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EDITORIAL

Towards Installing the First Lunar Microgrid

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Abstract

The US National Aeronautics and Space Administration's (NASA) Artemis II lunar flyby mission paved the way for future moon landings and directed research toward installing the first lunar microgrid. NASA predicts that a solar-powered microgrid at the lunar South Pole (LunaGrid) will become operational in 2028 and will interconnect multiple nodes to support the Artemis Base Camp. The architecture of the LunaGrid microgrid will be modular for the integration of several fission reactors (in one nuclear power plant of up to 100 kW). The aim is to ensure a continuous supply of electricity to the Artemis Base Camp by 2030 during the 14-day lunar nights when solar power is not available. In addition, the Russian Federal Space Agency (ROSCOSMOS) and the China National Space Administration (CNSA) plan to install another nuclear power plant and accompanying microgrid on the moon by the mid-2030s to power their International Lunar Research Station (ILRS). It is therefore obvious that a race has already begun between the space superpowers in electrifying the moon. In addition to the components for electricity generation, each of the future lunar microgrids will contain components for transmission, distribution, storage and consumption of electricity, as well as all other devices and equipment that exist in islanded microgrids on Earth. However, current prices for delivery of each of these components, devices and equipment to the moon are more than one million US dollars per kilogram, and each of them will operate there under extreme environmental conditions. Therefore, the electrification of the moon represents a state-of-the-art challenge for all the interested researchers who will further contribute to advancing knowledge on this specific topic.

Keywords: electric power component, electrification, extreme lunar environment, lunar microgrid.

1 Introduction

For all humanity, the moon represents the next frontier of research and scientific discovery [1], the new place for mining rare-earth metals and nuclear fuels and for treating water [2], an alternative location for the clean energy generation for the needs on Moon and Earth [3–5], as well as an ideal stepping stone (i.e., the closest extraterrestrial solid ground) for future missions to Mars and other deep space targets [6]. Validation of everything that has been discovered so far and all plans regarding future missions and exploration on the moon depend on the installation of island and networked lunar microgrids. The US National Aeronautics and Space Administration (NASA) predicts that a lunar microgrid will become operational in 2028 [7], while the Russian Federal Space Agency Roscosmos (ROSCOSMOS) and the

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China National Space Administration (CNSA) plan to install another lunar microgrid by the mid-2030s [8]. The inevitable shift toward the electrification of the Moon serves as the motivation for writing this editorial.

Factors that may affect the location of a lunar base, different types of electricity consumption at such a base and state-of-the-art lunar technologies for electricity generation, storage, transmission and distribution were reviewed in [9]. A hierarchical control framework for the autonomous, reliable, and safe operation of networked lunar microgrids was also presented in [9]. In addition to the degradation phenomena in components of various space microgrids and state-of-the-art space technologies for electricity generation and storage, Reference [10] summarized needs, life cycle costs and economic challenges for future extraterrestrial microgrids. Moreover, Zdiri et al. [11] provided a review of microgrids in space applications. In particular, the review [11] categorized major space microgrid technologies according to their application, infrastructure, and end-user needs. Also, Zdiri et al. [11] considered space microgrid control and power management strategies and protection schemes. Furthermore, the energy requirements and currently used battery technologies for various space applications were reviewed and discussed in [12]. The reviews [9–12] included a few hundreds of research papers, which confirms the high significance of research on space microgrids and their components. In addition to the reviewed literature, there are a number of other publications that also represent the relevant state-of-the-art. An overview of the most important publications among them follows.

Various topics related to lunar base design and development are considered by a number of researchers in a handbook edited by Eckart and Aldrin [13]. A resiliency-based planning methodology for networked lunar microgrids using hybrid-edge rewiring was proposed in [14]. Optimal sizing and siting of a photovoltaic (PV) and battery based lunar microgrid was carried out in [15]. Optimization of electricity generation and energy storage capacities for lunar microgrids was also conducted in [16]. Energy storage requirements for a lunar DC microgrid system were considered in [17]. In [18], a high-fidelity simulation of a lunar power system consisted of two microgrids was used to test the performance of a three-level hierarchical control scheme. Some infrastructure needs, power architecture concepts and supervisory on-line control systems for lunar microgrids and habitation were considered in [19, 20]. An adaptive droop control approach for two networked lunar DC microgrids based on a power hardware-in-the-loop principle was developed in [21]. A DC microgrid consisting of PVs and an energy storage system for sustainable electricity generation at a lunar base was proposed in [22]. Electrification of the moon using nuclear reactors and refracted light was analyzed in [23, 24].

