# Space Microgrids for Future Manned Lunar Bases: A Review

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*Published in:*
IEEE Open Access Journal of Power and Energy

*DOI (link to publication from Publisher):*
10.1109/OAJPE.2021.3116674

*Publication date:*
2021

*Document Version*
Accepted author manuscript, peer reviewed version

# Space Microgrids for Future Manned Lunar Bases: A Review

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***Abstract*—Several space organizations have been planning to establish a permanent, manned base on the Moon in recent years. Such an installation demands a highly reliable electrical power system (EPS) to supply life support systems and scientific equipment and operate autonomously in a fully self-sufficient manner. This paper explores various technologies available for power generation, storage, and distribution for space microgrids on the Moon. Several factors affecting the cost and mass of the space missions are introduced and analysed to provide a comprehensive comparison among the available solutions. Besides, given the effect of base location on the design of a lunar electrical power system and the mission cost, various lunar sites are introduced and discussed. Finally, the control system requirements for the reliable and autonomous operation of space microgrids on the Moon are presented. The study is complemented by discussing promising future technological solutions that could be applied upon a lunar microgrid.**

***Index Terms*—Space microgrids, lunar power system state-of-the-art, solar power in space, lunar manned base, space exploration**

## I. Introduction

In recent years, several space organisations such as National Aeronautics and Space Administration (NASA), Japan Aerospace Exploration Agency (JAXA), China National Space Administration (CNSA) have planned to establish humans on the lunar surface from 2024 [1], 2030 [2], [3], and 2036 [4], respectively. Other space organisations show similar interests in building a lunar base [5], [6] and using the Moon for solar driven heavy industries [7]. This growing interest necessitates human establishments in these planets such as lunar habitats, scientific laboratories, resource utilisation plants, rovers, and vehicles.

The construction of a lunar base is based on several factors such as the lunar terrain, temperature range, and availability of water, power, and energy. Various space robotic missions in the form of orbiters or rovers are already taking place to identify the aforementioned factors. Following the International Space Station (ISS) paradigm, the manned lunar base deployment and subsequent expansions will be implemented in several phases [8] as shown in Table I. At present, various robotic missions are being carried out, denoting execution of *"Phase 0"*. Several space organizations are planning to deploy humans on the Moon in *"Phase 1"* starting from 2024 [1]–[4] and their presence is to be gradually expanded with more crew members and longer stay in *"Phase 2"*. Starting from *"Phase 3"*, the lunar establishment is planned to be self-sufficient for operation and in *"Phase 4"* a reliable and autonomous system will be operational, enabling safe, permanent human presence upon the Moon [8].

TABLE I: Phases of deployment of humans on the Moon

| Phase | Operation | Human presence | Stay period |
|---|---|---|---|
| 0 | Robotic site preparation | Minimum or not present | No stay |
| 1 | Human deployment initiation | 3 to 4 personnel | 4 to 6 months |
| 2 | Expansion | 10 personnel (approx.) | 1 year |
| 3 | Self-sufficiency | 10 to 100 personnel | Extended periods |
| 4 | Science and commercialization | More than 100 personnel | Unlimited duration |

Lunar electrical power systems (LEPSs) have several important aspects that fall into different categories, namely, power generation, transmission, distribution, storage, and power consumption, as well as power control and energy management systems. Although there are several power generation sources such as nuclear fission-based reactor [9], and electrostatic charge from lunar regolith [10], the Moon's atmosphere-less environment makes it favourable for the sun's energy to reach the surface without any hindrance. To support the base during the lunar night or eclipse periods, energy storage systems (ESSs) must be deployed. On the other hand, there are different types of electrical loads in a lunar habitat such as life support systems (LSSs), communication systems, laboratories and scientific establishments, exploration vehicles, and rovers along with their charging systems. Besides, for extended periods of stay, it is desirable to produce the required resources locally which results in increasing the energy demand [9]. Considering the complexity of the control task to coordinate different generation and consumption units and the challenges of human intervention especially under adverse operating conditions, having an autonomous and reliable control system is of vital importance. Moreover, the control system should guarantee the safe operation of the system and maintain the system efficiency by optimal resource utilization. A LEPS is a group of interconnected loads, local distributed energy resources and

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Manuscript received 27 May 2021; Revised 29 August 2021; Accepted 25 September 2021

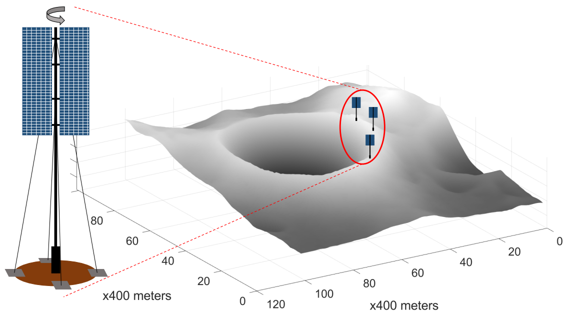


Fig. 1: Installing solar panels on towers on the rim of craters

ESS and can be defined as space microgrid on the Moon. Given the similarities between the space microgrids on the Moon and terrestrial renewable energy source (RES)-based isolated microgrids (IMGs), the solutions devised for terrestrial IMGs are applicable to space microgrids on the Moon and vice versa [11]. In the following sections, the term microgrids (MGs) or space MGs refers to space MGs on the Moon.

This paper provides a visionary study and state-of-the-art of the space MGs on the Moon, its technologies, requirements, and characteristics. Establishing a lunar base involves many sophisticated and costly space missions to transport different essential equipment to the Moon at the initial stage. Therefore, a comprehensive and extensive planning is essential. Various available technologies and different factors affecting the construction of the electrical power system (EPS) for a lunar base are discussed in this paper. The most apparent aspect is the location of the base and its relation to the MGs' equipment size, mass, and cost. The choices of power generation, distribution, and storage technologies are not only related to the mass, size, and cost of the space missions but also to the environmental, construction, and control complexity-related issues. Besides, the reliability and autonomy of the control system to maintain system performance under different normal and abnormal operating conditions is an essential requirement of space MGs that will be discussed in this paper.

The rest of this paper is organized as follows. The site selection for space MGs on the Moon is discussed in Section II. Section III is dedicated to different power generation technologies for a lunar base and their advantages and disadvantages. Different power-consuming units in a lunar base are discussed in Section IV. The promising types of ESSs along with a comparative analysis of their desired technical specifications are presented in Section V. Subsequently, various suitable MG design technologies are presented in Section VI. The control framework for the space MGs on the Moon and its requirements are discussed in Section VII. Finally, future trends in space MGs are highlighted in Section VIII. The paper is concluded in Section IX.

## II. Site Selection for Space MGs on the Moon

Establishing a human base on the lunar surface is dependent on various factors such as the solar irradiance profile, duration and frequency of the lunar night, partial and total eclipses, availability of water, site topography, and the possibility of establishing good communication with Earth. The amount of solar irradiance, the illumination-darkness period, and the temperature profile are among the main conditions that affect the power and energy production from photovoltaic (PV) cells. Besides, the PV cells might be severely damaged in the extremely hostile environment of the space, resulting in premature degradation, thereby performance deterioration. Thus, the ESS that is needed to support the loads over the eclipses should be sized regarding the power and energy produced by the PV arrays and their degradation state.

