilized fission instead of radioactive decay with Stirling or Brayton converters would be applicable for long-term human exploration missions at power levels greater than 1 kW [95]. The first reactors were flown in the 1960s by the US and USSR in the

System Nuclear Auxiliary Power (SNAP) and Radar Ocean Reconnaissance Satellite (RORSAT) programs, respectively, which launched a single reactor each with 0.5-6 kW of electrical power output [96]. Both reactors utilized thermoelectric or thermionic converters rather than the more efficient Stirling or Brayton cycles. Later studies provided insights into space-rated reactor design, but only recently have prototypes emerged. The development of the SP-100, an 825 kW fission reactor started in 1989 by NASA but was cancelled in 1994. Table 5 shows the main Stirling power module characteristics of the notional SP-100 nuclear reactor proposed for Mars Cargo Missions [97]. Later, in 2004, a scalable reactor concept with a power range of 10 kW to 100 kW, known as SAIRS, was conceptualized [96]. From 2006-2008 NASA, in partnership with the US Department of Energy National Labs, initiated a feasibility study on affordable fission surface power (FSP) technologies, concluding that a 40 kW system lasting eight years was deemed cost-effective and technically achievable [98]. This study considered higher powers, longer lifetimes, and a variety of conversion technologies, coolants, and fuel types. As a stepping stone to realizing this system, NASA developed the Kilopower Reactor Using Stirling Technology (KRUSTY) project which yielded a 1 kW prototype and was demoed in 2018 [99]. Fig. 3 illustrates the operating principle of NASA KRUSTY. All previous designs discussed here have relied on highly enriched uranium (HEU) which presents concerns with nuclear proliferation. In recent years, high-assay low-enriched uranium (HALEU) fuel designs have emerged in the terrestrial small modular reactor (SMR) market [100] and have become the baseline for NASA's FSP program [101], [102]. Several companies are working on a design for a relocatable, 40 kW, 10-year operating time HALEU reactor intended for deployment for the lunar surface [103].

A palpable optimism permeates the space community for space nuclear, capitalizing on increased interest in SMRs for remote, isolated communities. In parallel, NASA and DARPA have invested in the Demonstration Rocket for Agile Cislunar Operations (DRACO) Nuclear Thermal Propulsion (NTP) program [104]. Although significant differences exist in the reactor design, these investments signify a considerable shift in momentum toward nuclear generators in space.

TABLE 5. **Power module characteristics of the nuclear reactor proposed for Mars Cargo Missions [97].**

Characteristics of the SP-100 nuclear reactor	
Reactor Full Power Projected Operating Life	9.6 years
Operating Temperature	1355 K
Average Radiator Temperature	567 K
Radiator Physical Area	282 m^2
Total Module Mass	12975 Kg
Net Power	576 kW
System Efficiency	31%
PMR	0.044 kW/Kg

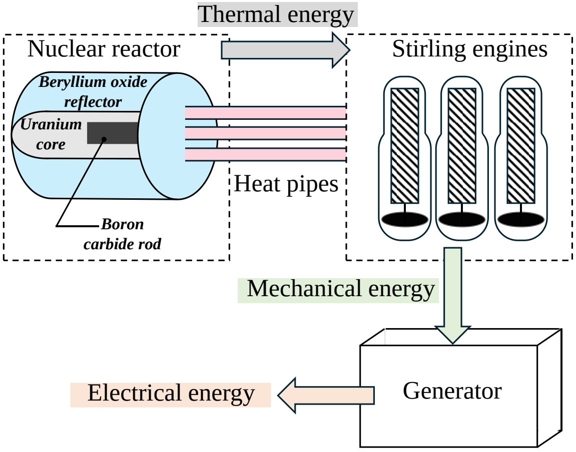


FIGURE 3. **Operating principles of NASA KRUSTY.**

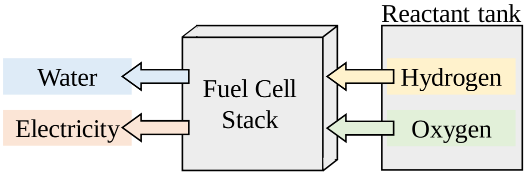
Nuclear technology is capable of providing power continuously for years, regardless of the space mission location and time of operation. In particular, space-rated, compact nuclear reactors are not dependent on the habitat's insolation. Thus, they can continuously supply power to a human base in space without needing a massive high-capacity energy storage system. Nevertheless, the components of the nuclear reactor, such as the coolant lines and radiator, are exposed to the same extreme environmental conditions, space debris, micro-meteorites, and dust that plague other generation technologies, affecting the reactor's efficiency, output power, and lifetime. Fission reactors for space are being designed to operate maintenance-free for up to 10-years [98],[105], [106]. Besides, when using a nuclear reactor to power a crewed space base, the issue of radiation protection must be addressed. Traditional shielding methods are heavy and bulky, and would significantly strain mission mass budgets. To solve the radiation problem, a modern approach involves two options: keeping a safe distance between the reactor and any habitable infrastructure or using regolith as shielding material [43], [44], [53]. Beyond substantial but surmountable technical hurdles, political, security, and social concerns remain obstacles to launching nuclear material since a failed launch could cause radioactive contamination on Earth and security concerns [107]. Use of HALEU coupled with improvements in fuel encapsulation, such as the TRi-structural ISOtropic (TRISO) fuel pellet design, mitigate this risk considerably.

Existing guidelines dictate that the whole-body radiation dose limit is 50 mSv/year. Therefore, to ensure the radiation dose stays within the permissible limit, a combination of reactor shielding and physical separation must be employed. One study proposed a minimum separation distance of 1.15km from a 10kW reactor. Increasing the power output or number of reactors requires either additional shielding or a greater keepout zone for astronauts [43]. Furthermore, safely disposing of spent nuclear fuel in space is an added challenge for this technology.

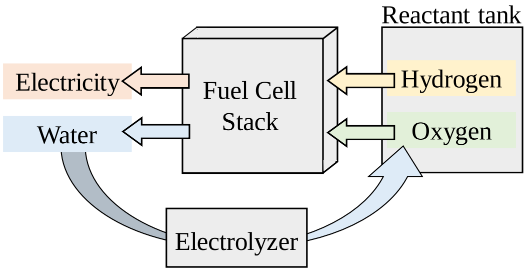
C. FUEL CELL TECHNOLOGY

Fuel cells are an alternative dual-purpose power generation and energy storage solution. The fuel cell is an electrochemical device that produces electricity through the electrochemical recombination of reactants, such as hydrogen and oxygen. It does not “burn” the hydrogen as an engine would. Instead, it combines these elements electrochemically using a catalyst and produces electricity and a byproduct (water, if the reactants are hydrogen and oxygen). Fuel cell technology can be classified as primary (not rechargeable) or secondary (rechargeable), depending on their design and intended application. Primary fuel cells for space use tanks of fuel and oxidant, which are gradually discharged and not replenished. Secondary fuel cells (also referred to as regenerative fuel cells) are designed to be rechargeable. Regenerative fuel cells use hydrogen and oxygen to produce water and electrical power. The water formed during the discharge reaction is stored and then electrolyzed back into hydrogen and oxygen during the charging part of the cycle [108]. Fig. 4 illustrates the main difference between the two types of fuel cells.

This technology can be designed and sized considering the particular requirements of each location and application. Fuel cells are capable of providing hundreds to thousands of Watts of power for extended periods of operation [42]- [45], [109], [110]. Several types of fuel cells are advantageous for extraterrestrial applications, such as proton exchange membrane (PEM), solid oxide (SO), and alkaline fuel cells (AFCs) [111], [112]. In 1965, the Gemini V spacecraft was the first spacecraft to use PEM fuel cells. AFC technology was used on all Apollo missions, the Apollo/Soyuz mission, Skylab, and the Space Shuttle [108], [109]. Fuel cell technologies reach an energy density between 456 and 830 Wh/kg for electric loads between 0.5 kW and 28.03 kW, respectively [113]. A comparison of the different fuel cells technologies is presented in Table 6.



(a) **Primary fuel cells**



(b) **Secondary fuel cells**

FIGURE 4. **Major difference between primary and regenerative fuel cell technologies.**

Primary fuel cells require a continuous supply of reactants to operate for extended periods of time. Resources are limited in space so fuel must either be carried with the habitat, refined from local resources, or recycled. For example, hydrogen and oxygen can come from hydrocarbons, oxides in regolith, or water electrolysis. Although the potential mass savings on energy storage over batteries are high, the current technological readiness of regenerative fuel cells remains low for space applications [114]. Large-scale energy storage capabilities would be enhanced by extra-terrestrial rated RFCs. Recent target metrics include maintenance-free 50,000 hour life, capacities of up to 1 MWhr by the 2030s, though more modest capabilities may be realized in the near-term [115].

V. ELECTROCHEMICAL ENERGY STORAGE SYSTEMS IN SPACE MICROGRIDS

For long-term space exploration, it is necessary to have a reliable energy storage system that can support habitats’ vital loads during critical situations, disturbances, and failures. Large-scale energy storage capabilities would be enhanced by extra-terrestrial rated RFCs. Recent target metrics aim at capabilities that include a large storage capability (~MWh, 5000 charging-discharging cycles), high specific energy (500 Wh/kg), radiation tolerance, and extremely low-temperature operational capability [45][17]. The type of

TABLE 6. **Comparison of fuel cells technologies**

Fuel cell technology	Efficiency (%)	Operating temperature (℃)	Output power (kW)	Lifetime	Advantages	Ref.
PEM	58	50 - 100	1 – 250	5 – 9 years	• Low corrosion problems • Low management problems • Low temperature • Quick start-up	[116], [117], [118], [119]
SO	35 - 43	600 - 1000	1 – 3000	5 years	• High efficiency • Fuel flexibility • Low management problems	[116], [117], [119], [120], [121]
AFC	60	90 - 100	10 – 100	4 years	• High performance • Used in military space	[116], [104], [119], [121], [122]

energy storage system depends on the space mission duration, location, and electric loads. Both batteries and fuel cells can serve as electrochemical energy storage devices [118]. This section discusses the potential battery types for space exploration. The main batteries are not rechargeable, and it is typically used for short mission durations. This battery type is for single use, and it provides power for a few minutes to a few hours. Such missions include planetary probes (Galileo, Deep Impact, and Huygens), sample return capsules (Stardust and Genesis), Mars Landers (MER), and Mars Rovers (Sojourner). Secondary batteries are rechargeable and are used extensively on both Earth-orbiting spacecraft missions and deep-space missions utilizing solar power. They have been used in orbital missions (Topography Experiment (TOPEX), Mars Global Surveyor, and Mars Reconnaissance Observer), Mars landers (Viking and Phoenix), and Mars rovers (Spirit, Opportunity, and Curiosity). Secondary batteries are preferred for long-term space exploration as they can be recharged by power generators and provide power for extended periods of time [123]. Table 7 provides an overview of the technical specifications of different battery types. Current trends are integrating Lithium-ion (Li-ion) secondary batteries into space missions as rechargeable energy storage solutions to power systems. Table 8 shows the rechargeable battery types used in different space missions since 2004 [124].

Nickel-Hydrogen (Ni-H$_2$) batteries have traditionally been used and can be characterized by their high cycle life (over 50,000) and wide operating temperature range [125]. However, the manufacturing of Ni-H$_2$ batteries is being phased out, and they may not be available for future space missions [124]. Li-ion batteries have higher specific energy (over 100 Wh/kg) and energy density (over 200 Wh/L), and are versatile in operating temperature ranges [124]. Fig. 5 displays the specific energy of various Li-ion batteries suitable for space use. Lithium Aluminum Titanium Phosphate (LATP), Lithium phosphorus oxynitride (LiPON), and Lithium lanthanum zirconium oxide (LLZO) battery types have the highest specific energy (250-350 Wh/kg).