An autonomous power control and energy management system for a lunar microgrid was modeled and optimized in [25, 26]. The need for energy storage using resources available at the lunar surface was considered in [27]. The size of a microgrid required for a potential habitat in lunar non-polar regions was optimized in [28]. The variations in key parameters of microgrids in extreme lunar environments, such as cable power losses, cable weight, and the weight of step-up/down converters, in relation to wire gauge, transmission capacity, voltage grade and distance were systematically analyzed in [29]. A systems engineering methodology to assess the trade-space of microgrid resilience and mass was established and demonstrated in [30]. A techno-economic analysis and optimal sizing of a hybrid lunar microgrid consisting of a PV system, an electrolyzer, a battery storage, a hydrogen storage tank, and a hydrogen fuel cell was performed in [31]. Key technological challenges and systemic solutions for long-term energy needs on a lunar base were discussed in [32]. MacRobbie et al. [33] showed that lunar made PV cells could be a viable technology to enable a sustainable In-Situ Resource Utilization (ISRU) based lunar infrastructure and modern economy.

Based on the review papers [9–12] and the publications reviewed here, it is evident that the electrification of the moon, as well as the microgrid architectures/configurations that could be installed there, have been considered by numerous scientists, researchers and engineers. If all current research results on lunar electrification are viewed through the prism of new knowledge about lunar service (environmental and operating) conditions, as well as the moon in general, gathered by NASA, ROSCOSMOS, CNSA, and other space agencies, then it is clear that there is still much that needs to be learned, discovered, explained, improved, innovated, etc. All future research will be even more interesting if the following facts are taken into account: (i) There are extreme environmental conditions on the moon. (ii)

The current costs of shipping material from the earth to the moon range roughly from one to 1.3 million US dollars per kilogram [34]. (iii) There are no launch pads on the moon for spacecraft to return to Earth. (iv) There are still no lunar facilities for rocket fuel production. (v) It has not yet been determined how and where radioactive waste from nuclear reactors will be stored and how the lunar environment will be protected. Thus, all interpretations of these topics could be of interest to readers of ICCK Transactions on Electric Power Networks and Systems, and potential authors are encouraged to write about them. Finally, this editorial provides potential authors with the newest knowledge about extreme lunar environment, some general and important details on lunar microgrid architectures and their components, as well as some research challenges in the conclusion.

2 Lunar Environment

Artemis II and more than a hundred other robotic spacecraft missions have confirmed and advanced scientists' understanding of the extreme lunar environment and the operation of electric power components and microgrids on the moon. Although the moon lacks an atmosphere or climate similar to Earth, the newest observations and collected data validated models relating to the lunar weather, water cycles, electrostatic dust levitation and micrometeorite impacts. According to [35–41] and other available literature, it is evident that a lot is already known about the extreme lunar environment. Some of these findings and details are given in the following paragraphs.

Based on how much sunlight reaches the lunar surface, planetary scientists distinguish the following primary illumination regions on the moon: Permanently Shadowed Regions (PSRs), Persistently Illuminated Regions (PIRs), and Periodically Illuminated Regions. Each of these illumination regions has its own climatic specificities. For the installation of the first microgrid on the moon, the most interesting are the crater rims at the lunar South Pole, where sunlight comes almost continuously throughout the year. Specifically, these crater rims are exposed to sunlight 80 to 90% of the time during the year. In such places, energy storage requirements should be minimized due to the absence of eclipses, while lunar surface operations should be maximized.

There are two primary lunar periods, namely: sidereal month (or true orbital period) which lasts 27.32 days and synodic month (or lunar phase cycle) which lasts 29.53 days. The sidereal month represents the actual physical time the moon takes to circle Earth 360 degrees (one full revolution). In addition, the synodic month is the time between consecutive identical phases, such as from one New Moon to another. A single "daytime" (sunlight) and "nighttime" (shadow) on the moon each last about 14.75 Earth days. Also, humans from Earth always see only one side of the moon because the Moon is tidally locked to Earth. The equatorial radius of the moon is exactly 1738.1 km, which is approximately 0.2725 the size of the Earth's equatorial radius (6378.1 km). Consequently, the gravitational acceleration on the surface of Moon is about one sixth of the gravitational acceleration on the surface of Earth.