TABLE II: Some highly illuminated lunar polar regions

| North Pole | | | South Pole | | |
|---|---|---|---|---|---|
| **Long.** | **Lat.** | **Average illumination (%)** | **Long.** | **Lat.** | **Average illumination (%)** |
| 326.44 | 89.65 | 72.60 | 222.84 | −89.45 | 76.00 |
| 110.38 | 89.85 | 78.10 | 203.97 | −89.78 | 81.00 |
| 126.80 | 89.37 | 84.60 | 245.94 | −89.31 | 75.60 |
| 130.56 | 89.35 | 84.01 | 204.27 | −89.78 | 86.71 |
| 127.94 | 89.36 | 83.87 | 123.64 | −88.81 | 85.50 |
| 128.94 | 89.36 | 82.02 | 197.05 | −89.69 | 85.24 |
| 242.24 | 88.06 | 86.08 | 198.43 | −89.69 | 84.44 |
| 232.04 | 87.31 | 81.55 | 205.14 | −89.79 | 82.37 |
| 7.22 | 87.20 | 82.16 | 123.95 | −88.80 | 82.37 |
| 8.11 | 87.00 | 79.53 | 37.07 | −85.30 | 85.95 |
| 7.78 | 87.05 | 77.87 | 37.57 | −85.55 | 82.34 |
| 8.07 | 86.99 | 76.51 | 243.22 | −85.73 | 79.54 |
| 7.02 | 87.12 | 76.94 | 356.80 | −85.96 | 80.61 |

**Illumination:** Given the proportional relation between the mass or volume budgets and the overall mission cost, a location with more illumination and less continuous darkness period is desired, to reduce the mass and size of the ESS, thereby the space mission cost. The data collected by several missions such as *Lunar Reconnaissance Orbiter (LRO)* and *Clementine* by NASA and *Kaguya* by JAXA have helped to map the illumination conditions on various locations of the Moon. In 1994, the *Clementine* mission identified continuously illuminated locations on the rim of the "*Peary crater*" near the Moon's North Pole [9]. Besides, the *Kaguya* mission identified a location on the rim of the "*Shackleton crater*" near the Moon's South Pole having 86% of the annual average solar irradiance and the longest eclipse of 11.5 Earth days [11]. Similarly, few locations near the Shackleton crater have been identified to have approximately six months of uninterrupted sunlight and six months of frequent changes between illumination and darkness [12] while continuous eclipse times varying from 71 to 120 hours [12], [13]. A location with a more frequent illumination-darkness cycle is preferable as ESSs can be recharged fast over the short illumination time, thereby lowering the needed ESS size [13]. On the other hand, at the non-polar regions, the lunar surface is continuously illuminated for about 15 days followed by a continuous darkness period of about 15 days [14]. Hence, polar regions are attractive for establishing a lunar base with less ESS requirements [8]. The candidate locations with high illumination are discussed in [15]–[17]. Some of the locations with a high average illumination (calculated over a period of 74 years [15], 20 years [16] and 1 year [17]) are listed in Table II.

Researchers have also identified a few locations where the ESS size can be reduced by installing solar panels on towers (see Fig. 1), and can eventually be completely removed by increasing the tower's height [13], [19]. It is theoretically

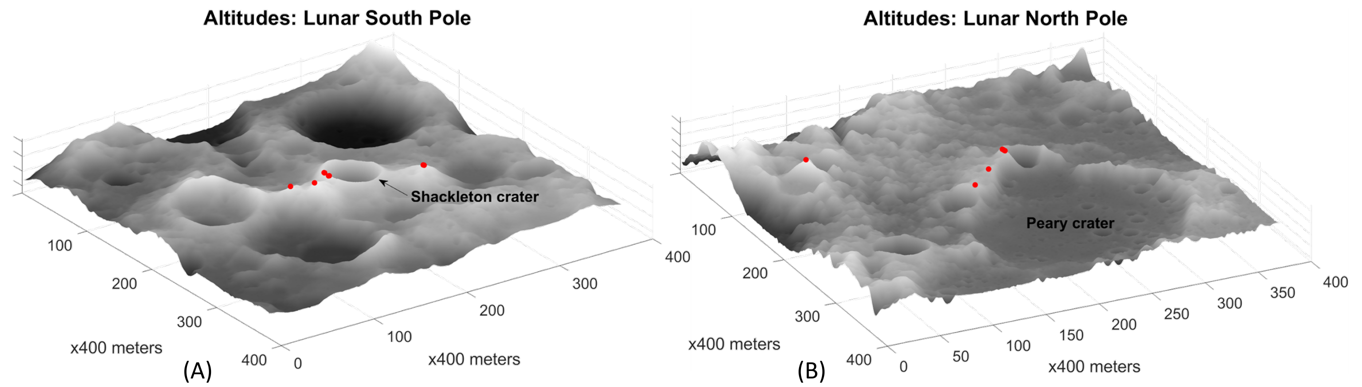


Fig. 2: Stereographic projection of lunar poles topography from latitude $\mp$87.5 to $\mp$90. (A) Lunar south pole. (B) Lunar north pole. Database recovered from [18]. Red dots indicate some of the highly illuminated areas provided in Table II [15]–[17].

calculated that installing a 100m-tower at a suitable location near the lunar North Pole reduces the ESS size by 4%. The ESS operation duration can be further reduced by 0.2hr/m with increasing the tower's height up to 300m. A 1500m-tower near the lunar North Pole may eliminate the ESS requirement. A different scenario exists near the lunar South Pole, requiring a 3000m-tower to eliminate the need for ESSs [13]. However, practically constructing such high towers may have its own challenges in terms of mass and construction.

While a location with high illumination is desirable, at the same time, the lunar base design should also ensure a site with the lowest meteoroid flux. To this day, the available data collected by spacecrafts and radars are limited, however, they can still contribute towards estimating the probability of occurrence of meteoroid collisions [20], [21]. The probability of meteoroid fluxes at low latitudes (0°–30°) are higher by 10% compared to high latitude (60°–90°). Therefore, polar regions are characterized by both high illumination periods and lower meteoroid impacts [22]. As discussed in [20], although all catastrophic phenomena cannot be totally defended, there are solutions such as appropriate shielding, buried, and distributed structures that can increase the resiliency of the design. A discussion of shielding approaches for lunar habitats intended for protection against meteoroid impacts using the Moon resources can be found in [23].

**Topography:** Even though the Moon's polar regions are more attractive for a future space base than regions of lower latitudes, the lunar poles represent a big challenge for the dynamical estimation of the power availability of PV cells. The reason lies in the Sun elevation, which is permanently around the horizon in latitudes near the poles. Therefore, the knowledge of topography 210 km[1] around the base site is of paramount importance. High terrain elevations can produce very long shadows in the range of kilometers, which can potentially cover the base site fully or partially. This might happen even with small soil elevations near the base site. In this respect, the digital elevation models (DEMs), provided by the *Lunar Orbiter Laser Altimeter (LOLA)* experiment, have been widely used to compute the topography of the Moon [25], [26], see Fig. 2. An accurate estimation of the Sun trajectory across the lunar polar horizon and the critical relief elevations[2] will allow computing accurately the solar energy availability upon the base site. Accordingly, an optimal ESS sizing and energy management system (EMS) can be implemented. Besides, given that the overall ESSs must supply all critical loads, even at the lunar day with the lowest solar irradiance, the overall lunar nodal cycle (∼18.6 years long) should be considered.