Despite the numerous benefits associated with Li-ion batteries, thermal-related safety concerns remain challenging due to the complete reliance on this battery class (e.g., overheating, thermal runaway and propagation, fire, and

TABLE 7. Missions Comparison of rechargeable batteries technologies

Battery Technology	Size	Operating Temp. (℃)	Lifetime (years)	Maintenance	Safety concerns	Specific energy (Wh/kg)	Ref.
Lithium Based (Li-ion, Li-Sulfur, or Li-metal)	Small	-40 to 65	5 to 6	Moderate	Low-moderate	100 to 150	[123], [124], [126], [127]
Nickel Based (Ni-cadmium, Ni-iron)	Average	-60 to 65	5 to 7	Low	Low-moderate	55 to 60	[123], [128], [129]
Sodium Based (Na-sulfur, Na-metal)	Average	-30 to 70	7	Moderate	High	30 to 40	[123]

TABLE 8. Rechargeable battery types used in different space missions since 2004 [124]

Mission	Launch Date	Destination	Battery system
Messenger	August 2004	Mercury	Ni-H$_2$
Deep Impact	January 2005	Comet	Ni-H$_2$
Mars Reconnaissance Orbiter	August 2005	Mars	Ni-H$_2$
Phoenix	August 2007	Mars	Li-ion (NCO)
Dawn	September 2007	Vesta & Ceres	Ni-H$_2$
Kepler	March 2009	Earth Orbit	Li-ion (LCO)
Lunar Reconnaissance Orbiter	June 2009	Moon	Li-ion (LCO)
LCROSS	June 2009	Moon	Li-ion (LCO)
Juno	August 2011	Jupiter	Li-ion (NCO)
GRAIL	September 2011	Moon	Li-ion (NCO)
Mars Science Laboratory	November 2011	Mars	Li-ion (NCO)
LADEE	September 2013	Moon	Li-ion (LCO)
MAVEN	November 2013	Mars	Li-ion (NCO)
Deep Space Climate Observatory (DSCOVR)	February 2015	L-1	Li-ion (LCO)
Magnetospheric Multiscale Satellites (MMS)	March 2015	Various Orbits	Li-ion (LCO)
OSIRIS-Rex	September 2016	Asteroid	Li-ion
Transiting Exoplanet Survey Satellite (TESS)	December 2017	HEO Orbit	Li-ion (NCO)
InSight	May 2018	Mars	Li-ion (NCA)
Mars 2020	July 2020	Mars	Li-ion (NCA)
James Webb Space Telescope (JWST)	December 2021	L-2	Li-ion (LCO)
JPSS2	November 2022	LEO	Li-ion (LCO)

Nickel-hydrogen (Ni-H$_2$), Lithium nickel cobalt oxide (NCO), Lithium Cobalt Oxide (LCO), and Lithium Nickel-Cobalt-Aluminum Oxide (NCA) explosion) [116], [117]. Besides, Li-ion batteries have limited low-temperature operational capability [41], [53], [123], [130]. Lithium Cobalt Oxide (LCO), Lithium-Sulfur (LiS), and Lithium Nickel-Cobalt-Aluminum Oxide (NCA) have the widest operating temperature capabilities (between −40 and 60℃) as shown in Table 7. Fig. 6 compares the operating temperature of different Li-ion battery types. As shown in Fig. 5 and 6, Lithium iron Phosphate (LFP), Lithium-Titanium-oxide (LTO), and Lithium-Nickel-Manganese-Cobalt-Oxide (NMC) have the lowest specific energy (150-200 Wh/kg) and the narrowest operating temperature ranges (between −10 and 35 ℃). The desired minimum operational temperature is −60 ℃ to −80 ℃ for surface missions [53], [123]. Then, since temperatures can reach far below that (as expressed in Table 1), thermal insulation and an active control system are required to keep the temperature within the operating range. Passive thermal insulation generally consists of multiple layers of coatings and surface finishes, heat sinks, and thermal insulation with low-conducting materials like layered blankets and foams. Multilayer materials are excessively used to prevent high thermal flux and reduce environmental temperatures and temperature gradients. Also, an Active Thermal Control System (ATCS) can be employed to heat and cool as required to maintain the operating temperature range of different electrical systems. ATCS involves electrically powered heaters using resistances and cold plates using refrigeration devices such as cryocoolers around the electrical equipment. Radioisotope heater units (RHUs) can also provide heat to battery modules, albeit uncontrolled.

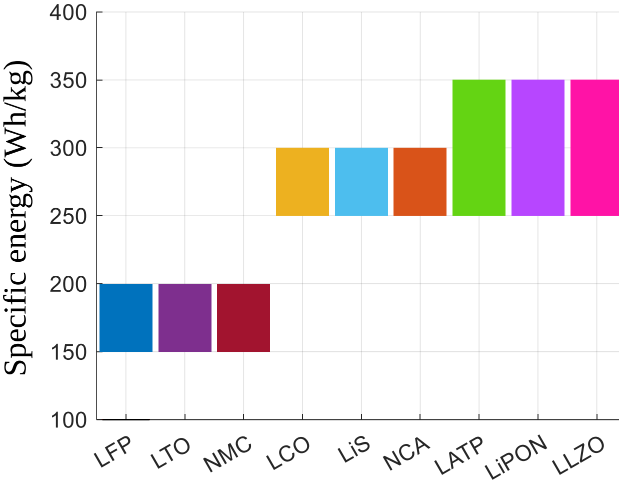


FIGURE 5. **Specific Energy ranges of different Li-based batteries.**

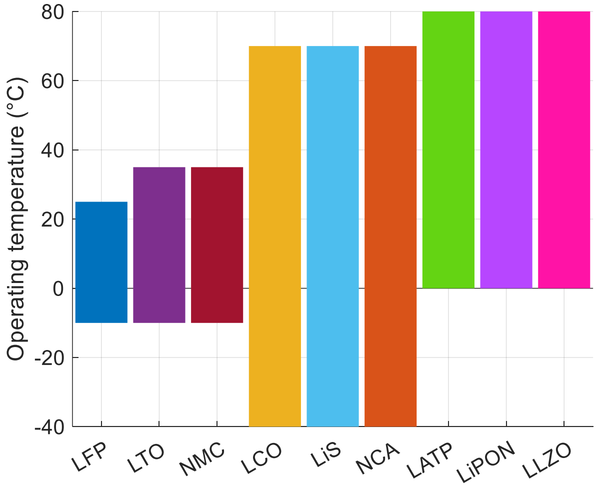


FIGURE 6. **Operating temperature ranges of different Li-based batteries.**

VI. POWER DISTRIBUTION SYSTEM FOR FUTURE SPACE APPLICATIONS

Space microgrids require robust power distribution system between power sources and loads [25.][34]. The power distribution system is considered as the conditioning and control system of unregulated power from sources and its transmission to a power bus for distribution to the intended electrical loads. Both ac and dc technologies are applicable for designing a power distribution system in extraterrestrial applications. Although most terrestrial power transmission is based on high voltage ac transmission, there are currently no space-based applications utilizing it. All existing space-based electrical power systems are dc, such as the one implemented in the International Space Station (ISS). Dc systems are characterized by higher efficiency due to lower line losses, no reactive power compensation, and absence of skin effect. Also, dc power distribution systems are relatively easy to install and maintain. However, ac systems have the advantage of easier voltage transformations. Also, the alternating nature in ac systems simplifies the circuit breaker protection implementations because of the zero-current switching during failures and transient situations. This naturally occurring feature makes an ac distribution system safer and easier to protect [42], [44]. The tradeoff between ac and dc transmission is not clear cut and more detailed trade studies need to be done that consider safety and life cycle costs [131]. Table 9 summarizes tradeoffs between ac and dc distribution systems.

Power distribution system weight, volume, and efficiency is affected by the system voltage level. Increasing the voltage level reduces the current a line must carry. This reduces the conductor mass and increases distribution efficiency. However, a higher voltage also requires higher voltage components, more insulation, and greater separation distances, which increases hardware volume and mass. ISS distribution voltages are approximately 160 Vdc [132]. This voltage level is not optimal for distributing energy for habitat level power loads, which may be distributed across tens of kilometers. To minimize the system losses and increase distribution efficiency, it is required to step up the voltage to a higher voltage level. High voltage distribution is expected to be relatively easy to install due to its lower overall system mass, low maintenance frequency based on terrestrial experience, and high adaptability to other surface-based

TABLE 9. Comparison between ac and dc distribution systems implementation in space microgrids

Power distribution architecture	Advantages	Disadvantages
dc	• Lower system losses • Easier to parallel DC lines • Flight heritage (e.g., ISS), for low voltage distribution networks	• Complex voltage transformations • More difficult to clear fault conditions • High possibility of dc arc faults
ac	• Simpler voltage transformations • Simpler circuit breaker implementations (for fault clearing conditions) • Higher technological readiness for distribution based on terrestrial applications	• Higher system losses • Not yet applied in space missions •

power systems. However, high-voltage systems pose a greater safety hazard than low-voltage systems.

Recent studies and trades have been conducted to identify the best architecture for extraterrestrial power grid [131], [133]. It has been shown that because of the limitations of high-voltage transistors, ac grid architectures have a faster time to implementation for major-scale power transmission. The transmission frequency has also been considered, and with transitioning to a higher than 50 Hz or 60 Hz frequency, mass can be saved on auxiliary components like transformers. These analyses and benefits have already been demonstrated in aircraft applications. Finally, different topologies including “radial”, “ring”, and “mesh” networks have been considered as each can provide their own benefit for distribution and control.

Overall, additional research, testing, and technology development will be required to clarify the tradeoff of power distribution systems for long term, deep space exploration, habitats, and missions [42].

Power distribution systems require power electronic components for switching, rectification, energy storage, voltage/current transformation, filtering, regulation, protection, and isolation [134]. For long term space exploration missions, the main characteristics and requirements of electronic components are:

- **High power density:** High-frequency operation reduces the mass and volume of the passive components (transformers, inductors, and filter capacitors).
- **High operating temperatures:** High-temperature power electronic components decrease the cooling requirements during night hours and thus reduce the complexity, size, and mass of the thermal transport and radiator subsystem.
- **High efficiency:** High-efficiency components reduce the power generation and storage needs for a given output power.
- **High radiation tolerance:** High radiation resistant components reduce mass and volume of shielding materials.
- **High voltage:** High voltage components reduce power transmission cable mass and volume.

Table 10 summarizes the desired numerical characteristics of the main power electronic devices required for long-term space exploration missions [50].

VII. SPACE MICROGRIDS MANAGEMENT AND CONTROL SYSTEM

An efficient electrical control and management system is necessary for extraterrestrial microgrids to support the power demand and optimize resource utilization. Ground-based management and control are used in different space missions and the ISS. However, the communication latency can be significant (up to or greater than 15 minutes for Mars missions), which can delay fault resolution and cause significant problems in voltage control, power flow, and load sharing, potentially resulting in loss of mission [135]. Thus, the control and management systems are required to be fully autonomous and independent in space microgrids [136]-[138]. In addition, such autonomy contributes to reducing the mission life support costs and minimizing the total weight of the power system [50], [139]. Autonomy can also provide higher levels of reliability by sensing hidden faults in the system and quickly responding to them by reconfiguring the power system following a failure. An autonomous power management and control system can also actively manage its own “health,” thereby increasing reliability, decreasing maintenance operations, and extending the life of the mission

TABLE 10. Desire characteristics of power electronics devices required for long term space exploration missions [50]

Component	Parameter	Desired value for space
Power capacitors	Volumetric efficiency	$\geq 1\ \mu F/cm^3$
	Energy density	4 to 5 J/cm^3
	Operating temperatures	250 to 300 °C
Power transformers	Power density	≥ 5 kVA/kg
	Switching frequency	≥ 500 kHz
	Operating temperatures	250 to 300 °C
	Efficiency	98 to 99%
Power switches	Current density	$\geq 500\ A/cm^3$
	Operating frequency	≥ 500 kHz
	Operating temperatures	250 to 300 °C
dc/dc converter	Operating frequency	≥ 500 kHz
	Operating temperatures	250 to 300 °C

[50]. The control system of a space power system mainly consists of scheduling and load prioritization subsystems:

A. SCHEDULING SUBSYSTEM

Due to the extreme cost of cargo transportation from Earth, future extraterrestrial power systems are required to be rigorously optimized in terms of mass reduction. To a certain extent, optimal power scheduling and dispatch can minimize the power system's total weight and size. This control system involves scheduling resources efficiently in addition to planning the loads and their operating modes based on power availability, demand, and losses. For example, rescheduling some activities (along with their power loads) from night to day hours helps in utilizing solar energy more efficiently and simultaneously saves energy storage system mass [45], [46].

