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Microgrid Systems in Space: A Comprehensive Exploration of Advanced Power Technologies, Energy Efficiency, and Sustainable Construction

Xiran Tan[1] *, Lauren Low[1], Lakshmi Chakka[1], Nicolas Chan[1]

[1]Northwood High School, Irvine, CA, USA
*Corresponding Author: xirantan7@gmail.com

Advisor: Emma Zschunke, EmmaZschunke@iusd.org

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Abstract

As humanity sets its sights on establishing habitats beyond Earth, ensuring sustainable space settlements becomes a crucial goal. Space presents unique and harsh conditions that require power solutions beyond the capabilities of traditional terrestrial power systems. This paper explored the critical factors, technologies, and construction techniques necessary for successfully implementing microgrid electricity systems in space settlements. The paper introduced several key technologies in the development of space microgrid systems, including wireless power transmission, advanced energy storage solutions, modular construction techniques, and smart grid technologies. Each of these technologies was explored in detail to demonstrate how they contribute to the overall sustainability and efficiency of space microgrids. Key findings highlighted the advantages of integrating these technologies to improve energy efficiency, stability, and resilience in extraterrestrial settings. Potential applications included the use of space-based solar power, nuclear fission, and hybrid systems to ensure continuous power availability, the use of supercapacitor to improve power storage systems, the use of various construction technologies. These results underscored the importance of microgrid systems for the successful establishment of sustainable space settlements.

Keywords: Microgrid system, Space settlement, Wireless power transmission, Energy storage, Sustainability, Space-based solar power

1. Introduction

The development of efficient and reliable power systems is critical for future space settlements. Compared to the land-based grid electricity system on Earth, possible inefficiencies in energy distribution, influence of different environment factors, limitations in scalability, and sustainability concerns need to be taken into consideration when developing electricity system in other planets for building space settlements. One promising solution is the use of microgrid systems—self-sustained electrical networks that provide a stable and reliable power supply. Microgrids are capable of seamlessly integrating various power sources, such as solar power, energy storage systems, and distributed generation, ensuring reliable power in isolated or challenging environments like space. Microgrids have advantages particularly in space environments. Their modular nature makes them scalable, allowing for gradual expansion to accommodate the increasing energy demands of a growing settlement. Moreover, the adaptability of microgrid systems has the potential to address the extraterrestrial environments. Settlements on extraterrestrial surfaces, such as the Moon or Mars, must contend with harsh conditions, including extreme temperature variations, high levels of radiation, and micrometeorite impacts, which require specifically designed technologies.

This paper aimed to explore the potential of microgrid systems for space settlements, focusing on their development, key technologies, energy efficiency, sustainable construction techniques, and adaptability in extraterrestrial settings.

2. Methods

A systematic literature review was conducted to explore the application of microgrid systems in space settlements. This review was designed to compile and synthesize existing research pertaining to the technological, operational, and construction aspects of microgrid systems relevant to extraterrestrial environments.

The review included an extensive search across multiple academic and technical databases, including IEEE Xplore, ScienceDirect, Google Scholar, NASA, etc. These sources were selected for their broad coverage of peer-reviewed journals, conference proceedings, and technical reports. Articles were selected based on their significance, excellence, and timeliness. Only studies that made significant contributions to the understanding of microgrid technologies and related applications, provided detailed descriptions of technological advancements, or proposed innovative strategies for addressing unique challenges in space environments were included. The publication date was also considered, with a preference for materials published in the last 10 years to ensure the information is up-to-date.

After identifying suitable studies, a systematic approach was taken to assess their contributions. The literature was categorized based on key aspects, including power generation methods, transmission technologies, energy storage solutions, and construction techniques. The data extracted from each study were organized to allow for a comparative analysis of different technologies and their potential applications in space settlements.

3. Results

3.1 Implementation

Microgrid power systems convert energy from sustainable sources, such as solar panels or space-based solar power, into usable electricity. They ensure efficient energy storage for long-term use. Microgrid power systems involve integrating various essential technologies that would be applied to energy generation and transmission section, power storage system section, and power management section, aiming to be highly beneficial for sustainable construction in space by providing relatively stable power supplies to operations and sustaining life in the settlements.