The Moon's surface is covered by a layer of unconsolidated rocky debris, dust and boulders known as lunar regolith. The regolith layer was formed by intense micrometeorite impacts and solar wind bombardment. The thickness of the regolith layer on the moon ranges from 4 to 5 meters in the lunar mare regions and up to 10 to 15 meters in the lunar highlands. The lunar regolith could be used as a building or shielding material and as a source from which to extract oxygen from its oxygen-containing minerals. For lunar regolith at 250 K, the thermal conductivity and the average density were found to be in the ranges of 0.01-0.03 W/(m·K) and 1825-1960 kg/m^3, respectively. The specific heat of lunar regolith is heavily dependent on temperature, ranging from about 300 J/(kg·K) at 100 K to about 800 J/(kg·K) at 350 K. Lunar regolith is also highly electrostatic due to solar wind bombardment and the lack of an atmosphere, which causes fine dust particles to accumulate strong electrical charges. These charged particles can spontaneously detach, levitate, and cling tightly to PV panels and other components, devices and equipment. ISRU focuses on processing lunar regolith to extract critical life-support consumables and building materials.

On the surface of the moon, water exists in the form of water vapor and ice. This means that any water vapor that reaches the surface of the moon from comets, micrometeorites and other meteorites remained trapped in PSRs because the temperatures are very low there and there is no significant atmosphere. NASA, ROSCOSMOS, CNSA, and other space agencies plan to harvest these trapped amounts of water vapor and ice and produce drinking water and rocket fuel (hydrogen and oxygen). "Daytime" temperatures near the lunar equator reach 114-124

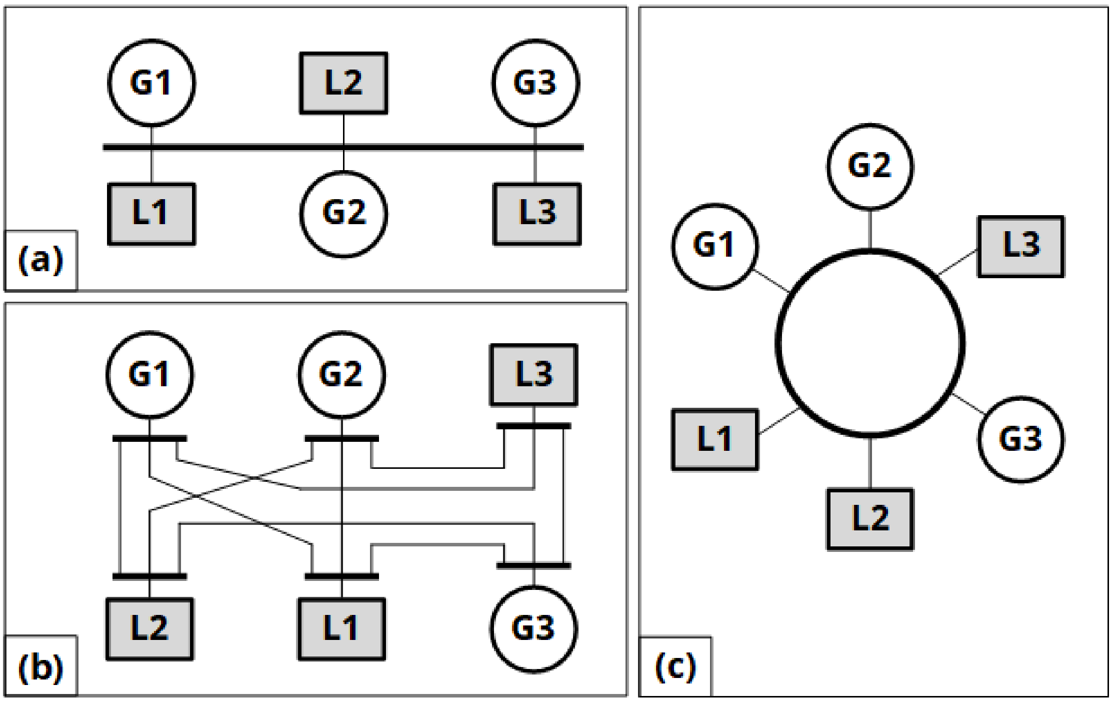

Figure 1. Potential architectures of lunar microgrids; (a) Radial architecture; (b) Mesh architecture; and (c) Ring architecture. G1, G2 and G3 stand for electricity generation, i.e., generators, and L1, L2 and L3 stand for electricity consumption, i.e., loads.