B. LOAD PRIORITIZATION SUBSYSTEM

Optimal power distribution and prioritization during emergencies and failures enhance the efficiency and safety of the electrical systems. This subsystem controls power distribution during failures and ensures the operation of the critical loads in the habitat. Besides, it helps in the system recovery process from faulty conditions, which improves the reliability and resilience of the power system [49]. Load prioritization and management are determined based on the mission type, the habitat’s phase of operation (crewed, uncrewed, or transition), and failure severity. For instance, monitoring and robotic loads are prioritized in uncrewed missions, while crewed missions prioritize life support loads [46].

VIII. POWER SYSTEM DEGRADATION IN SPACE: CAUSES AND EFFECTS

Extraterrestrial electrical power systems are subjected to many environmental threats, causing degradation of the system components [64], [140]. Such degradation is characterized by a gradual deterioration of the individual components’ performance and system efficiency. As a result, the lifetime of the system will be reduced, which adversely affects the mission cost and duration [57]. These threats include:

- **Dust:** On many extraterrestrial planets, dust particles exist on the surface. While dust might not cause the individual components to degrade from an electrical operations perspective, it will cause the overall system performance to degrade (e.g. through shading of solar panels) and can cause physical degradation from inserting itself between interconnects.
- **Atomic oxygen:** Atomic oxygen (AO) oxidizes many metals, especially silver, copper, and osmium used in spacecrafts. AO reacts strongly with materials containing carbon, nitrogen, sulfur, and hydrogen bonds and causes component erosion.
- **Vacuum:** Pressures of less than 10^{-9} torr have been measured on the lunar surface [141], causes outgassing, which is the release of volatiles from materials.
- **Solar ultraviolet (UV) radiation:** UV radiation damages polymers by either cross-linking (hardening) or chain scission (weakening). UV under high vacuum also creates oxygen vacancies in oxides, leading to significant damages.
- **High-energy charged particle radiation:** The three main sources of charged particle radiation naturally occurring in space are galactic cosmic rays, solar proton events, and trapped radiation belts. Depending on the material, charged particles result in cross-linking or chain scission, resulting in materials embrittlement.
- **Plasma:** space plasmas are comprised of approximately equal amounts of ions and free electrons. The composition depends heavily on location within the solar system. In much of the solar system, hydrogen and helium ions dominate, while the plasma species near atmospheres reflect the planetary composition. The Jovian magnetosphere, for example, has a mixture of variably charged oxygen, sulfur, and sodium [142]. Interaction of plasma with habitat surfaces can cause surface charging, deep dielectric charging, ion sputtering, arcing and parasitic currents in some power components, as well as reattraction of contaminating ions [143].
- **Temperature extremes and thermal cycling:** Cyclic temperature variations lead to cracking, peeling, spalling or formation of pinholes in the coating, which then allows AO to attack the underlying materials. For example thermal cycles on the Moon are approximately between -130 °C to +120 °C [144].
- **Micrometeorites:** Components of the extraterrestrial habitats are exposed to micrometeorites traveling at great speeds. While typical impact speeds in Low Earth Orbit (LEO) range from 10-20 km/s, the upper limit on impact speed from solar system objects is the sum of the solar system escape velocity and the habitat’s motion about the Sun, about 72 km/s at 1 Astronomical Unit (AU) [145]. Seasonal increases in meteoroid activity can be attributed to regular intersections with cometary debris clouds, resulting in meteor showers. Space debris populations vary with the solar cycle: as the Sun’s activity increases, the atmosphere heats up, increasing the drag on space debris. Large space debris (>10 cm) can be tracked and avoided, but there is no current way to avoid the impacts of small debris. Hypervelocity impacts (relative velocity greater than the material speed of sound) can cause significant material and electrical damage to spacecraft and habitat systems. Surface erosion of critical optics or other sensors, structural damage to seals, and puncture of pressurized bulkheads present serious risks to fluid, electrical, and thermal management systems [146]. Plasmas generated from

these impacts can cause disturbances in electrical devices due to electromagnetic pulses associated with these impacts [147].

Beyond the scope of this discussion is the launch and landing environment. Although short in duration, the vibration load of a launch from the Earth's surface to orbit or landing from orbit to the surface of a planetary body induces survivability requirements on the mechanical structures of power systems.

A. DEGRADATION OF PV SYSTEMS

Solar cell degradation in space is caused primarily by the exposure to strong particle radiation. These particles have energies that range from near-zero to several hundred million electron volts. Charged particles are one of the major concerns of PV manufacturers and space research societies considering the severe damage that they can cause. The radiation-induced degradation of PV-cells is due to the modification in the semiconductor crystal structure due to ions or nuclei particles that strike the solar cells' wafers [148]-[151]. A single strong solar proton event (SPE) may permanently reduce the energy efficiency of monocrystalline silicon solar cells by about 20–25% and the efficiency of multijunction PV cells by about 5–10% [83]. Moreover, constant exposure to galactic cosmic rays is expected to cause a 2–3% annual degradation of PV system performance [46].

Thermal cycles in space environment also have a significant effect on PV system degradation and lifetime [152]. Extreme temperature variations cause thermal stresses and eventually cracking of solar panels and delamination of several layers in the heterostructure of the solar cells [59]. In addition, micrometeorite impacts can crack and obscure cover glasses and cause anomalous charging, leading to further damage from arcing. Fig. 7 summarizes PV cell degradation causes and effects in space environment.

B. DEGRADATION OF ENERGY STORAGE SYSTEMS

Extreme temperature variation in outer space is the main cause for fast degradation of energy storage systems. Low temperature affects the performance and life of the batteries. At an operating temperature as low as -130°C, Li-ion batteries, the main battery type used for space application, show slow chemical-reaction activity and charge-transfer velocity [153], which leads to the decrease of ionic conductivity in electrolytes [154] and lithium-ion diffusivity within electrodes [155]. Such a decrease will result in the reduction of energy and power capability, and sometimes even complete failure. Besides, high operating temperature increases the risk of thermal runaway and accelerates performance degradation [153].

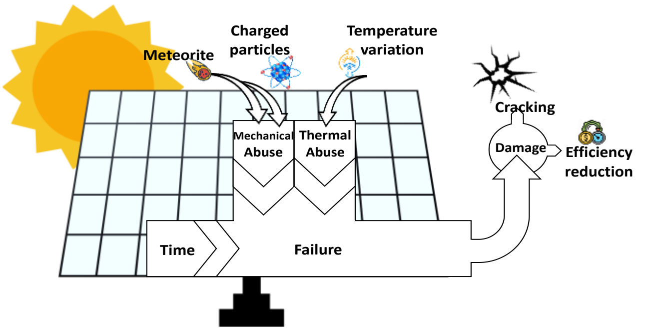


FIGURE 7. PV degradation causes and effects.

Electrical fatigue of the energy storage system due to voltage variation and continuous load fluctuation caused by high inrush current of some loads, is another factor that accelerates degradation and decreases the system efficiency [156]. Energy storage systems in space environment are also exposed to different mechanical disturbances such as vibration and micrometeorites, which have a considerable negative impact on the energy storage system performance [157]. Some experimental studies demonstrated that mechanical vibration could enhance heat transfer and reduce the maximum temperature rise [158]; however; continuous vibration conditions in space increase the risk of thermal runaway causing fire in the interior environment of the habitat. Also, fast micrometeorite strikes are one of the most critical scenarios with possible catastrophic damages, such as explosion of the battery packs. To optimize the battery design and management for extraterrestrial applications, all degradation causes and effects should be studied and considered [159].The effect of radiation on energy storage systems is insignificant since most battery cells are shielded and covered. Fig. 8 shows aging mechanisms and the impact of degradation on energy storage.

C. DEGRADATION OF POWER DISTRIBUTION SYSTEMS

Many of the environmental conditions that affect generation and storage elements can damage distribution systems as well. Micrometeorites can puncture or sever electrical cables, requiring redundant distribution cables. High-energy charged particles and cold temperatures can embrittle cable insulation, making it more susceptible to abrasion and more serious physical damage. Radiation can also cause catastrophic damage to power semiconductor devices through single-event burnouts, hampering the ability to buck and boost voltages from bus to distribution levels. The vacuum of space and thermal insulating properties of many regolith materials necessitate thermal rejection systems that utilize radiation alone. Depending on transmission cable inefficiencies, this may have to be accounted for. Long (km

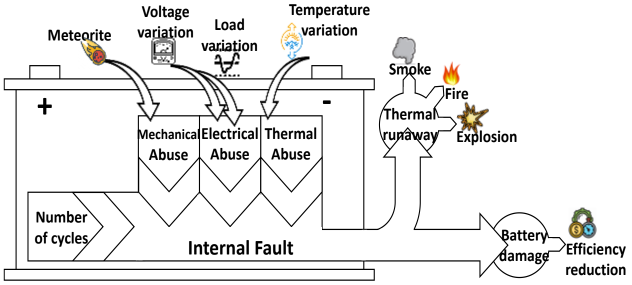


FIGURE 8. Energy storage degradation causes and effects.

scale) distribution cables coupled with the ambient magnetic fields induce anomalous voltages and potential power surges during geomagnetic storms.

D. DEGRADATION OF NUCLEAR SYSTEMS

With the exception of RTGs, the performance and longevity of nuclear systems in the space environment are not well characterized. RTGs are famously robust and reliable systems that have allowed the Voyager probes to last for half a century, though with exponentially decreasing (but predictable) power output as the radioisotopes decay to more stable products [160]. Systems on planetary bodies such as the Moon and Mars must contend with dust buildup on surfaces, including radiators. Apollo astronauts reported batteries overheating on the Lunar Roving Vehicle and a number of instruments did not perform as expected due to thermal control problems [161]. Nevertheless, recent studies with Lunar simulant have not shown decreased efficiency of RTGs due to degraded radiator performance, although the authors note significant variation in their results from trial to trial that suggest further study is warranted [162].

Newer systems with fission reactors will have similar challenges. Like RTGs, the nuclear fuel will gradually be depleted and the reactor will provide less power over time. The dynamic conversion techniques will require radiators to maintain a cold reservoir and will be similarly susceptible to any impact to radiator performance from dust buildup. Because fission systems use working fluids and moving mechanisms, they are susceptible to mechanical fatigue and damage from thermal cycling stresses and micrometeoroid impacts that RTGs are resilient against [163].

IX. EXTRATERRESTRIAL MICROGRID CHALLENGES AND SOLUTIONS

Extraterrestrial microgrid implementation encounters significant challenges in terms of design, operation, and cost. Microgrid systems should be designed to withstand extreme environmental conditions of outer space and restricted maintenance intervals while maintaining high reliability and optimized operational efficiency. Furthermore, to guarantee continuous power supply, advanced engineering solutions and redundant systems are required for long-term space exploration missions. Given the high expenses associated with the system transportation, cost is another critical factor, imposing the development of lightweight, robust, and cost-effective technologies.