**Temperature:** Having an accurate knowledge of the base site temperature is of vital importance not only for the estimation of energy generation and consumption (thereby the stability of the space MG [27]), but also for crew safety. In this regard, it has been proposed to estimate the temperature over the surface of the Moon using the profile of solar irradiance reaching the lunar soil and physical properties of the regolith [28], [29]. Another approximation is based on analytical models that consider the Sun position and the temperatures obtained experimentally [30].

## III. Power Generation Technologies in Space MGs

Electrical energy is needed to run the vital instruments in a lunar manned base, such as LSSs, resource utilisation systems, communication systems, electric vehicles (EVs) and rover charging systems, and electrostatic field shielding [9]. Although there are multiple ways to generate electrical power on the Earth, solar power is the most abundant power source on the lunar surface. Nonetheless, nuclear power is also a viable candidate [9], while new concepts based on harnessing the lunar regolith (lunar soil) electrostatic charge have been also proposed [10]. An overview of different power generation technologies for LEPS is given in Table III.

### A. *Solar Photovoltaic Technology*

A significant part of the electrical energy required by satellites and space missions is generated from solar energy using PV arrays [8]. Nowadays, the multi-junction (MJ) PV cells based on III-V semiconductors are the most widely used due to

[1]This longitude is computed by considering the highest and the lowest elevations over the surface of the Moon as well as the average lunar radius and the angular diameter of Sun [24].

[2]The angle of an elevation, in a specific longitude, that is the highest relative to an observer at the base site.

TABLE III: Advantages and disadvantages of lunar power generation technologies

| Power generation technology | Advantage | Disadvantage |
|---|---|---|
| Solar PV panels | • No additional or heavy infrastructure and logistics are required for installation<br>• Can be installed near the human base. Therefore, long-distance power transmission is not needed<br>• Easy expansion in case more power is needed<br>• No environmental and safety-related issues<br>• Tried, tested, and widely used technology for space applications<br>• Highly reliable, resilient, robust, and stable | • Power generation depends on the location, topography of the terrain, illumination, and solar irradiance, and temperature<br>• Lunar dust accumulated on the panels will reduce the power generation. Therefore, the panels will need frequent cleaning<br>• Degradation due to ultraviolet irradiation, nuclei/ion particles radiation, galactic cosmic rays (GCRs), space debris, micro-meteorites, vacuum, extreme temperatures cycles, and electrostatic fields |
| Nuclear fission based kilopower reactor (KRUSTY) | • Smaller mass and volume<br>• Power generation is independent of location and illumination conditions<br>• More modules can be installed in case more power is needed | • Due to the nuclear radiation, reactors should be placed at a safe distance, or shielding is required. Therefore, long-distance power transmission is needed<br>• Shielding may require additional logistics to stack regolith bags around the reactor<br>• Expanding power generation capacity may be difficult as more shielding might be needed, or distance from the base needs to be increased<br>• Proper disposal of nuclear waste might be a challenge<br>• Environmental safety is a primary concern given the hazards of any launch |
| Lunar regolith electrostatic charge | • Charged lunar dust, which may create several problems, can be neutralized | • Technology is still undergoing laboratory tests |

the high efficiency, relatively cheap and mature manufacturing processes, and *radiation hardness* [31]. Particularly, the triple-junction (TJ) GaInP/GaAs/Ge architecture is widely used for space applications with efficiencies around 30% [31]. However, such an architecture is limited by the mismatches between the photo-generated currents of the three layers. In this regard, the inverted metamorphic (IMM) and upright metamorphic (UMM) manufacturing processes have been proposed to optimize the current mismatching between the sub-cells by using compounds with different bandgaps. Recently, UMM PV cells have reached efficiencies around 40%. Nevertheless, buffer layers should be used to progressively release the strain defects in the joints [31], [32].

On the Moon, due to the absence of atmosphere, solar power generation is not affected by environmental factors like cloud coverage and diffusion of solar radiation. However, the almost null atmosphere of the Moon (technically considered an exosphere) along with its weak magnetic field allows space debris, micro-meteorites to reach the lunar surface and also ultraviolet irradiation, nuclei/ion particle radiation and galactic cosmic rays to reach the PV cells resulting in cells degradation. Besides, conditions as vacuum, extreme temperature cycles, and electrostatic fields contribute to the degradation of PV cells [33]. Deep temperature cycles results in the lifetime reduction of the PV connectors due to the thermal stress. Although degradation of PV-cells in space environment is caused by different reasons, the radiation-induced degradation of PV-cells is among the main concerns due to its serious damages. The lifetime reduction of PV-cells due to the radiation-induced degradation depends on many factors such as incident particles type, energy, flux, and fluence, cell material, operating temperature, light intensity, etc., and can be partially recovered by applying annealing processes. Furthermore, the PV cell degradation dependency on temperature has been shown to be of vital importance. Studies dedicated to the effect of low lunar temperatures upon the lifetime of III-V PV cells are still scarce and yet to be thoroughly investigated.

The operating temperature of the solar PV arrays on the Moon results from a thermal equilibrium between the lunar soil, arrays, and surroundings. PV arrays' maximum operating temperature on the Moon can be close to the maximum lunar surface temperature, which is $122.78°C$ [34] and from $-193.15°C$ to $-163.15°C$ near the *Shackleton crater* [30], [35]. A detailed study should be carried out to determine the approximate PV arrays' operating temperature considering the terrain's characteristics, illumination, reflections, the arrays' installation height, materials, etc.

Regarding the PV cells efficiency, the operational temperatures affect the bandgap energy of the semiconductor [36] while, the efficiency of a MJ PV cell depends on the bandgap energy combination of different layers [37]. In general, the efficiency of the PV cell decreases with increase in temperature due to the non-linear dependency of the series and shunt resistances of the PV cells with the temperature [38]–[40]. However, the efficiency increases again when the temperature reduces.

The power generation from the PV panels highly depends on the orientation of the panels and inclination angle [9]. Moreover, the continuously varying solar incidence angle on the solar panel surface significantly changes the panel output power [41]. To address this problem, a fixed 60° tent-shaped array is proposed in [42] that can maintain a flat power profile throughout the day, but it provides only 42% of the output power compared to a solar tracking array. Another approach

TABLE IV: Comparison between Earth-based and space-based PV technologies

| Earth-based PV Technologies | Space-based PV Technologies |
|---|---|
| Usually cheaper while having simpler architectures. | More complex architectures given the highly harmful environment of outer space. |
| The main focus is on reducing the cost and increasing efficiency by improving the manufacturing process. | Focus is not only on the reduction of costs and increasing of efficiency, but also the reduction of weight and volume while keeping a high level of radiation shielding and mechanical strength, tolerance to extreme temperature cycles, high levels of UV radiation and vacuum, mechanical stress due to maneuverings at deployment stage and under thermal stress, and lowest sensibility of efficiency to temperature changes. |
| Silicon-based PV-cells are the most widely used technologies with the highest laboratory-based efficiency of about 26.7% and 24.4% for mono-crystalline and poly-crystalline technologies, respectively [44], [45]. | The space-based PV-cells started since the beginning of the space age in the 1950s by using Silicon-based PV-cells with efficiencies of $7-8\%$ [46], then shifted to the use of more robust MJ configurations against nuclei/ion radiation with efficiencies of about $35\%$ [47], or even higher than $40\%$ by using light concentrators [48]*. |

* No more than 10 to 50 suns of concentration for space applications is recommended due to the complexity increase of thermal holder designs [49].

for solar array configuration is given in [11], where a triangular shape of three arrays on a tower is proposed showing increased solar irradiation harnessing throughout a year.