°C (387-397 K), while "nighttime" temperatures get to -173° C (100 K). The lunar poles are even colder, where an average temperature of -183 °C (90 K) was measured at the bottoms of several permanently shadowed craters at the lunar South Pole (i.e., PSRs), making it the coldest temperature measured anywhere in the Solar System. This average temperature never exceeds -173 °C (100 K).

The Moon's atmosphere is very thin, contains small amounts of gases such as helium, neon, hydrogen and argon and is known as the exosphere. Because it has no significant density, the exosphere cannot accumulate heat and transfer heat by convection (free or forced), or form the currents of gases that would drive traditional wind turbines. Thus, from the standpoints of thermophysics, aerodynamics and fluid mechanics, the exosphere can be considered a vacuum (i.e., a space that contains little to no matter).

3 Lunar Microgrids and Their Components

In general, a lunar microgrid is a group of interconnected electricity generation components (generators and batteries) and electricity consumptions (loads) acting as a single controllable entity. A lunar microgrid should operate in either island or networked mode. As on Earth, the architecture of future lunar microgrids can be radial, mesh, or ring-shaped. Figure 1 shows potential radial (Figure 1(a)), mesh (Figure 1(b)) and ring (Figure 1(c)) architectures of future lunar microgrids with three generators (G1, G2 and G3) and three loads (L1, L2 and L3). These architectures will be hybrid microgrids that utilize both DC and AC power types. DC power will be used for habitat, ISRU, energy storage and rovers, while three-phase and single-phase AC power will be used for electricity transmission/distribution and specific sensitive payloads. As for the power frequency and voltage in the first lunar microgrid, they should be in the ranges of 60-1000 Hz and 0.6-6 KV [42], respectively. To provide continuous, highly efficient electricity supply for the Artemis Base Camp, NASA and researchers at Sandia National Laboratories have designed a closed Brayton cycle generator that produces AC power at a frequency of 1 kHz.

Ring architectures add roughly 50% more mass than a radial design, while mesh architectures double it. While ring and mesh architectures drastically increase microgrid reliability, they require significantly more additional mass of power cables, critical cable accessories and converters [35, 42]. AC and DC microgrid architectures are generally comparable in mass for the voltage range from 1 to 3 kV. Accordingly, increasing voltage in a lunar microgrid up to 3 kV has large mass advantages [35]. At a single voltage