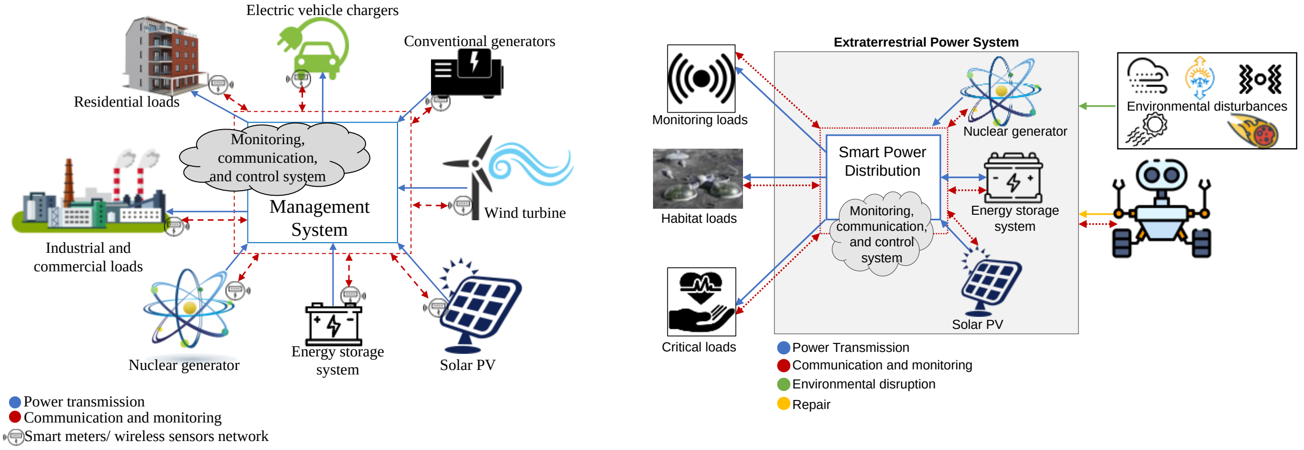
Due to some similarities between the extraterrestrial microgrids and islanded, terrestrial, renewable energy-based dc microgrids shown in Fig. 9, the verified strategies developed for terrestrial dc microgrids could be applied to space microgrids. In contrast, other system challenges may demand the development of new technologies [53].

A. DESIGN AND TECHNOLOGICAL CHALLENGES

In extraterrestrial microgrids, the communication system's delays and failures are among Fig. the most serious concerns that need significant consideration. One suggested solution relies on a communication-less and hierarchical control system, which has already shown promising results in islanded terrestrial microgrids [53].

Besides, the electrical power system in a space habitat should have the ability to be easily and effectively maintained and repaired throughout its operational life. Maintainability of the system is a crucial aspect of system design and management, as it affects the system reliability and availability. Similar to terrestrial power system, the main considerations of power systems maintainability are:

- **Modularity and standardization:** designing power systems with modular components and standardized interfaces makes it easier to replace or upgrade individual parts without affecting the entire system.
- **Accessibility:** Ensure that components requiring regular maintenance or replacement are easily accessible.
- **Diagnostic and remote monitoring:** It can help identify potential issues before they lead to system failures. This proactive approach can significantly improve maintainability by allowing for timely interventions.



(a) Terrestrial microgrid

(b) Extraterrestrial microgrid

FIGURE 9. Evaluation of islanded terrestrial and extraterrestrial microgrids architectures.

- **Predictive management:** It involves monitoring the condition of components in real-time. This allows for maintenance to be performed based on the actual condition of equipment.
- **Reliability-centered maintenance:** Reliability-centered maintenance is a systematic approach that prioritizes maintenance activities based on the criticality of components to overall system reliability. It involves analyzing failure modes and determining the most effective maintenance strategies for each component.

Other research methodologies and algorithms already developed for terrestrial microgrids can be extended to facilitate the design process of extraterrestrial microgrids. Such methods include reliability assessment and enhancement algorithms. Fault tree analysis was used to evaluate the reliability of terrestrial renewable-based microgrids in different studies such as [164] and [165]. A similar approach was implemented in [166] to assess the reliability of extraterrestrial microgrids. This study proved the effectiveness of fault tree analysis in assessing the microgrid’s reliability and hardening the design of future extraterrestrial power systems.

B. OPERATIONAL CHALLENGES

Power system stability in extraterrestrial microgrids should be ensured under multiple failures and cascading faults. Thus, finding optimal space microgrid topologies to improve system reliability and resilience while satisfying a minimum weight, size, and cost is crucial. This challenge could be solved by applying one of the developed and verified topologies implemented in islanded terrestrial dc microgrids. The standardized topologies are radial, ring, and mesh architectures with additional lines for redundancy [167]. Several faults and failures in space microgrids threaten the regular operation of the system and lead to disastrous damage and loss of life. Therefore, space microgrids must have fault-tolerant control systems capable of maintaining system operation under fault and emergency conditions.

Besides, the lack of inherent inertia is also one of the main challenges of islanded microgrids, which leads to potentially unstable systems. Lack of inertia is also a primary stability challenge of extraterrestrial microgrids. Different solutions have been proposed in the literature for terrestrial renewable energy-based microgrids to provide the required artificial inertial. Droop control implementation at low control levels is commonly used [168].

Furthermore, extraterrestrial microgrids are characterized by variable power demand profiles due to the unstable environmental conditions in space. Power demand variation is also one of the islanded terrestrial microgrid challenges. To reduce those fluctuations, a multi-microgrid system was proposed in [169]. This solution could also be implemented in extraterrestrial microgrids to improve their reliability, efficiency, and stability.

C. COST CHALLENGES

Due to the substantial costs associated with transporting systems to extraterrestrial environments, understanding expected costs is needed to help select technology and compare design architectures and mission scenarios. The major cost driver for space systems is weight [170]. In this respect, LCC is an essential system engineering metric and fundamental for long-term space mission planning. LCC estimation of extraterrestrial systems includes three main stages, which are usually estimated separately. The three main LCC factors are:

- **Design and development:** Those factors represent the cost estimate of the hardware design, development, test, and evaluation. Parametric cost models provide the most effective estimates of space hardware costs early in the mission cycle. NASA uses three different parametric models for crewed space systems' design and development cost: the commercial PRICE-H space hardware cost model, the NASA-Air Force Cost Model (NAFCOM), and the Advanced Missions Cost Model (AMCM) [170]. The cost estimate for this phase can vary significantly due to the unique requirement of each technology and mission. The main factors affecting the cost include system complexity, safety requirements, material selection, environmental adaptability, and redundancy and reliability constraints. For example, the development of nuclear fission reactors is highly complex, requiring control systems, advanced radiation shielding, and reliable cooling and thermal management mechanisms, all of which considerably raise design and engineering costs. In contrast, simpler systems like solar arrays, though still expensive for extraterrestrial applications, involve fewer components and are generally easier to design. According to historical data, the average cost for the design, development, test, and evaluation phase of a crewed planetary mission is approximately $4.7 billion [171].
- **Launch and emplacement:** Those factors consist of two components, the cost of launch to LEO and the additional cost for emplacement at the mission location beyond LEO, such as the Moon or Mars. System mass determines the launch and emplacement cost, which directly depends on the cost per kilogram. The Space Shuttle cost to launch to LEO with Falcon 9 is approximately $5k/kg [172]. The emplacement cost depends on the ratio of the total initial LEO mass to the final payload mass. Typical initial/final mass ratios from LEO to the moon or Mars and landing or return are summarized in Table 11.
- **Operations and maintenance:** Those factors include any material and spares provided, crew training, ground support, mission control and planning, data analysis, and sustaining engineering. The operations phase of a human space mission begins after launch and continues until the crew returns to Earth. The system complexity and the

TABLE 11. Initial/final mass ratio beyond LEO

Mission destination	Initial/final mass ratio
LEO to Moon orbit and landing	6.7
LEO to Moon orbit and return to Earth	5.0
LEO to Mars orbit and landing	4.8
LEO to Mars orbit and return to Earth	13.2

mission duration are the two major drivers of operations cost [172]. Complex human missions, severe environments, and higher risk aversion increase design and development costs and operations and maintenance costs. Therefore, space operations costs can be approximately predicted as an additional percentage of the system development cost every year. The ten-year operations cost is approximately 157% of the development cost [170].

Since system mass is the main parameter used to determine all LCC cost phases, Table 12 estimates the weight of the non-redundant space microgrid proposed in [46] and shown in Fig. 10. The considered system is proposed for six astronauts' habitats on the lunar equator. It consists of a nuclear generator (N), a solar power generator (S), an electrochemical energy storage system (ES), three boost converters (C_1, C_2, and C_3), three buck converters (C_4, C_5, and C_6), and a dc common bus (GB) that connects the total generation with the different load types.

Optimizing the level of redundancy for high system reliability and total weight is crucial for long-term space exploration missions. In this respect, [173] presented a mathematical model to balance the reliability and cost of space power systems. Thedeveloped model considers the expected cost due to subsystem and component failures and its effect on the reliability of the whole system. Overall, additional analyses are still needed to further understand the trade-offs between reliability, redundancy, and cost for varying risk postures.

TABLE 12. Weight estimate of the power system components [174], [175]

Subsystem or component	Weight (Kg)
Nuclear generator with Stirling converter (16kW)	1920
Solar generator (15 kW)	810
Energy storage system – Li-ion batteries (1500 kWh)	8,850
dc/dc converter (15 kW)	16

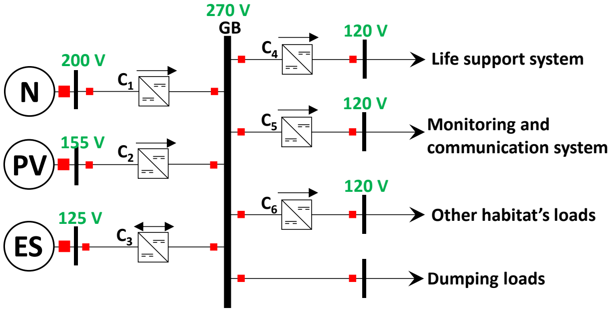


FIGURE 10. Architecture of dc radial power distribution system for long-term space missions [18].

X. CONCLUSION

A primary pillar in constructing an extraterrestrial habitat is to design and implement an efficient and fully autonomous power system. While the specific technical requirements will be different for each habitat location, the development of systematic requirements to meet this goal is an ongoing effort between government agencies, industry partners, and academia. To fully develop these requirements, a review of all available and advanced technologies for generating, storing, controlling, and distributing power is necessary for future human establishment in space and long-term space exploration.

Long-term human presence in space requires reliable and sustainable power sources. Both nuclear and solar power represent effective solutions to meet the unique energy requirements of extraterrestrial environments. Nuclear power is characterized by its high energy density and provides a robust and continuous power supply, critical for deep-space missions and habitats established in regions with limited solar exposure. Compact fission reactor technologies at the tens of kW-scale represent a promising solution that can provide consistent power for long-duration missions and ensure crew survival in environments with little insolation or long periods of darkness. Alternatively, solar power remains a highly attractive option for space habitats implemented in sun-rich environments, such as the Moon or Mars. Advances in multi-junction PV cells have significantly improved the efficiency and reliability of solar power systems, making them a viable and cost-effective energy source for future space habitats. However, long night cycles limit the performance of solar power technologies. Thus, solar-powered extraterrestrial habitats must be equipped with an energy storage solution to guarantee sustainable power supply. Electrochemical energy storage technologies such as Li-ion batteries are characterized by their high specific energy relative to other battery chemistries, reliability, and ability to operate in extreme conditions, making them suitable for such applications. However, depending on the total energy storage capacity required, the mass of batteries may be prohibitively large. Fuel cells characterized by high energy density are an alternative dual-purpose power generation and energy storage solution. While the technological readiness of regenerative fuel cells is currently low, significant progress in recent years gives reason for optimism.

Considering the advantages and disadvantages of nuclear and solar power, integrating both technologies and an efficient energy storage system is essential to developing future space habitats that mitigates the risks of one or the other. This hybrid approach offers complementary benefits that guarantee a balanced and resilient energy strategy; it ensures load support under varying conditions and provides redundancy and security in the energy supply. Energy storage systems can support the habitat's different functions during critical situations. An efficient and autonomous electrical control and management system is necessary to optimize resource utilization and load distribution.