***Comparing Earth-based and space-based PV technologies:*** Outer space conditions such as vacuum, extreme temperature cycles, the impact of space debris and micro-meteorites, and intense ultra-violet (UV) radiations are prevented on Earth thanks to the presence of the atmosphere. However, such an atmosphere also adversely affects the PV power production since the solar beams have to travel across different gases while suffering modifications in the intensity and direction due to absorption, scattering, surface albedo, and cloud overlapping [43]. On the other hand, unlike in outer space where either no magnetic shielding exists, or the magnetic lines strength is too weak, on the Earth there exists a magnetosphere that prevents the intense radiation by nuclei particles, ions, and GCRs. In this regard, the requirements for Earth-based PV-arrays are different from those related to space-based PV-arrays. While the former is mostly focused on the reduction of costs by increasing the efficiency of the modules and improving the whole manufacturing process, the major goal of the latter is achieving the lowest weight and volume and the highest tolerance to the extreme environmental conditions. The main differences between the Earth-based and space-based PV technologies are summarized in Table IV. To efficiently incorporate the PV technology in space MGs with an extended lifetime, new materials, architecture, shielding, and hardening strategies are still under investigation.

### *B. Nuclear Fission-based Power*

Nuclear-based power sources are also used for generating power in several space missions. In early deep space missions like *Cassini Probe* and *Mars Curiosity Rover*, isotope-based EPSs are used. However, for more than 1kW electrical power, a large amount of isotope is required, making an isotope-based EPS impractical for lunar bases [9]. Instead, a nuclear fission-based power generation source with Stirling technology is proposed as an alternative to solar power [9], [50]. This nuclear fission-based power source is named as “Kilopower Reactor Using Stirling TechnologY (KRUSTY)”. In 2018, a 1kW-kilopower reactor was tested at Nevada National Security Site. The reactors consist of sodium heat pipes to transfer the heat generated from the highly enriched uranium core to Stirling engines [51]. This successful test has prompted the technology to increase the power level from 1kW to 10kW. Several 1 or 10kW units can be grouped to create a modular power generation system [51]. In these modules, the uranium reactor cores need to generate 43kW of thermal power to generate 10kW of electrical power and transfer the heat to the power conversion system through sodium heat pumps [51]. Different types of reactors namely *single converter to heat pipe, secondary heat exchanger architecture,* and *radiatively coupled heat exchangers* are discussed in [51].

The kilopower nuclear reactors come at the peril of constant, harmful radiation, to which the long-term exposure is detrimental to all living organisms. To mitigate the radiation hazards, the reactors need to be placed at a safe distance and have appropriate shielding [9], [52]. According to the current guidelines, the whole-body radiation dose limit is 5rem/year or equivalently 50mSv/year. Therefore, a minimum distance of 1.15km is required from a 10kW reactor to keep the radiation dose below the limit [9]. The required separation distance is directly proportional to the number of reactors. For three and six modules of 10kW reactors, the distance should be 1.99km and 2.81km, respectively. Furthermore, placing the reactors at a distance will increase the logistics and mass for transporting power from the generation site to the crew living quarters. The required distance can be reduced by introducing an appropriate shielding mechanism. There are several considerations about various types of shielding that can be found in [9], some of them are listed in Table V [9]. Moreover, proper disposal of nuclear waste may also prove to be a challenge. Presently, for terrestrial nuclear waste, deep geological disposal is widely accepted and considered to be the best solution. While for lunar base missions, suitable solution to dispose nuclear waste from the KRUSTY reactor are yet to be investigated which is out of the scope of this study.

### *C. Lunar Regolith Electrostatic Charge*

Electrical power can also be harnessed from the lunar regolith electrostatic charge [10]. Due to the absence of the atmosphere, the lunar regolith is constantly bombarded with electrons and protons from the solar wind, creating a negative electrostatic charge on the lunar dust particles and the dust particles are suspended about one meter above the lunar surface. This phenomenon was observed by *Clementine* and *Surveyor* spacecraft and also caused major problems during the *Apollo17* mission [10]. Through capacitive coupling, the electrostatic power generator can neutralize the charged particles. A sequential charging and discharging of a thin

TABLE V: Different types of shielding for nuclear fission-based kilopower reactors

| Shielding type | Considerations |
|---|---|
| Stacking regolith bags or blocks around the reactor | • Ideally, the reactor should be completely covered from all sides, including the top of it<br>• Shielding from some areas around the reactor will have partial shielding, and other areas will be exposed to radiation<br>• Lunar terrain can be used for partial shielding |
| Digging a pit and burying the reactor in the regolith | • Digging a pit will require additional logistics and resources to be transported to the Moon<br>• The digging logistics and resources will need an additional power source before the reactor being installed<br>• A feasibility study is needed with consideration of the required pit depth and regolith density<br>• There should be a provision for electrical connection from the pit to the surface<br>• A partial shielding or restricted area over the pit is needed. Lunar regolith can also be placed over the pit for shielding |
| Using the lunar terrain | • Identification of a crater with sufficient depth and suitable terrain to place the reactor and establish necessary connections from the reactor to the lunar surface<br>• The open area above the crater should be restricted for use<br>• Further shielding can be installed to limit the area exposed to radiations inside or above the crater |

film array of capacitors can produce a train of DC pulses. The charge collected by the motorized track thin-film flexible capacitors (and thereby the generated power) depends on the area and hovering speed over the regolith. Since there is no adequate data available about the charge density of the lunar regolith, the power collected from this technique is not known completely. However, few reports indicate the availability of several thousand volts on the lunar regolith. A simulation study performed by NASA indicates that the lunar regolith is 700V negatively charged. Besides, according to [10], 40 capacitive array units are needed to collect 147W per array. Experiments are still ongoing to determine the feasibility of harvesting electrostatic power from the lunar regolith [10].

## IV. Power Consumption Units for Space MGs

The lunar base consists of various types of power-consuming units (loads). The most apparent loads are related to the crew habitat and the base camp, consisting of LSSs such as heating, cooling, regenerating the habitable atmosphere, supplying astronauts with food and water besides the power needed for the operational equipment like computers, lights, and experimental gear. Additional LSS equipment may include biomass composting and waste processing units, all contributing substantially to the overall habitat electrical consumption profile [53]. The base can also include laboratories depending on the mission [9]. The laboratories can have different instruments similar to the habitat besides specialized scientific instruments. Moreover, human-carrying EVs may be used for transportation, carrying out maintenance tasks, or visit various locations [14]. Autonomous or remotely controlled electrical rovers may also be used to further explore the lunar environment and collect samples. Therefore, charging stations are needed to charge these rovers and vehicles [9], [14]. Communication systems are one of the other vital loads for a lunar base. The base should constantly be in communication with the ground station on Earth. Communication can be established through communication systems placed in the direct line of sight or through an orbiter spacecraft which collects the information from the lunar base and relays it to the earth ground station. Moreover, communication is needed among different lunar establishments and units.