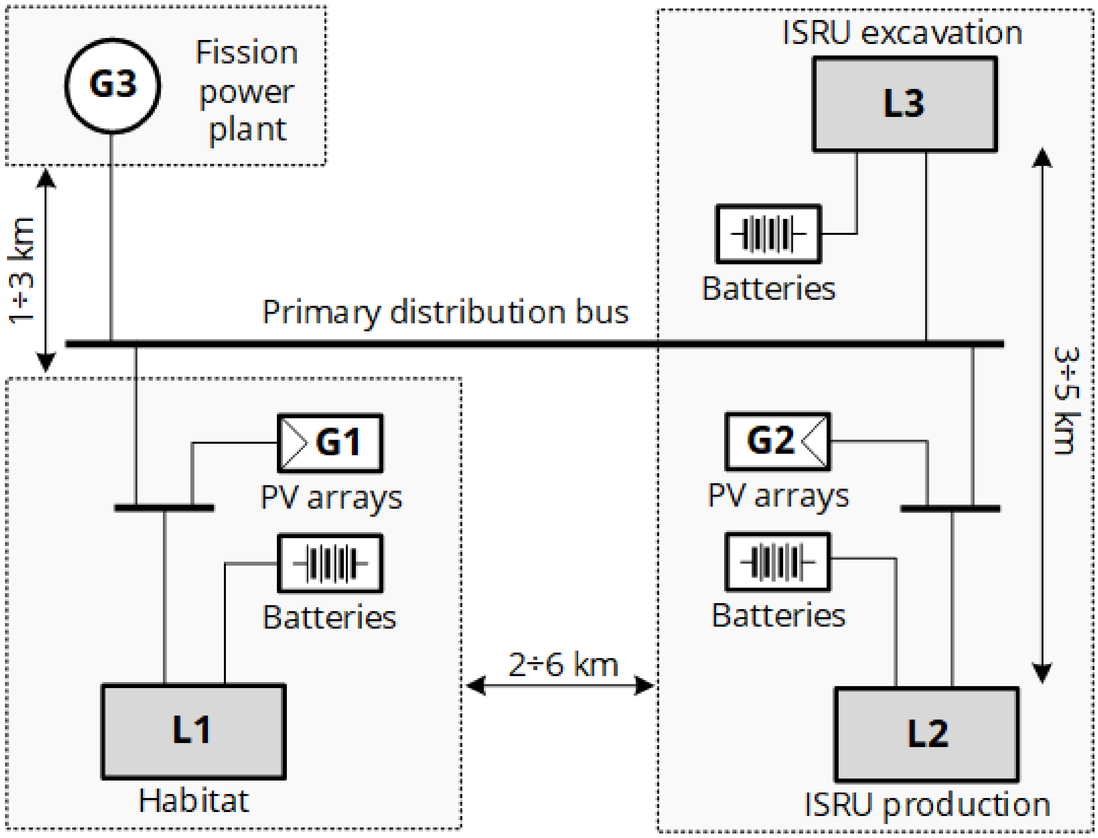

Figure 2. Possible features of a fission-PV-battery hybrid radial microgrid for the lunar South Pole.

from the range of 1-3 kV, the mass benefit of one DC architecture over the corresponding AC architecture is slight, that is, marginal [35, 42]. In addition, at voltages higher than 3 kV, the mass of a DC architecture is lower than the mass of a corresponding AC architecture. The most important factor for decreasing mass of the first lunar microgrid architecture is to increase voltage in it (for instance, to 6 kV). All these comparisons are valid under the assumption that the masses of power cables, critical cable accessories (connectors) and converters are taken into account, but not the masses of electricity generators and battery energy storage systems. According to NASA's researches and plans [35, 42], the first lunar microgrid should be hybrid, radial, islanded and modular. Figure 2 shows a fission-PV-battery hybrid radial microgrid for the habitat, ISRU needs, various rovers and sensitive payloads at the lunar South Pole, the so-called LunaGrid.

LunaGrid will become operational by the end of this decade and will support the Artemis Base Camp. Just like every island microgrid on Earth, LunaGrid will have its own size and level of complexity, as well as the following key components: (i) electricity generators, (ii) battery energy storage systems, (iii) electrical loads, (iv) transmission and distribution lines, and (v) an autonomous control system.

The nuclear power plant connected to LunaGrid will have the ability to integrate several fission reactors with a total power of up to 100 kW [43]. Initially, this nuclear power plant will contain only one 40 kW fission reactor that will be mobile (carried by a special rover) and separated at least 1 km from other assets (habitat, ISRU excavation and ISRU production) [35, 42]. This NASA's project is known as Fission Surface Power (FSP) Project. FSP will provide electricity during periods of darkness, targets an operational lifespan of 10 years and will weigh less than 6000 kg (with up to 150 kg/kW) [44, 45]. Also, this FSP has a low technology readiness level, which represents its basic limitation. Special PV arrays are also planned to be used to power the loads in LunaGrid shown in Figure 2. This project, led by STMD's Game Changing Development program and NASA Langley Research Center in collaboration with NASA Glenn Research Center, is known as the Vertical Solar Array Technology (VSAT) project [35, 42]. VSATs are autonomous deployment systems of about 30 meter masts and minimized mass (as well as volume), 10 kW of power at a DC voltage of 100 V, stable on steep terrain and resistant to the abrasive effects of lunar regolith [35, 42]. VSATs cannot provide electricity all year round and have a lower technology readiness level. Although it is not indicated in Figure 2, hydrogen fuel cells [31], regenerative fuel cells (having a low technology readiness level) [42], thermoelectric generators [46], radioisotope power systems (which convert heat produced by natural isotopic decay into electricity) [47, 48], or laser power beaming architectures [49] could also be used as electricity sources for LunaGrid and other lunar microgrids.

According to Figure 2, each asset is paired with its own battery energy storage system to provide a supplemental source of electricity during the lunar "nighttime". However, today's battery energy storage systems are heavy and cannot operate well at extremely low temperatures [42]. In this regard, some global companies are already working together on developing, integrating and optimizing scalable energy storages for the harsh thermal and vacuum conditions that exist on the lunar surface [50].