Given the various technological requirements for extraterrestrial microgrids, this article highlights the importance of verified strategies developed for terrestrial dc microgrids in advancing space microgrids-related research. For example, a communication-less and hierarchical control system, which has already shown promising results in islanded terrestrial microgrids, can be an efficient solution worth studying to limit the communication system's challenges in space. Besides, the system maintainability strategy followed for terrestrial microgrids can help in proposing an effective maintainability approach for space microgrids. Power system reliability studies can also be an effective starting point for reliability assessment of the proposed space microgrids.

In conclusion, this article summarizes the current state-of-the-art technologies as documented in the available literature and explores the technological challenges and characteristics needed for future power microgrids for extraterrestrial habitats.

ACKNOWLEDGMENT

This work was partially supported by a Space Technology Research Institute Grant (80NSSC19K1076) from NASA’s Space Technology Research Grants Program. The authors would like to acknowledge the valuable contributions of Thomas Cusson and Andrew DePalma from the Power Electronics & Drives Advanced Research Laboratory (PEARL) at the University of Connecticut.

REFERENCES

[1] JAXA. “The JAXA Space Exploration Innovation Hub Center CoProduces Results on Remote and Automatic Control to Build Lunar Base”. [Online]. Available: https://global.jaxa.jp/press/2019/03/20190328a.html
[2] European Space Agency (ESA). “Lunar Exploration – ESA’s missions”. [online] Available: https://www.esa.int/Education/Teach_with_the_Moon/Lunar_Exploration_ESA_s_missions
[3] European Space Agency (ESA). “Moon habitat blueprint at Venice Biennale”. [online] Available: https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Moon_habitat_blueprint_at_Venice_Biennale
[4] National Aeronautics and Space Administration (NASA). “NASA Artemis”. [online] Available: https://www.nasa.gov/specials/artemis/
[5] A. Thompson. “China sets out preliminary crewed lunar landing plan”. [online] Available: https://spacenews.com/china-sets-out-preliminary-crewed-lunar-landing-plan/
[6] C. Muhao, et al. "Review of space habitat designs for long term space explorations." Progress in Aerospace Sciences 122 (2021): 100692.
[7] S. K. published, “India wants to land astronauts on the moon in 2040,” Space.com, Oct. 18, 2023. https://www.space.com/india-land-astronauts-moon-2040
[8] R. D. Launius, “Can we colonize the solar system? Human biology and survival in the extreme space environment,” Endeavour, vol. 34, no. 3, pp. 122–129, 2010.
[9] P. Brennan, “The Habitable Zone | The Search For Life,” Exoplanet Exploration: Planets Beyond our Solar System, Apr. 02, 2021. https://exoplanets.nasa.gov/search-for-life/habitable-zone/
[10] R. D. Launius, “Space exploration,” in Springer eBooks, 2016, pp. 635–649. doi: 10.1007/978-3-319-07052-0_39.
[11] M. Fox-Powell, J. E. Hallsworth, C. R. Cousins, and C. S. Cockell, “Ionic strength is a barrier to the habitability of Mars,” Astrobiology, vol. 16, no. 6, pp. 427–442, Jun. 2016, doi: 10.1089/ast.2015.1432.
[12] H. Shaftel, “10 Things: Planetary Atmospheres”, 2018. [online] Available: https://solarsystem.nasa.gov/news/436/10-things-planetary-atmospheres/
[13] NASA Science, “Earth with Clouds 3D Model,” NASA Solar System Exploration, Apr. 25, 2019. [Online]. Available: https://solarsystem.nasa.gov/planets/earth/in-depth/
[14] T. Sharp and V. Stein, “What Is Earth’s Average Temperature?,” Space.com, Feb. 25, 2022. https://www.space.com/17816-earth-temperature.html
[15] R. Heller et al., “Formation, habitability, and detection of extrasolar moons,” Astrobiology, vol. 14, no. 9, pp. 798–835, Sep. 2014, doi: 10.1089/ast.2014.1147.
[16] R. C. Elphic et al., “The Lunar Atmosphere and Dust Environment Explorer Mission,” Space Science Reviews, vol. 185, no. 1–4, pp. 3–25, Nov. 2014, doi: 10.1007/s11214-014-0113-z.
[17] National Aeronautics and Space Administration (NASA). “Lunar Reconnaissance Orbiter: Temperature Variation on the Moon”. [online] Available: https://lunar.gsfc.nasa.gov/images/lithos/LROlitho7temperaturevariation27May2014.pdf
[18] E. Furfaro, “Is There Weather on the Moon? We asked a NASA Scientist: Episode 34”. [online] Available: https://www.nasa.gov/feature/is-there-weather-on-the-moon-we-asked-a-nasa-scientist-episode-34
[19] B. M. Jakosky et al., “The Mars Atmosphere and Volatile Evolution (MAVEN) mission,” Space Science Reviews, vol. 195, no. 1–4, pp. 3–48, Apr. 2015, doi: 10.1007/s11214-015-0139-x.
[20] National Aeronautics and Space Administration (NASA). “In depth | Mars – NASA Solar System Exploration,” NASA Solar System Exploration. https://solarsystem.nasa.gov/planets/mars/in-depth/
[21] J. Gordon, T. Sharp, and N. T. Tillman, “What is the temperature on Mars?,” Space.com, Feb. 2022, [Online]. Available: https://www.space.com/16907-what-is-the-temperature-of-mars.html
[22] T. Owen, K. Biemann, D. R. Rushneck, J. E. Biller, D. W. Howarth, and A. L. Lafleur, “The composition of the atmosphere at the surface of Mars,” Journal of Geophysical Research, vol. 82, no. 28, pp. 4635–4639, Sep. 1977, doi: 10.1029/js082i028p04635.
[23] A. Sánchez-Lavega, S. Lebonnois, T. Imamura, P. L. Read, and D. Luz, “The atmospheric dynamics of Venus,” Space Science Reviews, vol. 212, no. 3–4, pp. 1541–1616, Aug. 2017, doi: 10.1007/s11214-017-0389-x.
[24] National Aeronautics and Space Administration (NASA). “Venus,” NASA Solar System Exploration. https://solarsystem.nasa.gov/planets/venus/overview/
[25] European Space Agency (ESA). “The unexpected temperature profile of Venus’s atmosphere.” https://www.esa.int/Science_Exploration/Space_Science/Venus_Express/The_unexpected_temperature_profile_of_Venus_s_atmosphere
[26] X. Zhu, “Comparison of Formation, Atmosphere and Habitability for Mercury and Venus,” Highlights in Science, Engineering and Technology, vol. 38, pp. 653–658, Mar. 2023, doi: https://doi.org/10.54097/hset.v38i.5918.
[27] National Aeronautics and Space Administration (NASA). “In depth | Mercury – NASA Solar System Exploration,” NASA Solar System Exploration. https://solarsystem.nasa.gov/planets/mercury/in-depth/
[28] N. T. Tillman, “Mercury’s atmosphere,” Space.com, Oct. 2016, [Online]. Available: https://www.space.com/18644-mercury-atmosphere.html
[29] D. T. Hall, D. F. Strobel, P. D. Feldman, M. A. McGrath, and H. A. Weaver, “Detection of an oxygen atmosphere on Jupiter’s

moon Europa," Nature, vol. 373, no. 6516, pp. 677–679, Feb. 1995, doi: 10.1038/373677a0.
[30] National Aeronautics and Space Administration (NASA). "Europa," NASA Solar System Exploration. https://solarsystem.nasa.gov/moons/jupiter-moons/europa/in-depth/
[31] D. Boucher, "Europa's Atmosphere: Composition and Origins," Exoplanet Science, Jan. 16, 2023. https://exoplanetscience.org/europas-atmosphere-composition-and-origins
[32] Y. L. Yung and X. Chen, "Stability of an oxygen atmosphere on Ganymede," Icarus, vol. 30, no. 1, pp. 97–103, Jan. 1977, doi: 10.1016/0019-1035(77)90124-5.
[33] National Aeronautics and Space Administration (NASA). "In depth | Ganymede – NASA Solar System Exploration," NASA Solar System Exploration. https://solarsystem.nasa.gov/moons/jupiter-moons/ganymede/in-depth/
[34] S. M. Horst, "Titan's atmosphere and climate," Journal of Geophysical Research: Planets, vol. 122, no. 3, pp. 432–482, Mar. 2017, doi: 10.1002/2016je005240.
[35] S. Rodriguez et al., "Science goals and new mission concepts for future exploration of Titan's atmosphere, geology and habitability: titan POlar scout/orbitEr and in situ lake lander and DrONe explorer (POSEIDON)," Experimental Astronomy, vol. 54, no. 2–3, pp. 911–973, Jan. 2022, doi: 10.1007/s10686-021-09815-8.
[36] J. Castillo-Rogez et al., "Concepts for the future exploration of dwarf planet Ceres' habitability," The Planetary Science Journal, vol. 3, no. 2, p. 41, Feb. 2022, doi: 10.3847/psj/ac34ee.
[37] National Aeronautics and Space Administration (NASA). "In depth | CERES – NASA Solar System Exploration," NASA Solar System Exploration. https://solarsystem.nasa.gov/planets/dwarf-planets/ceres/in-depth/
[38] C. Garraffo, J. J. Drake, and O. Cohen, "The Space Weather of Proxima Centauri B," The Astrophysical Journal, vol. 833, no. 1, p. L4, Nov. 2016, doi: 10.3847/2041-8205/833/1/l4.
[39] V. Meadows et al., "The Habitability of Proxima Centauri b: Environmental States and Observational Discriminants," Astrobiology, vol. 18, no. 2, pp. 133–189, Feb. 2018, doi: 10.1089/ast.2016.1589.
[40] H. Jones, "Power Management for Space Advanced Life Support " Power, vol. 1, p. 2527, 2002. [online] Available: https://ntrs.nasa.gov/citations/20040013168.
[41] Mason, Lee, and Michelle Rucker. "Common power and energy storage solutions to support lunar and Mars surface exploration missions." International Astronautical Congress (IAC). 2019. [online] Available: https://ntrs.nasa.gov/api/citations/20190032521/downloads/20190032521.pdf
[42] Z. Khan, A. Vranis, A. Zavoico, S. Freid, and B. Manners, "Power system concepts for the lunar outpost: A review of the power generation, energy storage, Power Management and Distribution (PMAD) system requirements and potential technologies for development of the lunar outpost," in AIP Conference Proceedings, 2006, vol. 813, no. 1, pp. 1083–1092.
[43] A. J. Colozza, "Small Lunar Base Camp and In Situ Resource Utilization Oxygen Production Facility Power System Comparison," techreport, 2020, [online] Available: https://ntrs.nasa.gov/citations/20200001622.
[44] D. V. Pombo, "A Hybrid Power System for a Permanent Colony on Mars," Space: Science & Technology, 2021.
[45] Lyons, Valerie J., et al. "Draft Space Power and Energy Storage Roadmap, Technology Area 03." NASA Office of the Chief Technologist (2010).
[46] L. Chebbo, et al. "Modeling and Operation of Microgrids for Deep Space Habitats Under Environmental Disturbances." 2023 IEEE Power and Energy Conference at Illinois (PECI). IEEE, 2023.
[47] A. D. Bintoudi, C. Timplalexis, G. Mendes, J. M. Guerrero, and C. Demoulias, ''Design of space microgrid for manned lunar base: Spinning-in terrestrial technologies,'' in Proc. Eur. Space Power Conf. (ESPC), Sep. 2019, pp. 1–8.
[48] S. P. Barave and B. H. Chowdhury, "Hybrid AC/DC Power Distribution Solution for Future Space Applications," 2007 IEEE Power Engineering Society General Meeting, Tampa, FL, USA, 2007, pp. 1-7, doi: 10.1109/PES.2007.385901.
[49] B. Ansley, S. T. Engler, and K. Binsted. "Mars habitat power consumption constraints, prioritization, and optimization." Journal of Space Safety Engineering 6.4 (2019): 256-264.
[50] D. Jose, et al. "An overview of power capability requirements for exploration missions." 1st Space Exploration Conference: Continuing the Voyage of Discovery. 2005.
[51] H. Jones, "Power Management for Space Advanced Life Support," Power, vol. 1, p. 2527, 2002. [online] Available: https://ntrs.nasa.gov/citations/20040013168.
[52] M. S. Anderson et al., "Life support baseline values and assumptions document," techreport, 2018. [online] Available: https://ntrs.nasa.gov/citations/20180001338.
[53] D. Saha et al., "Space Microgrids for Future Manned Lunar Bases: A Review," in IEEE Open Access Journal of Power and Energy, vol. 8, pp. 570-583, 2021, doi: 10.1109/OAJPE.2021.3116674
[54] B. Volz, "A day in space: Here's what an astronaut's daily routine looks like," WKMG, https://www.clickorlando.com/news/space-news/2020/11/14/a-day-in-space-heres-what-an-astronauts-daily-routine-looks-like/ (accessed Nov. 29, 2023).
[55] H. Benaroya, 'Lunar habitats: A brief overview of issues and concepts', REACH, vol. 7–8, pp. 14–33, 2017.
[56] P. S. Committee, 'Standard: Electrical Power Systems for Unmanned Spacecraft (AIAA S-122-2007)'. American Institute of Aeronautics and Astronautics, Inc., 2007.
[57] J. M. Raya-Armenta, N. Bazmohammadi, J. C. Vasquez, and J. M. Guerrero, "A short review of radiation-induced degradation of III–V photovoltaic cells for space applications," Solar Energy Materials and Solar Cells, vol. 233, p. 111379, Dec. 2021, doi: 10.1016/j.solmat.2021.111379.
[58] J. M. Hickman, H. Curtis, and G. A. Landis, "Design Considerations for Lunar Base Photovoltaic Power Systems," 21st Photovoltaic Specialists Conference, NASA Technical Memorandum 103642, May 1990, [Online]. Available: https://ntrs.nasa.gov/api/citations/19910004946/downloads/19910004946.pdf
[59] R. Verduci et al., "Solar Energy in Space Applications: Review and Technology Perspectives," Advanced Energy Materials, vol. 12, no. 29, p. 2200125, Jun. 2022, doi: 10.1002/aenm.202200125.
[60] M. Yamaguchi, T. Takamoto, K. Araki, and N. J. Ekins-Daukes, "Multi-junction III–V solar cells: current status and future potential," Solar Energy, vol. 79, no. 1, pp. 78–85, Jul. 2005, doi: 10.1016/j.solener.2004.09.018.
[61] X. Zhao et al., "Degradation characteristics of electron and proton irradiated InGaAsP/InGaAs dual junction solar cell," Solar Energy Materials and Solar Cells, vol. 206, p. 110339, Mar. 2020, doi: 10.1016/j.solmat.2019.110339.
[62] M. Yamaguchi, F. Dimroth, J. F. Geisz, and N. J. Ekins-Daukes, "Multi-junction solar cells paving the way for super high-efficiency," Journal of Applied Physics, vol. 129, no. 24, Jun. 2021, doi: 10.1063/5.0048653.
[63] D. W. Cardwell et al., "Very High Specific Power ELO Solar Cells (>3 kW/kg) for UAV, Space, and Portable Power Applications," 2017 IEEE 44th Photovoltaic Specialist Conference (PVSC), Jun. 2017, doi: 10.1109/pvsc.2017.8366552.
[64] T. Mintz et al., ''Simulation of a lunar surface base power distribution network for the constellation lunar surface systems,'' Glenn Res. Center, Cleveland, OH, USA, Tech. Rep. NASA/TM-2010-216084, 2010.
[65] A. J. Colozza, J. Appelbaum, and M. Crutchik, "A photovoltaic catenary-tent array for the Martian surface," STIN, vol. 93, p. 26703, May 1993, [Online]. Available: https://ntrs.nasa.gov/api/citations/19930017514/downloads/19930017514.pdf
[66] A. J. Colozza, ''Power system mass analysis for hydrogen reduction oxygen production on the lunar surface,'' NASA, Washington, DC, USA, Tech. Rep. NASA/CR-2009-21550, 2009.