For extended lunar missions, it is desired to utilize the Moon's locally available resources. Therefore, in-situ resource utilisation (ISRU) can be established to produce oxygen and propellants from the regolith, which needs both electrical and thermal power. The motors to scoop, filter, and transport the regolith, and the electrolyzer consume electrical power to operate, while thermal power is required to melt the lunar regolith inside a boiler [9]. The thermal power can be supplied by the electrical heaters [9], however such choice increases the electrical power demand. Instead, solar thermal systems may be used [54]–[56], in which solar irradiation is concentrated and focused on a heat receiver that conducts the heat to a chamber to melt ilmenite [54]. In another approach, the solar concentrators are used to focus the solar radiations to the optical waveguides made up of optical fibers [55]. The optical waveguide transfers the solar irradiation to the regolith [55]. More information about the design and implementation of different solar concentrators for ISRU can be found in [56].

The power required by the lunar base habitat depends on the number of crew, and it is estimated to be 28.05kW for six crew members [9]. In [57], a continuous power supply of around 35kW is estimated for a lunar base with less than 10 crew members. To produce lunar propellants in the range of metric tons, 10 to 20kW of power is needed by the ISRU [58]. As the power required by the ISRU is dependent on the production rate and process, it can vary from tens to hundreds of kW for both thermal and electrical power [9]. It is estimated that for a production rate of about 1.63kg/hr, the plant needs 9.3kW of electrical power and 16.5kW of thermal power [9]. Furthermore, the power needs of the EVs and rovers depends on several factors such as their range, self-discharge rate, energy storage capacities, lunar terrain, and the regolith physical properties. The EVs used by the crew can be pressurized for their convenience which will need additional power resources [14]. The power required for the communication systems is also dependent on the transmission distance, data rate, bandwidth, and frequency of communication [9]. The nominal power

TABLE VI: Power range of several lunar power consuming units and the factors affecting their power requirements

| Power consuming unit | Active power range (kW) | Survival power range (kW) | Power requirement factors |
|---|---|---|---|
| Lunar habitat | 30 to more than 100 | 0.5 to 2 | Around 5kW to 10kW per person |
| Laboratory | 4 to 10 | 0.5 to 2 | Depend on the mission type, nature, and objectives |
| Crewed electric vehicle | 1 to 3 (Unpressurized)<br>3 to 30 (Pressurized) | 0.2 to 0.5 (Unpressurized)<br>0.5 to 3 (Pressurized) | Depend on the required pressure in vehicles and the number of persons |
| Electric rover | 0.1 to 7 | less than 0.2 to 1 | Depend on rover size and nature of experiments |
| Charging station | 1 to 10 | 0.5 to 2 | Depend on the #EVs and their requirements |
| ISRU | 10 to 100 (Thermal)<br>10 to 100 (Electrical) | 1 to 5 | Depend on the production rate and oxygen requirement |
| Water and ice exploration tools | 10 to 100 (Thermal)<br>10 to 100 (Electrical) | – | Depend on the amount of water needed by ISRU |
| Communication systems | 0.3 to 1 per transmitter | Not applicable | Depend on the required communication, namely communication with the orbiter, ground station, or other lunar establishments |
| Lunar night time operation and heating systems | 1 to 2 | Not applicable | To maintain safe operating temperatures of equipment and support the reliable operation at nighttime |
| Sensors and other supporting equipment | 2 to 10 | Not applicable | Depend on their type, rate of information acquisition and transmission |

ranges of these systems and the factors affecting their power requirements are presented in Table VI [9], [14]. During the lunar night and partial or total eclipses, only critical loads, mainly LSS and communication systems are operated, whereas other non-essential loads can be put in a low-power state (survival/idle power state).

## V. Energy Storage Technologies for Space MGs

To operate under the lunar harsh environmental conditions, ESSs have to survive the acceleration, vibration, shock, radiation, and extreme temperatures and pressures. For space surface missions, it is desired to have an ESS with high specific energy (more than 250Wh/kg), high energy density (more than 500Wh/l), long calendar life (more than 5 years), long cycle life (more than 1000 complete cycles), radiation tolerance and operational capabilities in extremely low temperatures of less than $-40°$C [59]. The high specific energy and energy density help to reduce the mass and volume of the ESS, respectively. Different ESS types used in space missions include primary (non-rechargeable) and secondary (rechargeable) batteries, fuel cells (FCs), capacitors, and flywheels [8], [59]. Primary batteries are for single-use, which provide power for a few minutes to a few hours. Secondary batteries and FCs are used in space missions that require a large amount of power for many hours to days. Capacitors are used when repeated high-power short-duration pulses (in the range of seconds) are required [59]. Flywheels proved to be a potential ESS with the introduction of Integrated Power and Attitude Control System in 1974 [60] that could lead to a significantly smaller and lighter spacecraft [61], [62] compared to an ESS based on nickel-hydrogen (Ni-$H_2$) batteries. Utilisation of flywheels within the context of the Moon, due to the lack of atmosphere, boosts their efficiency and performance [8], [63]. However, lately efforts towards that direction seem to be paused. An overview of different energy storage technologies for space MGs is given in Table VII [8], [59], [63]. Overall, rechargeable batteries and FCs seem to be favorable for space surface missions as they have the desired specifications and can serve the load for long hours [59].

***Rechargeable Batteries***: Presently, Ni-$H_2$ and lithium-ion (Li-ion) rechargeable batteries are used in space missions. However, despite having a high cycle life (more than 50,000 cycles at 30% depth of discharge), due to the low specific energy

TABLE VII: Advantages and disadvantages of different energy storage technologies

| ESS type | Advantage | Disadvantage |
|---|---|---|
| Battery | • Lowest mass and complexity for short discharge durations<br>• Higher charging efficiency than RFC. Therefore, fast charging is possible during short illumination periods | • Large mass for long discharge durations<br>• Energy conversion and energy storage units are packaged into a single unit. So, independent sizing of them is not possible |
| RFC | • Less mass for long discharge durations<br>• Energy conversion and energy capacity units are separate. Therefore, independent sizing of them is possible<br>• Reactants can be stored at cryogenic temperatures. Thereby, the storage volume is reduced | • Reactants can be stored at increased pressure to reduce the system volume, but additional compressors are required. The requirement of compressors can be eliminated if the electrolysis is performed at increased pressures, but it increases the line and component mass to sustain the increased pressure |
| Capacitor | • Suitable for applications requiring repeated high discharge pulses for a short duration. Thereby, extending the lifetime of batteries | • Super-capacitors that are presently under development, have higher specific energy than the standard double-layer capacitors. But, they are for non-space applications<br>• Can be only used for short-duration high-discharge pulses |
| Flywheel | • High efficiency and lifetime (over 15 years), power and voltage levels, quick power delivery, environmentally friendly, and with less maintenance requirements | • Low energy density, high mass and self-discharge rate<br>• Deep discharge is not achievable |