The first part of the total electricity consumption in LunaGrid refers to the habitat and consists of crew demands of 20 kW and maintenance demands of about 2 kW. The 20 kW active load includes the needs of four crew members during their activities (30 or more days 4 times per year), while the 2 kW "keep-alive" power should maintain basic habitation systems (for critical temperature control, avionics and health monitoring) during uncrewed periods [42]. The second part of the total load in LunaGrid relates to ISRU needs and includes peak power of 60-70 kW for the needs of regolith mining and its conversion into other resources, as well as maintenance demands of about 12 kW "keep-alive" power for ISRU operations during periods of heavy insolation [42]. The third part of the consumption, amounting to 500 W to 1000 W [42], relates to specific sensitive payloads, that is, lunar science and exploration using various rovers and ultra-sensitive instrumentation. Moreover, it will be possible to connect additional power loads to the primary electricity distribution bus of LunaGrid [35].

For the hybrid radial microgrid in Figure 2, the total length of transmission and distribution lines should be between 6 and 14 km, and their power-carrying capacity should be approximately 100 kW [42]. As for DC lines, constraints related to radiation hardening of electronic components limit the DC voltage to a value lower than or equal to 1.5 kV. However, the DC voltage of 1.5 kV is not sufficient for the transmission of electricity and it needs to be increased [42]. As is known, the electricity can be transmitted more efficiently at AC voltages, which leaves the possibility of switching from the transmission of 100 kW to several hundred MW or one GW in the future. When all advanced cable, connector and converter technologies are available, a three-phase AC voltage of 3 kV (with a frequency of 1 kHz) represents the optimal mass-minimizing solution for long-distance distribution and transmission lines in LunaGrid. Indeed, this solution has been singled out and recommended by NASA [42]. Cable lines in LunaGrid will primarily run subsurface and be heavily shielded to protect against the electrostatic and abrasive lunar regolith, extreme temperature variations, and micrometeoroid impacts. Specifically, autonomous and teleoperated rovers will automatically unspool, install and interconnect these cable lines below the lunar surface.

The autonomous control system of the first lunar microgrid will rely on a hierarchical multi-layer control strategy to balance power across the habitat, ISRU-based infrastructure, rovers and landers. Such a strategy was chosen with the aim of increasing the resilience, reliability and autonomy of LunaGrid [35]. According to [35], this control system will have a central microgrid controller (called Lunar Controller), a local habitat controller (called Habitat Controller) and a local ISRU-based infrastructure controller (called ISRU Controller). In general, the autonomous control system of LunaGrid will coordinate generators, balance electrical loads, regulate voltages, reconfigurate microgrid, achieve fault-tolerance, prevent cascading failures, achieve interoperability, maintain microgrid stability, etc.

4 Conclusion

Based on the content of the previous sections, potential authors may find it interesting to focus on the following challenges:

- Optimal sizing and siting of a hybrid lunar microgrid consisting of a PV system, a fission reactor, a thermoelectric generator, an electrolyzer, a battery energy storage system, a hydrogen storage tank, and a regenerative fuel cell, or any other similar lunar microgrid.
- A techno-economic analysis and optimization of a hybrid lunar microgrid that would contain a radioisotope power system or a laser power beaming architecture instead of a fission reactor.

- Possibilities for increasing the technology readiness level of the Fission Surface Power, Vertical Solar Array Technology, regenerative fuel cells and other components of lunar microgrids.
- Increasing DC voltage for electricity transmission in lunar microgrids from 1.5 kV to 3 or 6 kV.
- Research related to improving the energy conversion efficiency of thermoelectric generators and their potential applications on the moon.
- Possibilities for reducing the current prices of delivering electric power components, devices and equipment to the moon and establishing the price for shipping ISRU products and other cargo to the earth.
- Extending lifespans of electric power components, devices and equipment used in lunar microgrids.
- Building launch pads on the moon for spacecraft to return to Earth and their energy needs.
- Production of rocket fuel on the moon and its use for the generation of electricity.
- Effects of extreme lunar environmental conditions on the continuously permissible currents (ampacities) of regolith-buried power cables.
- Management and storage of radioactive waste on the moon.
- Is there a need to protect the lunar environment?

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Conflicts of Interest

Dardan Klimenta served as an Editor-in-Chief of the *ICCK Transactions on Electric Power Networks and Systems* at the time of manuscript submission. To ensure the integrity of the peer-review process, Dardan Klimenta was not involved in the editorial handling, peer review, or decision-making process for this manuscript, which was handled independently by another editor. The remaining authors declare no conflicts of interest.

AI Use Statement

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Ethical Approval and Consent to Participate

Not applicable.

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