[67] A. D. Bintoudi, C. Timplalexis, G. Mendes, J. M. Guerrero, and C. S. Demoulias, “Design of Space Microgrid for Manned Lunar Base: 'Spinning-in Terrestrial Technologies,” 2019 European Space Power Conference (ESPC), Sep. 2019, doi: 10.1109/espc.2019.8932024.

[68] S. Potter, “Three companies to help NASA advance solar array technology for Moon,” NASA, Aug. 2022, [Online] Available: https://www.nasa.gov/press-release/three-companies-to-help-nasa-advance-solar-array-technology-for-moon

[69] D. A. Scheiman and D. B. Snyder, ‘Low intensity low temperature (LILT) measurements of state-of-the-art triple junction solar cells for space missions’, in 2008 33rd IEEE Photovoltaic Specialists Conference, 2008, pp. 1–6.

[70] A. Bermudez-Garcia, P. Voarino, and O. Raccurt, “Environments, needs and opportunities for future space photovoltaic power generation: A review,” Applied Energy, vol. 290, p. 116757, May 2021, doi: 10.1016/j.apenergy.2021.116757.

[71] A. M. Baker, “Future power system for space exploration: Executive Summary,” European Space Agency (ESA), Feb. 2002. https://nebula.esa.int/sites/default/files/neb_study/435/C14565ExS.pdf

[72] S. D. Fraser "Power system options for mars surface exploration: Past, present and future." Mars: Prospective Energy and Material Resources (2009): 1-23.

[73] L. M. Holmes, A. M. Calomino “NASA Utilization of Space Nuclear Systems for Robotic and Human Exploration Missions Response”, 2022. [online] Available: https://www.nasa.gov/sites/default/files/atoms/files/50777_nasa_eo_13972_report_rev_11b_final1_tagged.pdf

[74] R. V. Bugga and E. J. Brandon, “Energy storage for the next generation of robotic space exploration,” The Electrochemical Society Interface, vol. 29, no. 1, pp. 59–63, Mar. 2020, doi: 10.1149/2.f08201if.

[75] P. A. Iles, “Evolution of space solar cells,” Solar Energy Materials and Solar Cells, vol. 68, no. 1, pp. 1–13, Apr. 2001, doi: 10.1016/s0927-0248(00)00341-x.

[76] N. V. Latukhina, A. Rogozin, G. V. Puzyrnaya, D. A. Lizunkova, A. C. Гуртов, and S. Ivkov, “Efficient silicon solar cells for space and Ground-Based aircraft,” Procedia Engineering, vol. 104, pp. 157–161, Jan. 2015, doi: 10.1016/j.proeng.2015.04.107.

[77] M. Yamaguchi, “Radiation-resistant solar cells for space use,” Solar Energy Materials and Solar Cells, vol. 68, no. 1, pp. 31–53, Apr. 2001, doi: 10.1016/s0927-0248(00)00344-5.

[78] B. Anspaugh, “GaAs Solar Cell Radiation Handbook,” 1996. Accessed: Aug. 13, 2023. [Online]. Available: https://ntrs.nasa.gov/api/citations/19970037642/downloads/19970037642.pdf

[79] M. Yamaguchi, Y. Ohmachi, T. Oh’hara, Y. Kadota, M. Imaizumi, and S. Matsuda, “GaAs solar cells grown on Si substrates for space use,” Progress in Photovoltaics, vol. 9, no. 3, pp. 191–201, Jan. 2001, doi: 10.1002/pip.366.

[80] N. Papež, R. Dallaev, Ş. Ţălu, and J. Kastyl, “Overview of the current state of gallium Arsenide-Based solar cells,” Materials, vol. 14, no. 11, p. 3075, Jun. 2021, doi: 10.3390/ma14113075.

[81] J. Schön et al., “Improvements in ultra-light and flexible epitaxial lift-off GaInP/GaAs/GaInAs solar cells for space applications,” Progress in Photovoltaics, vol. 30, no. 8, pp. 1003–1011, Feb. 2022, doi: 10.1002/pip.3542.

[82] S. Pandey, “Ge/GaAs/InGaP Triple-Junction Solar Cells for Space Exploration.” [online] Available: https://443.ece.illinois.edu/files/2019/05/SolarCellReportPandeyWaterMarked.pdf

[83] J. Li et al., “A brief review of High efficiency III-V solar cells for space application,” Frontiers in Physics, vol. 8, Feb. 2021, doi: 10.3389/fphy.2020.631925.

[84] J. Yang, Q. Bao, L. Shen, and L. Ding, “Potential applications for perovskite solar cells in space,” Nano Energy, vol. 76, p. 105019, Oct. 2020, doi: 10.1016/j.nanoen.2020.105019.

[85] Y. Tu et al., “Perovskite solar cells for space applications: progress and challenges,” Advanced Materials, vol. 33, no. 21, p. 2006545, Apr. 2021, doi: 10.1002/adma.202006545.

[86] A. Sinha et al., ‘UV-induced degradation of high-efficiency solar cells with different architectures’, in 2020 47th IEEE Photovoltaic Specialists Conference (PVSC), 2020, pp. 1990–1991.

[87] J. R. Wertz, D. F. Everett, and J. J. Puschell, ‘Space mission engineering: the new SMAD’, 2011.

[88] World Nuclear Association. “Nuclear reactors for space,” 2021. [Online] Available: https://world-nuclear.org/information-library/non-power-nuclear-applications/transport/nuclear-reactors-for-space.aspx

[89] National Aeronautics and Space Administration (NASA). “Technology – NASA RPS: Radioisotope Power Systems,” NASA RPS: Radioisotope Power Systems. [Online] Available: https://rps.nasa.gov/technology/

[90] National Aeronautics and Space Administration (NASA). “What is Plutonium-238? – NASA RPS: Radioisotope Power Systems,” NASA RPS: Radioisotope Power Systems. [Online] Available: https://rps.nasa.gov/resources/60/what-is-plutonium-238/

[91] G. R. Schmidt, T. J. Sutliff, and L. A. Dudzinksi, ‘Radioisotope power: A key technology for deep space exploration’, Radioisotopes--Applications in Physical Sciences, pp. 419–456, 2011.

[92] J. S. Dustin and R. A. Borrelli, “Assessment of alternative radionuclides for use in a radioisotope thermoelectric generator,” Nuclear Engineering and Design, vol. 385. Elsevier BV, p. 111475, Dec. 2021. doi: 10.1016/j.nucengdes.2021.111475.

[93] Bennett, G. L., Hemler, R. J., and Schock, A., “Space Nuclear Power: An Overview,” J. Prop. & Power, Vol. 12, No. 5, 1996.

[94] Mason, L. S., “A Comparison of Energy Conversion Technologies for Space Nuclear Power Systems,” In Proc. of AIAA Propulsion and Energy Forum, 2018.

[95] D. T. Palac, L. Mason, M. G. Houts, and S. Harlow, “Fission Surface Power Technology Development Update,” AIAA SPACE 2010 Conference & Exposition, Aug. 2010, doi: 10.2514/6.2010-8711.

[96] M. S. El-Genk, ‘Deployment history and design considerations for space reactor power systems’, Acta Astronautica, vol. 64, no. 9, pp. 833–849, 2009.

[97] R. Frisbee and N. Hoffman, ‘SP-100 nuclear electric propulsion for Mars cargo missions’, in 29th Joint Propulsion Conference and Exhibit, 1993, p. 2092.

[98] National Aeronautics and Space Administration (NASA). System concepts for affordable fission surface power, https://ntrs.nasa.gov/api/citations/20080013229/downloads/20080013229.pdf (accessed Nov. 29, 2023).