TABLE VIII: Different Li-ion batteries and their technical specifications

| Battery | Specific energy (Wh/kg) | Energy density (Wh/l) | Cycle life (cycles) | Calendar life (Years) | Operating temperature range (°C) |
|---|---|---|---|---|---|
| LFP (Long life) | 150 – 200 | 300 – 400 | More than 100,000 | 20 | -10 to 25 |
| LFP (with Alternate Anodes) | 250 – 300 | 300 – 400 | Less than 500 | ∼5 | -40 to 30 |
| LTO | 150 – 200 | 300 – 400 | More than 100,000 | 20 | -10 to 25 |
| NMC (Long life) | 150 – 200 | 300 – 400 | More than 100,000 | 20 | -10 to 25 |
| NMC (High Energy) | 150 – 200 | 300 – 400 | More than 500 | ∼5 | -40 to 30 |
| NMC (with Alternate Anodes) | 250 – 300 | 300 – 400 | Less than 500 | ∼5 | -40 to 30 |
| LiPON | 250 – 350 | 300 – 400 | More than 100,000 | More than 20 | 10 to 80 |
| LLZO | 250 – 350 | 300 – 400 | More than 100,000 | More than 20 | 10 to 80 |
| LATP | 250 – 350 | 300 – 400 | More than 100,000 | More than 20 | 10 to 80 |
| LiS | 250 – 300 | 300 – 350 | 100 – 500 | ∼5 | -40 to 30 |
| LCO | 250 – 300 | 300 – 400 | Less than 500 | ∼5 | -40 to 30 |
| NCA | 250 – 300 | 300 – 400 | Less than 500 | ∼5 | -40 to 30 |

LFP: Lithium Iron Phosphate; LTO: Lithium Titanium Oxide; NMC: Lithium Nickel Manganese Cobalt oxide; LiPON: Lithium Phosphorus Oxynitride; LLZO: Lithium Lanthanum Zirconium Oxide; LATP: Lithium Aluminum Titanium Phosphate; Li-S: Lithium – Sulfur; LCO: Lithium Cobalt Oxide; NCA: Lithium Nickel Cobalt Aluminum Oxide

(∼30Wh/kg) and low energy density (30 Wh/l), Ni-$H_2$ batteries are slowly being replaced with Li-ion batteries. Li-ion batteries have higher specific energy (∼100Wh/kg) and energy density (more than 200Wh/l) along with significant mass advantage and operational capability over a wide range of temperature compared to Ni-$H_2$ batteries [8], [59]. Though space-qualified Li-ion batteries are capable of meeting the technical and non-technical requirements of space missions, researchers are working to mitigate their limited low-temperature operational capability [11], [58], [59]. Li-ion batteries are desired to operate at low temperatures of $-60°$ to $-80°$C for surface missions [59]. An overview of technical specifications of different batteries are given in Table VIII [59].

The batteries and other electrical equipment may need passive thermal insulation 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 insulations with low conducting materials like layered blankets and foams. Multilayer materials are excessively used to prevent the high thermal flux, reduction of the environmental temperatures, and temperature gradients [64]. Also, Active Thermal Control System (ATCS) can be employed to heat and cool as required to maintain the operating temperature range of different electrical systems as mentioned in [65]. ATCS involves electrically powered heaters using resistances and cooler plates using refrigeration devices such as cryocoolers around the electrical equipment [66].

***Fuel Cells:*** FCs are also a favorable solution for extended-duration surface space missions. They can supply hundreds of watts of power for long extended periods of operation [59]. There are several types of FCs, out of which proton exchange membrane (PEM), solid oxide (SO), and regenerative fuel cells (RFCs) are advantageous for lunar base applications [59], [67], [68]. A PEM-FC consists of a polymeric proton-conducting membrane with a reaction-specific catalyzed hydrogen and oxygen electrode on each side of the cell [59], [68]. A SO-FC consists of an electrically insulating anionic conducting ceramic through which the oxygen anions pass, after reduction in the cathode, to oxidize the hydrogen into the water at the anode. During the process, water vapour is produced as a byproduct that is continuously removed as it negatively impacts the overall reaction [68]. A RFC integrates a FC, an electrolyzer, and a multi-fluid reactant storage system [58], [59], [67], [69], thereby making FCs a rechargeable ESS to serve long-duration lunar surface missions. RFCs generally have separate electrolyzer and FC stacks but recently *unitized RFCs* have being developed to merge the FC and electrolyzer [59]. Among the two types of RFCs, namely, PEM-RFC and SO-RFC, SO-RFC needs more power to charge and has more mass comparing to PEM-RFCs for a similar system volume [68]. Moreover, SO electrolyzers cannot achieve the final gas storage pressure in the electrochemical process and additional mechanical pressurization systems are required. In general, electrochemical pressurization is more efficient than mechanical pressurization systems [68]. Therefore, considering the advantages and efficiency, PEM-RFCs seem very promising for space surface missions [59], [67], [68].

RFCs can be designed and sized considering the specific needs of each location. The permanently shadowed regions inside the lunar craters can allow cryogenic storage of the reactant tanks. The temperature at the floor of *Shackleton crater* is about $-193.15$°C and it never exceeds a temperature of about $-163.15$°C [35]. These extreme cold temperatures may allow reaching cryogenic temperatures ($-150$°C to $-273$°C) without any energy consumption for cooling. However, additional energy and specific infrastructures (like pumps) are required to transport the reactants to the surface [8].

***Comparison between Rechargeable Batteries and RFCs***: In general, for long discharge duration, RFCs are shown to have an advantage over the rechargeable batteries in terms of mass and specific energy [9], [58], [67], [68]. In [9], two EPSs including solar PVs assisted by batteries and RFCs are analyzed. During the lunar night, the specific energy of RFC system was more than 830Wh/kg when all the loads were supplied at normal power levels. While it was about 456Wh/kg when only the survival power need of the loads was supplied. The specific energy of the RFC system in both cases (with normal and survival power demand) was more than the specific energy of 200Wh/kg for the battery. This is because all the components of the RFC are designed for a fixed maximum

TABLE IX: Comparison of different lunar power transmission systems

| Transmission system | | Payload/Output Power ($P_{out}$) (kW) | Source input power ($P_{in}$) (kW) | $P_{out}/P_{in}$ | Power Transfer subsystem mass (kg) | Specific mass (kg/kW) |
|---|---|---|---|---|---|---|
| **For payload distance = 1 km** | | | | | | |
| Cable | DC - 1 kV | 10 | 11.73 | 0.852 | 766.5 | 76.7 |
| | DC - 2 kV | 10 | 11.73 | 0.852 | 550.5 | 55.1 |
| | DC - 3 kV | 10 | 11.25 | 0.889 | 647.1 | 64.7 |
| | DC - 5 kV | 10 | 11.19 | 0.893 | 709.1 | 70.9 |
| | AC (3-Ph) - 1 kV; 400 Hz | 10 | 12.03 | 0.831 | 1 001.1 | 100.1 |
| | AC (3-Ph) - 2 kV; 400 Hz | 10 | 11.80 | 0.847 | 901.0 | 90.1 |
| | AC (3-Ph) - 3 kV; 400 Hz | 10 | 11.65 | 0.858 | 909.7 | 91.0 |
| | AC (3-Ph) - 5 kV; 400 Hz | 10 | 11.58 | 0.863 | 1 043.5 | 104.3 |
| RF | 2.45 GHz | 10 | 220.34 | 0.045 | 2 449.2 | 244.9 |
| | 5.8 GHz | 10 | 78.98 | 0.126 | 1 228.7 | 122.9 |
| Laser | 293 K | 10 | 50.58 | 0.197 | 1 777.2 | 177.7 |
| | 325 K | 10 | 63.22 | 0.158 | 1 677.2 | 167.7 |
| Cable | DC - 1 kV | 50 | 58.19 | 0.859 | 2 193.7 | 43.9 |
| | AC (3-Ph) - 1 kV; 400 Hz | 50 | 63.55 | 0.786 | 2 458.6 | 49.2 |
| RF | 2.45 GHz | 50 | 979.29 | 0.051 | 10 239.8 | 204.8 |
| | 5.8 GHz | 50 | 351.04 | 0.142 | 4 815.5 | 96.3 |
| Laser | 293 K | 50 | 217.14 | 0.230 | 7 561.1 | 151.2 |
| | 325 K | 50 | 271.43 | 0.184 | 7 199.1 | 144.0 |
| **For payload distance = 5 km** | | | | | | |
| Cable | DC - 1 kV | 10 | 12.38 | 0.807 | 4 567.0 | 456.7 |
| | AC (3-Ph) - 1 kV; 400 Hz | 10 | 13.59 | 0.735 | 3 571.2 | 357.1 |
| RF | 2.45 GHz | 10 | 5 508.51 | 0.001 | 52 744.8 | 5 274.5 |
| | 5.8 GHz | 10 | 1 974.58 | 0.005 | 22 233.1 | 2 223.3 |