[99] M. Gibson, D. Poston, P. Mcclure, T. Godfroy, M. Briggs, and J. Sanzi, “Kilopower Reactor Using Stirling Technology (KRUSTY) Nuclear Ground Test Results and Lessons Learned,” 2018. Available: https://ntrs.nasa.gov/api/citations/20180007389/downloads/20180007389.pdf

[100] L. Carlson, J. Miller, and Z. Wu, “Implications of HALEU fuel on the design of SMRs and micro-reactors,” Nuclear Engineering and Design, vol. 389. Elsevier BV, p. 111648, Apr. 2022. doi: 10.1016/j.nucengdes.2022.111648.

[101] A. Peakman and B. Lindley, ‘A review of nuclear electric fission space reactor technologies for achieving high-power output and operating with HALEU fuel’, Progress in Nuclear Energy, vol. 163, p. 104815, 2023.

[102] L. Kaldon, “Fission Surface Power Project Overview,” https://ntrs.nasa.gov, Jan. 29, 2024. https://ntrs.nasa.gov/api/citations/20240001002/downloads/FSP%20Overview%20UKSA%2029%20Jan%2024%20FINALv2.pdf

[103] National Aeronautics and Space Administration (NASA). “NASA announces Artemis Concept Awards for Nuclear Power on moon,” NASA, https://www.nasa.gov/news-release/nasa-announces-artemis-concept-awards-for-nuclear-power-on-moon/ (accessed Nov. 29, 2023).

[104] “DARPA Kicks Off Design, Fabrication for DRACO Experimental NTR Vehicle,” DARPA RSS, https://www.darpa.mil/news-events/2023-07-26 (accessed Jul. 26, 2023).

[105] L. S. Mason, H. S. Bloomfield, and D. C. Hainley, “SP-100 power system conceptual design for lunar base applications,” Sixth Symposium on Space Nuclear Power Systems, Jan. 1989, [Online]. Available: https://ntrs.nasa.gov/api/citations/19900005714/downloads/19900005714.pdf

[106] T. Q. A. Nguyen, “Powering human settlements in space,” ACS Central Science, vol. 6, no. 4, pp. 450–452, Apr. 2020, doi: 10.1021/acscentsci.0c00382.

[107] Camp, A., Klein, A., McClure, P., McCallum, P., and Voss, S., “Potential Improvements to the Nuclear Safety and Launch Approval Process for Nuclear Reactors Utilized for Space Power and Propulsion Applications: A Report to the Nuclear Power and Propulsion Technical Discipline Team,” NASA/TM-2019-220256 (2019). https://ntrs.nasa.gov/api/citations/20190001430/downloads/20190001430.pdf

[108] Energy Efficiency and Renewable Energy, “Fuel cells,” Energy.gov, https://www.energy.gov/eere/fuelcells/fuel-cells (accessed Nov. 29, 2023).

[109] K. A. Burke, “Fuel cells for space science applications,” 1st International Energy Conversion Engineering Conference (IECEC), Jun. 2003, doi: 10.2514/6.2003-5938.

[110] Energy efficiency & Renewable Energy, “FUEL CELL TECHNOLOGIES ,” www.energy.gov, https://www.energy.gov/eere/fuelcells/articles/us-department-energy-hydrogen-and-fuel-cell-technologies-office-overview (accessed Nov. 29, 2023).

[111] M. C. Guzik, I. Jakupca, R. P. Gilligan, W. R. Bennett, P. J. Smith, and J. Fincannon, “Regenerative Fuel Cell Power Systems for Lunar and Martian Surface Exploration,” American Institute of Aeronautics and Astronautics, Sep. 2017, doi: 10.2514/6.2017-5368.K

[112] M. C. Guzik, R. P. Gilligan, P. J. Smith, and I. Jakupca, “Energy storage for lunar surface exploration,” 2018 AIAA SPACE and Astronautics Forum and Exposition, Sep. 2018, doi: 10.2514/6.2018-5106.

[113] M. Kaczmarzyk and M. Musiał, “Parametric study of a lunar base power systems,” Energies, vol. 14, no. 4, p. 1141, Feb. 2021, doi: 10.3390/en14041141.

[114] J. Owen, I. Shaikhislamov, H. Lammer, L. Fossati, and M. Khodachenko, “Hydrogen dominated atmospheres on terrestrial mass planets: evidence, origin and evolution,” Space Science Reviews, vol. 216, no. 8, pp. 1–24, 2020.

[115] J. Scott, “Envisioned Future Priorities for: ‘LIVE: Power and Energy Storage,’” 2023. Available: https://www.nasa.gov/wp-content/uploads/2023/06/live-power-and-energy-storage-update-8-april-tagged-1.pdf

[116] Tran, M-K, et al., “A Review of Lithium-Ion Thermal Runaway Modeling and Diagnosis Approaches,” Processes, Vol. 10, No. 1192 (2022).

[117] Anand, M. D., et al, “Lithium-Ion cells for space applications: Aspects of durability,” Advances in Space Research, Vol. 72, pp 2948-2958 (2023).

[118] C. Dupont, L. Littré, E. Claude, and F. Sassenage, ‘Regenerative Fuel Cell System for Space Exploration Applications’, 9th European Conference for Aeronautics and Space Sciences (EUCASS),2022.

[119] M. Perry and T. F. Fuller, “A historical perspective of fuel cell technology in the 20th century,” Journal of the Electrochemical Society, vol. 149, no. 7, p. S59, Jan. 2002, doi: 10.1149/1.1488651.

[120] Y. Sone, “Fuel cell development for space applications: fuel cell system in a closed environment,” Journal of Power Sources, vol. 137, no. 2, pp. 269–276, Oct. 2004, doi: 10.1016/j.jpowsour.2004.03.051.

[121] K. Kordesch et al., “Alkaline fuel cells applications,” Journal of Power Sources, vol. 86, no. 1–2, pp. 162–165, Mar. 2000, doi: 10.1016/s0378-7753(99)00429-2.

[122] E. Gietl Boeing, Houston, E. Gholdston Boeing, B. Manners, and R. Delventhal, “The Electric Power System of the International Space Station_A Platform for Power Technology Development,” 2000. Accessed: Aug. 14, 2023. [Online]. Available: https://ntrs.nasa.gov/api/citations/20000063506/downloads/20000063506.pdf

[123] J. Blosiu et al., Energy Storage Technologies for Future Planetary Science Missions Work Performed Under the Planetary Science Program Support Task, document JPL D-101146, Dec. 2017. [Online]. Available: https:// solarsystem.nasa.gov/resources/549/energy-storage-technologies-forfuture-planetary-science-missions/

[124] A. D. Pathak, S. Saha, V. K. Bharti, M. M. Gaikwad, and C. S. Sharma, “A review on battery technology for space application,” Journal of Energy Storage, vol. 61, p. 106792, May 2023, doi: https://doi.org/10.1016/j.est.2023.106792.

[125] G. Halpert, “The design and application of nickel—cadmium batteries in space,” Journal of Power Sources, vol. 15, no. 2–3, pp. 119–140, Jun. 1985, doi: 10.1016/0378-7753(85)80067-7.

[126] R. V. Bugga, M. C. Smart, J. Whitacre, and W. C. West, “Lithium Ion Batteries for Space Applications,” IEEE Aerospace Conference, Jan. 2007, doi: 10.1109/aero.2007.352728.

[127] Walker, W., et al. "Thermo-electrochemical evaluation of lithium-ion batteries for space applications." Journal of Power Sources, vol. 298, p. 217-227, 2015.

[128] S. M. A. S. Bukhari, J. Maqsood, M. Q. Baig, S. Ashraf, and T. A. Khan, “Comparison of Characteristics -- Lead Acid, Nickel Based, Lead Crystal and Lithium Based Batteries,” 2015 17th UKSim-AMSS International Conference on Modelling and Simulation (UKSim), Mar. 2015, doi: 10.1109/uksim.2015.69.

[129] A. K. Shukla, “Nickel-based rechargeable batteries,” Journal of Power Sources, vol. 100, no. 1–2, pp. 125–148, Nov. 2001, doi: 10.1016/s0378-7753(01)00890-4.

[130] C. R. Mercer, A. Jankovsky, C. M. Reid, T. B. Miller, and M. A. Hoberecht, “Energy Storage Technology Development for Space Exploration,” AIAA, Aug. 2010, doi: 10.2514/6.2010-8709.

[131] G. L. Thomas, M. Granger, and J. Csank, ‘Lunar Microgrid Trade Studies to Define Interface Converter Requirements’, in ASCEND 2023, 2023, p. 4784.

[132] National Aeronautics and Space Administration (NASA), “Energy Storage Technologies for Future Planetary Science Missions,” science.nasa.gov, https://science.nasa.gov/wp-content/uploads/2023/09/uap-independent-study-team-final-report.pdf (accessed Nov. 29, 2023).

[133] G. L. Kimnach and J. V. Soltis, “Power Management and Distribution Trades Studies for a Deep-Space Mission Scientific Spacecraft,” ntrs.nasa.gov, Jan. 01, 2004. https://ntrs.nasa.gov/citations/20040111432 (accessed Feb. 01, 2024).

[134] M. Elbuluk, A. Hammoud, and R. Patterson, "Power electronic components, circuits and systems for deep space missions." 2005 IEEE 36th Power Electronics Specialists Conference. IEEE, 2005.

[135] J. T. Csank et al., ‘‘A control framework for autonomous smart grids for space power applications,’’ in Proc. 70th Int. Astron. Congr. (IAC), 2019, pp. 1–6, Paper IAC-19,C3,4,3,x50434. [Online]. Available: https://iafastro.directory/iac/archive/browse/IAC-19/C3/4/50434/

[136] J. F. Soeder et al., ‘‘Overview of intelligent power controller development for human deep space exploration,’’ in Proc. 12th Int. Energy Convers. Eng. Conf., Jul. 2014, p. 3833.

[137] B. Walls, “Utility Aspects of Space Power: Load Management Versus Source Management,” NASA Technical Memorandum, vol. 108496, 1995, Accessed: Aug. 14, 2023. [Online]. Available: https://ntrs.nasa.gov/api/citations/19960001955/downloads/19960001955.pdf

[138] National Aeronautics and Space Administration (NASA). “2022 SOA Power Chapter,” Feb. 2023. [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/3._soa_power_2022.pdf

[139] V. Lyons, G. Gonzalez, M. Houts, C. Iannello, J. Scott, and S. Surampudi, “Space power and energy Storage roadmap Technology Area 03,” 2012. [Online]. Available: https://www.nasa.gov/pdf/501328main_TA03-ID_rev7_NRC_wTASR.pdf

[140] M. M. Finckenor and Kim K De Groh, "National Aeronautics and Space Administration Space Environmental Effects," 2015. [Online]. Available: https://www.nasa.gov/sites/default/files/files/NP-2015-03-015-JSC_Space_Environment-ISS-Mini-Book-2015-508.pdf

[141] F. S. Johnson, "Lunar atmosphere," Reviews of Geophysics, vol. 9, no. 3. American Geophysical Union (AGU), pp. 813–823, Aug. 1971. doi: 10.1029/rg009i003p00813.

[142] N. Divine and H. B. Garrett, 'Charged particle distributions in Jupiter's magnetosphere', Journal of Geophysical Research: Space Physics, vol. 88, no. A9, pp. 6889–6903, 1983.

[143] H. B. Garrett, 'The charging of spacecraft surfaces', Reviews of Geophysics, vol. 19, no. 4, pp. 577–616, 1981.

[144] T. Sharp, "What is the Temperature on the Moon?," Space.com, Oct. 27, 2017. [Online]. Available: https://www.space.com/18175-moon-temperature.html

[145] D. A. Crawford and P. H. Schultz, 'Electromagnetic properties of impact-generated plasma, vapor and debris', International Journal of Impact Engineering, vol. 23, no. 1, Part 1, pp. 169–180, 1999.

[146] G. Drolshagen, 'Impact effects from small size meteoroids and space debris', Advances in Space Research, vol. 41, no. 7, pp. 1123–1131, 2008.

[147] S. Close et al., 'Detection of electromagnetic pulses produced by hypervelocity micro particle impact plasmas', Physics of Plasmas, vol. 20, no. 9, 2013.

[148] N. Gruginskie et al., "Electron radiation–induced degradation of GaAs solar cells with different architectures," Progress in Photovoltaics, vol. 28, no. 4, pp. 266–278, Jan. 2020, doi: 10.1002/pip.3224.

[149] R. A. Stall, M. Schurman, C. M. Sulyma, A. Gerger, and E. Gaddy, "UV Degradation of Space Solar Cell Assemblies under High Temperature and Irradiance," IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC), Jun. 2018, doi: 10.1109/pvsc.2018.8547643.

[150] D. Jordan and S. Kurtz, "Photovoltaic Degradation Rates-An Analytical Review," Progress in Photovoltaics, vol. 21, no. 1, pp. 12–29, Oct. 2011, doi: 10.1002/pip.1182.

[151] A. M. Delleur and T. W. Kerslake, "Electrical Performance from Bifacial Illumination International Space Station Photovoltaic Array," Journal of Spacecraft and Rockets, vol. 42, no. 1, pp. 171–176, Jan. 2005, doi: https://doi.org/10.2514/1.5660.

[152] B. Phillips, T. Schneider, J. Vaughn, and K. Wright, "Space Environment Testing of Photovoltaic Array Systems at NASA's Marshall Space Flight Center." Accessed: Aug. 14, 2023. [Online]. Available: https://ntrs.nasa.gov/api/citations/20150022334/downloads/20150022334.pdf

[153] S. Ma et al., "Temperature effect and thermal impact in lithium-ion batteries: A review," Progress in Natural Science: Materials International, vol. 28, no. 6, pp. 653–666, Dec. 2018, doi: 10.1016/j.pnsc.2018.11.002.

[154] H. C. Shiao, D. L. Chua, H.-P. Lin, S. Slane, and M. Salomon, "Low temperature electrolytes for Li-ion PVDF cells," Journal of Power Sources, vol. 87, no. 1–2, pp. 167–173, Apr. 2000, doi: 10.1016/s0378-7753(99)00470-x.

[155] S. S. Zhang, K. Xu, and T. R. Jow, "Low temperature performance of graphite electrode in Li-ion cells," Electrochimica Acta, vol. 48, no. 3, pp. 241–246, Dec. 2002, doi: 10.1016/s0013-4686(02)00620-5.

[156] X. Han et al., "A review on the key issues of the lithium ion battery degradation among the whole life cycle," eTransportation, vol. 1, p. 100005, Aug. 2019, doi: 10.1016/j.etran.2019.100005.

[157] B. Liu et al., "Safety issues and mechanisms of lithium-ion battery cell upon mechanical abusive loading: A review," Energy Storage Materials, vol. 24, pp. 85–112, Jan. 2020, doi: 10.1016/j.ensm.2019.06.036.

[158] W.-D. Du and S. Chen, "Effect of mechanical vibration on phase change material based thermal management module of a lithium-ion battery at high ambient temperature," Journal of Energy Storage, vol. 59, p. 106465, Mar. 2023, doi: 10.1016/j.est.2022.106465.

[159] J. Biswas, P. Q. Malzone, and F. Rößler, "Energy storage selection and operation for night-time survival of small lunar surface systems," Acta Astronautica, vol. 185, pp. 308–318, Aug. 2021, doi: 10.1016/j.actaastro.2021.04.042.

[160] F. de Winter, G. Stapfer, and E. Medina, "The Design of a Nuclear Power Supply with a 50 Year Life Expectancy: The JPL Voyager's SiGe MHW RTG," SAE Technical Paper Series. SAE International, Aug. 02, 1999. doi: 10.4271/1999-01-2586.

[161] J. Gaier, "The Effects of Lunar Dust on EVA Systems During the Apollo Missions," 2007. Available: https://ntrs.nasa.gov/api/citations/20070021819/downloads/20070021819.pdf

[162] M. Wittal, S. Miaule, M. Nacif, A. Swanger, and J. Mantovani, "RTG Radiator Efficiency in the Presence of Lunar Dust." Available: https://ntrs.nasa.gov/api/citations/20220005147/downloads/Earth_and_Space_2022___RTG_Radiator_Efficiency_in_the_Presence_of_Lunar_Dust_conference.pdf

[163] Siamidis, J., "Heat Rejection Concepts for Lunar Fission Surface Power Applications", In Proc. of 4th International Energy Conversion Engineering Conference and Exhibit (IECEC) pp.4196, 2006.

[164] X. Shi and A. M. Bazzi, "Fault tree reliability analysis of a micro-grid using Monte Carlo simulations," 2015 IEEE Power and Energy Conference at Illinois (PECI), Champaign, IL, USA, 2015, pp. 1-5, doi: 10.1109/PECI.2015.7064928.

[165] X. Shi and A. M. Bazzi, "Reliability modeling and analysis of a micro-grid with significant clean energy penetration," 2015 9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia), Seoul, Korea (South), 2015, pp. 202-207, doi: 10.1109/ICPE.2015.7167787.

[166] L. Chebbo and A. Bazzi, "Reliability Modeling and Analysis of DC Space Microgrids," 2023 IEEE Fifth International Conference on DC Microgrids (ICDCM), Auckland, New Zealand, 2023, pp. 1-6, doi: 10.1109/ICDCM54452.2023.10433614.

[167] S. Sen and V. Kumar, ''Microgrid control: A comprehensive survey,'' Annu. Rev. Control, vol. 45, pp. 118–151, Jan. 2018.

[168] U. B. Tayab, M. A. H. Roslan, L. J. Hwai, and M. Kashif, "A review of droop control techniques for microgrid," Renewable & Sustainable Energy Reviews, vol. 76, pp. 717–727, Sep. 2017, doi: 10.1016/j.rser.2017.03.028.

[169] D. Saha, N. Bazmohammadi, J. C. Vasquez, and J. M. Guerrero, "Multiple Microgrids: A review of architectures and operation and control strategies," Energies, vol. 16, no. 2, p. 600, Jan. 2023, doi: 10.3390/en16020600.

[170] H. Jones, "Estimating the Life Cycle Cost of Space Systems," 2015. Available: https://ntrs.nasa.gov/api/citations/20160001190/downloads/20160001190.pdf

[171] National Aeronautics and Space Administration (NASA), "Cost Estimating Module: Space Systems Engineering, version 1.0," https://ntrs.nasa.gov. https://s3vi.ndc.nasa.gov/ssri-kb/static/resources/18.%20Cost_Module_V1.0.pdf

[172] N. Adilov, P. Alexander, B. Cunningham, and N. Albertson, "An analysis of launch cost reductions for low Earth orbit satellites." Available: https://www.accessecon.com/Pubs/EB/2022/Volume42/EB-22-V42-I3-P130.pdf

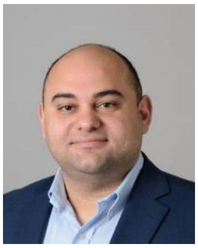
[173] R. Suich, L. Richard, and Patterson, "Balancing Reliability and Cost to Choose the Best Power SUbsystem." Accessed: Nov. 05, 2024. [Online]. Available: https://ntrs.nasa.gov/api/citations/19910015638/downloads/19910015638.pdf

[174] M. Ewert, T. Chen, and C. Powell, "Life Support Baseline Values and Assumptions Document," 2022. Available: https://ntrs.nasa.gov/api/citations/20210024855/downloads/BVAD_2.15.22-final.pdf

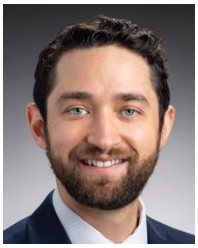
[175] GE Aerospace, Available: https://www.geaerospace.com/sites/default/files/15kW-Silicon-Carbide-Bidirectional-Converter.pdf

Leila Chebbo (Graduate Student Member, IEEE) received the B.E. in Electric Power and Machines from Beirut Arab University, Beirut, Lebanon, in 2017. In 2020, she received the M.Sc degree in Energy Studies and M.E. degree in Engineering Management from the American University of Beirut, Beirut, Lebanon. She is currently pursuing the Ph.D. degree in Electrical Engineering with the University of Connecticut, Storrs, CT, USA. Since 2022, she has been part of the Resilient Extraterrestrial Habitat institute (RETHi), where she worked on the development of the power system of the Space Habitat Simulator. She was a Power Systems intern with Dominion Energy during Summer 2023. Her research interests include power system modeling, operation, optimization, and resiliency.

Muhammed Ali Gultekin (Graduate student Member, IEEE) received the B.Sc. degree in control and automation engineering and the M.Sc. degree in electrical engineering from Istanbul Technical University, Istanbul, Turkey, in 2016 and 2020, respectively. He is currently working toward his Ph.D. degree in electrical engineering with the University of Connecticut, Storrs, CT, USA. He was a Power Electronics Intern with IMCORP during the summer of 2022. His research interests include modeling and control of electric machines and drives, condition monitoring and fault tolerant operation of power electronic systems.



Ali Bazzi (Senior Member, IEEE) received the B.E. and M.E. degrees in electrical engineering from the American University of Beirut, Beirut, Lebanon, in 2006 and 2007, respectively, and the Ph.D. degree from the University of Illinois at Urbana-Champaign (UIUC), Urbana, IL, USA, in 2010. He is currently an Associate Professor of electrical and computer engineering with the University of Connecticut (UConn), Storrs, CT, USA. In 2012, he was an Assistant Professor with UConn, where he established and currently directs the Power Electronics and Drives Advanced Research Laboratory. He was also an Associate Professor with the American University of Beirut, during 2018–2020, a Senior Power Electronics Electrical Engineer with Delphi Electronics and Safety during 2011–2012, a Visiting Assistant Professor with UIUC during spring 2011, an Engineer with Bitrode Corporation in the summers of 2008 and 2009, and a Research and Teaching Assistant with UIUC between 2007 and 2010. He has more than 120 peer-reviewed and refereed technical publications and 10 U.S. patents. His research interests include power electronics design, control, optimization, fault diagnosis, and reliability modeling in motor drives, solar photovoltaics, microgrids, and other applications. Dr. Bazzi was on the organizing and technical committees of many IEEE conferences. He was the recipient of the NSF CAREER Award in 2018, Mavis Memorial Scholarship at UIUC in 2009, Outstanding Teaching Award from the ECE Department at UConn in 2014, Outstanding Research Award from the ECE Department at UConn in 2023, and Research Excellence Award at UConn in 2015 and 2018. From 2016 to 2021, the UTC Professorship for Engineering Innovation at UConn, and in 2022, he became thank the Charles H. Knapp Associate Professor of electrical engineering with UConn. In 2021, he was the General Chair of the IEEE International Electric Machines and Drives Conference.



Sean A. Q. Young received the B.S. degrees in aerospace engineering and physics from The University of Texas at Austin, Austin, TX, USA, and the Ph.D. degree from the Department of Aeronautics and Astronautics, Stanford University, Stanford, CA, USA, in 2021. He was a member of the Space Environment and Satellite Systems Laboratory, Stanford University. His graduate research was funded by a NASA Space Technology Research Fellowship and concerned the interaction of the space environment with spacecraft and methods for using those interactions to power electronics. Sean is currently a member of the Senior Professional Staff at Johns Hopkins University Applied Physics Laboratory where he continues work on the space environment, space weather, and is an active member in the Surface Power Focus Group of the Lunar Surface Innovation Initiative.

Joseph P. Kozak (Member, IEEE) received the B.S. and M.S degrees in Engineering Physics and Electrical Engineering from the University of Pittsburgh, and the Ph.D degree in Electrical Engineering from the Center for Power Electronic Systems (CPES) at Virginia Tech. Since 2021, he has been a senior electrical engineer at the Johns Hopkins University - Applied Physics Lab, and is currently serving as the Chief Technologist for the Spacecraft Power Engineering group. His research interests include robustness, reliability, and physics of failure of wide bandgap semiconductors, and their packaging and implementation into high-reliability, power electronic converters and systems.