output power except the storage tanks and reactants. Therefore, the specific energy of the RFC system is directly proportional to the operating time at a given power level [9]. With longer operation, the mass of other components does not increase and only the reactants and storage tanks need to support the ESS requirements. Moreover, RFCs have separate energy conversion (FC and electrolyzer) and energy storage units (reactants storage tanks), permitting independent sizing of both [67], [68]. While in batteries, both energy conversion and storage are packaged in one unit [67]. Comparing RFCs and batteries in terms of system mass and discharge time, a breakpoint at around 10 to 18 hours of discharge time has been observed [58]. Up to the breakpoint, the mass of the battery system is less than the RFC while it becomes higher afterwards. The charging efficiency of RFCs are lower than that of batteries [12], resulting in a longer duration to recharge RFCs. Therefore, the use of RFCs may be insufficient at locations with short illumination-darkness periods, requiring fast charging during short illumination intervals. To reduce the charging time, additional solar power may be needed [12].

## VI. Power Distribution System for Space MGs

Power generation is desired to be near the habitat and the ISRU in space MGs. However, this might be possible in case of solar PV-based generation, while in the case of nuclear fission-based kilopower reactor, a significant distance is needed to reduce the shielding requirements and harmful radiation [9]. Hence, a distribution system is required to bring the generated power to the point of consumption.

The power distribution system can be designed based on either AC or DC technologies. 3-phase AC systems are widely used in terrestrial EPSs at different voltage levels [8] as well as aircraft EPSs [11]. In permanent crewed space installations such as the ISS, the station EPS is designed at 120V DC [8]. Although the transmission system is more efficient at higher voltages, there are no space EPS applications with a voltage more than 160V DC [8]. In general, DC systems are more efficient due to the absence of the *skin effect*, lower line losses, and no reactive power compensation, while allowing simpler design and construction [8], [11].

A high-frequency AC system of 50kW with a high-voltage transmission line is simulated in [70] for lunar EPS. It is observed that the leakage inductance of the transformer is 10 times the transmission line, and the combined leakages of the two transformers are 60% of the alternator inductance. Therefore, only 30 to 35kW of power could be transmitted with a 10% increase in alternator speed. The alternator test unit is able to deliver full power by increasing the system frequency to 1750Hz, and installing 90$\mu$F-capacitors per phase. Increasing the AC system frequency reduces the size of the capacitors and the power converters, but the transmission line mass increases as the skin effect and the inductive reactance is directly proportional to the system frequency [8]. Thus, studies have shown that increasing the system frequency does not significantly reduce the overall system mass [8]. Moreover, power transmission on or beneath the lunar regolith may also involve significant power losses. The lunar regolith is composed of iron oxide, which may inductively couple to long transmission lines and produces substantial power loss [41]. Also, due to the low conductivity of the lunar regolith, charged clouds of lunar dust move around the surface, necessitating additional protection relays and grounding wells for reliable operation [8].

A space MG on the Moon may have the requirement to transmit about 50kW of power from 0.1km to 10km. The power can be transported using wired AC and DC power cables, wireless beamed power using radio frequency (RF) and solid-state lasers [65]. A similar approach is discussed in [57], where a solar power station in the lunar orbit can generate power and beam it to the lunar base using the microwave. Different power transmission technologies require certain supporting equipment which adds to the total EPS mass while some components also need passive and active thermal management system for heating and cooling [65]. For AC and DC power cables, the power transmission system mass is directly proportional to the power levels. At higher voltages, although the conductor size reduces [11], [65], the wire insulation mass and thickness increases [65]. Using the RF systems, power can be transferred at a frequency of 2.45GHz or 5.8GHz. It involves an assembly of ATCS cooled magnetron, and passively cooled transmit antenna and rectenna arrays. At 5.8GHz frequency, free space transmission efficiency increases, and therefore the power subsystem mass and input power is reduced compared to 2.45GHz systems [65]. However, both the power at the input source and the subsystem mass increases in orders of magnitude with an increase in transmission distance, due to the increase in free space losses [65]. By increasing the antenna aperture area, the free space loss can be reduced, but the spacecraft stowage constraints limit its size. The laser system consists of an AlGaAs/Ge quantum well solid-state laser diode module with 0.5% efficiency at 800nm and 293K temperature. A perfectly circular transmission beam is maintained to achieve 91.2% transmission efficiency. ATCS is critically essential to maintain the laser module operating temperature at 293K for good efficiency. Reducing the laser diode aperture size decreases the mass of the system and source input power, but the thermal control heat fluxes and associated cooling requirements increase [65].

In terms of power transfer efficiency, cable power transmission has a higher efficiency of more than 70% to transmit 10kW of power for 1km. For the same distance and power, RF and laser systems have an efficiency of less than 13% and 20%, respectively. This is due to the added power conversion steps, free space transmission loss, and laser beam aperture size. The high frequency transmission at 5.8GHz was more efficient than the low frequency at 2.45GHz [65].

Though space MGs involve power generation, conversion, transmission and distribution, in general, it is observed that power transmission using cables (specifically DC cables) has the lowest mass and the highest efficiency. However, for heavy machinery, DC motors are generally larger and heavier than AC motors for similar power and torque. Therefore, additional AC buses with AC-AC power converters or solid-state transformers, for controlling the voltage and frequency, can provide a mass advantage. Thus, hybrid AC/DC transmission and distribution systems can also prove to be advantageous considering safety and reliability [71], [72]. Table IX shows a comparison among different power transmission technologies [65].

## VII. Space MGs Control Framework

An efficient control and power management system to guarantee power demand satisfaction and optimizing resource utilization in a space MG is of vital importance. Presently for spacecraft and space base applications, the power schedules are prepared and communicated by the ground station. For ISS, three teams at different ground control centers communicate the power scheduling made with the consideration of specific requirements and constraints of different systems [73]. This ground-based scheduling is possible because of the low communication latency as the spacecraft revolves around the Earth. However, in the case of space missions, sometimes the communication latency can be significant (up to or greater than 15 minutes for Mars missions) [74]. At a download bandwidth of 300kbps, the round trip communication delay can be around 10 sec for lunar space missions [75]. The delay in communication even in the order of few seconds can create problems in voltage control, power flow, and load sharing resulting in severe faults, as the time scales for these controls are even smaller than a second. Moreover, the lunar base may not always be in direct line of sight communication with the Earth, and the control signals may have to be communicated through an orbiter around the Moon, further increasing the delay. Besides, during an emergency, it might not be possible to establish communication with the Earth-based station. Also, the crew may not be experts in the area [76]. Thus, autonomous and independent control systems are essential for a space MG.

In general, space MG control and operation management involve scheduling resources, planning the loads and their operating modes (active or survival), communicating vital information, coordinating resources, ensuring the timely occurrence of missions, and detecting, identifying, isolating, and recovering from faulty conditions among others [73], [74].

Considering the similarities between terrestrial and space MGs the control systems architectures implemented for terrestrial RES-based MGs can also be extended to space MGs on the Moon. In general, the control architecture of terrestrial MGs can be categorized into centralized, decentralized, distributed, and hierarchical control. Hence, a similar approach can be followed for the autonomous control of space MGs. In a centralized architecture, a central controller collects and processes all information and makes the operating schedule, and sends it to the lower execution level. The lowest level is also responsible for monitoring and protecting the system in case of a fault or malfunction. In the case of decentralized control, there is no communication between the controllers and the control relies on the changes in voltage (and frequency in case of AC) [77], [78]. The lack of communication between the controllers has shown difficulty to reach the global optimum [79]. In Distributed control architecture, the controllers communicate among themselves to achieve a common goal [77], [78]. A delay or a disruption in communication can be catastrophic for such system in space, where accessibility is both limited and costly. Taking into account the various control tasks and complexity of the operation, control decisions can be distributed in several layers resulting in a hierarchical control structure (HCS) [80]. In a HCS, the lower layers have a higher processing rate than the higher layers while the scheduling horizon increases going up in the hierarchy. In this way, the computational burden is distributed from a single central controller to several subsequent controllers. In [74], a HCS is proposed for a lunar base, which is composed of reactive controllers (at the lowest level), subsystem controllers in the middle, and the topmost manager layer as shown in Fig. 3. Information, measurements, and control actions correspond solemnly to the subsystem each

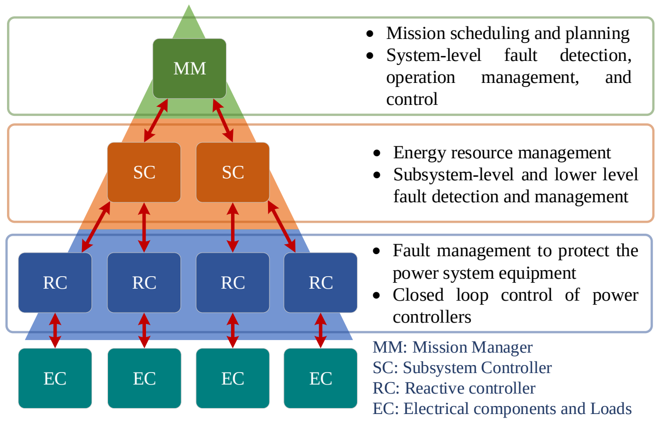


Fig. 3: Hierarchical control architecture for space MG control

controller corresponds to, while the topmost control layer has the system's global perspective. The subsystem-level controller detects the faults in sensors and short circuit currents of small magnitude and commands mismatch among others using model-based state estimation [74]. The topmost layer deals with the faults that stem from multiple subsystems, denoting a system-level incident that is out of the scope of subsystem-level controllers. A model-free control framework [81] allows topology changes and promotes continuous operation of the system in faulty conditions, proving to be beneficial despite of lower performance in terms of dynamics and disturbances.

Other than fault management, EMS and maintenance, mitigation, and recovery (MMR) are also a vital part of the space MGs control paradigm [74]. The EMS performs planning and scheduling of the loads according to the power system generation and load profiles. The EMS ensures providing the required power to the loads considering their priorities to complete assigned missions without violating the system's technical constraints. The priorities of each load is assigned based on the relative importance of loads with respect to each other and considering the level of seriousness of the emergency situation and the space mission [76], [82]. The loads related to LSS of the crew members must be of higher priority than the loads related to experiments and laboratories. The MMR ensures the power availability to the loads in case of faults or need for system maintenance by re-configuring the power distribution system to avoid load shedding [74].

Adaptability and scalability are also other important aspects of the control systems for lunar applications. The control system should be adaptable to lunar base expansions and other future missions and have the capability to work with new requirements [76]. Besides, including new equipment and future expansions should be possible in a straightforward manner. Finally, validating the developed control system under different simulated normal and abnormal operating conditions should be performed to approve the controller performance before its deployment and avoid costly tests.

In conclusion, although the stability, reliability, service continuity, fault tolerance, power quality, and control system scalability are important in any power system, their importance is substantially increased in isolated systems. Specifically, considering the limited accessibility of the space MGs from the Earth and costly missions, these factors are considered as design principles of space power systems [71] and their control framework. Besides, considering that the crew might not be the domain expert, deploying autonomous and intelligent decision support systems is necessary.

## VIII. Future Trends in Space MGs

Some of the challenges in space MGs can be solved by adopting the verified strategies developed for terrestrial applications, while others may demand development of totally new technologies. Given the striking similarities between space MGs and terrestrial RES-based IMGs, the solutions devised for terrestrial IMGs are applicable to space MGs and vice versa. One of the challenges that all IMGs suffer from is the lack of inherent inertia, which leads to potentially unstable systems. Several solutions have been proposed, all of which aim at enrichment of the EPS with artificial inertia, a method that is usually applied at lower control levels via the implementation of droop control and its variants.

Furthermore, in IMGs characterised by variable consumption profiles, there can be frequent fluctuations in voltage (and frequency in the case of AC systems). To reduce these fluctuations, multiple MGs can be connected to each other forming a multi-microgrid system where each MG has its power generation, consumption, and storage units. This strategy could also be employed in a space MG to enhance the overall system stability, reliability, and efficiency. However, appropriate methodologies for efficient sectionalizing of the space MG and distributing loads and power resources across different zones are required.

Selection of a suitable topology for a space MG is not a trivial task since several important factors such as system reliability, mass, volume, and cost are involved. Besides, system stability should be ensured under multiple or cascading faults. The standardised topologies deployed in DC IMGs are radial, ring, and mesh architectures [77], [78], all of which can be enhanced with additional line redundancies. Thus, considerable endeavours should be made to find the optimal topologies for space MGs with a wealth of experience from terrestrial IMGs.

Space MGs are prone to several faults and failures that might threaten their normal operation or even catastrophic damage and loss of life. Thereby, fault tolerant control systems capable of maintaining system operation under fault and emergency conditions are of vital importance for MGs on the Moon. The faults occurring at the communication layer are among the most severe issues that need serious consideration. One promising solution is relying on hierarchical and communication-less control schemes, which have already shown satisfactory results in terrestrial applications.

## IX. Conclusion

Construction of a lunar base demands at foremost the design of a resilient and reliable EPS. Such endeavor involves identifying a suitable location and advanced technologies for power generation, storage, and transmission/distribution, as well as an efficient control framework for autonomous operation.

This paper summarized the factors affecting the lunar base's location and state-of-the-art of different lunar power generation, storage, and transmission/distribution technologies. Moreover, different types of power-consuming units in a lunar base were identified, and their power requirements were discussed. For the autonomous, reliable, and safe operation of the EPS, a hierarchical control framework was presented. Finally, a discussion of several promising future technological solutions to accelerate the establishment of human presence on the Moon were underlined.

## Acknowledgment

This work was supported by VILLUM FONDEN under the VILLUM Investigator Grant (no. 25920): Center for Research on Microgrids (CROM).

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