Power Generation and Transmission

Power generation and transmission are fundamental parts in the development of space microgrid system. Establishing a reliable and efficient power infrastructure is essential to space settlements, enabling life support, research, and other critical activities. This subsection explored various technologies for generating and transmitting power in space. By analyzing these technologies, we aim to identify their potential applications, benefits, and challenges in supporting the long-term sustainability of space habitats.

- *Space-Based Solar Power and Wireless Power Transmission Technologies*

An ideal power generation method is Space-Based Solar Power (SBSP), with greater accessibility in space. SBSP involves placing solar panels in orbit, allowing continuous energy capture without interruptions from atmospheric interference or the day/night cycle. This approach ensures that energy can be collected throughout all phases of a settlement, providing a potentially unlimited energy supply, which is especially crucial for space habitats that must function independently of Earth. The primary implementation for SBSP is having microwave transmitting solar satellites and laser transmitting solar satellites that have solar panels placed to convert solar radiation into microwave or laser.

To transmit energy from orbit to ground, SBSP systems primarily rely on Wireless Power Transmission (WPT), including microwave transmission, laser transmission, and radio frequency transmission upon demands from the energy sources. WPT offers flexibility in power distribution without the constraints of physical infrastructure, which can be challenging to install and maintain in harsh extraterrestrial environments. According to Ayling A., et al. (2024), while numerous small sources in the phased arrays are used to focus the transmitted energy on multiple receivers with the adjusting capability of each element, energy can be received at multiple selected locations through WPT without moving the transmitter.

To explore the potential of microwave-based WPT in real-world space applications, MAPLE (Microwave Array Power Transfer LEO Experiment) developed by the Caltech team aims to test the feasibility of microwave-based wireless power transmission from low earth orbit to earth or space receptors. Successfully detecting the MAPLE's beam in all three attempted beam-to-Earth experiments has demonstrated microwave-based WPT's potential for space energy generation and transmission.

Laser power transmission (LPT), a promising WPT method, is particularly effective when paired with optimized power conversion materials. For instance, Zheng., et al. (2024) report that laser power converters (LPCs) used in LPT paired with specific wavelengths can achieve power conversion efficiencies (PCE) of up to 74.7% at 808 nm, making laser transmission a highly efficient method for energy transfer when paired with GaAs-based converters. To illustrate the variation in efficiency by wavelength and material, Table 1 adapted from Zheng Y., et al. (2024) provides a comparative summary of LPC efficiency across different laser wavelengths and materials. This table helps visualize how adjustments in wavelength and material, such as using GaAs at 808 nm, can yield optimal efficiency for specific LPT applications, supporting the importance of matching the laser source with the receiving material for improved performance.

Table 1. Efficiency and laser density by wavelength and material (Zheng et al., 2024).

Year	Wavelength (nm)	Materials	Efficiency (%)	Laser density (W/cm^2)
1977	850	$Al_xGa_{1-x}As$-GaAs	46.0	0.5
1991	806	$Al_{0.3}Ga_{0.7}As$	52.1	0.1
2007	810	GaAs	52.7	22
2008	810	$Al_{0.05}Ga_{0.45}In_{0.05}As$	54.9	36.5
2016	850	GaAs	64.3	36.5
2021	858	AlGaAs-GaAs	68.9	11.4
2022	808	GaAs	74.7	7
2010	1030	Si	35.0	20-30
2013	1550	InGaAsP/InP	44.6	0.1
2018	1064	$In_{0.24}Ga_{0.76}As$/GaAs	46.8	6
2020	1064	$In_{0.23}Ga_{0.77}As$	50.8	3.2–6.5
2002	532	InGaP	40.0	0.26
2021	638	InGaP	43.0	17
2023	532	$FAPbBr_3$	43.02	0.07
2023	660	PBDB-TF:BTP-eC9	36.2	0.01

Each type of WPT has distinct advantages: laser beams can be more focused, offering highly efficient point-to-point energy transfer, while microwave beams are less affected by atmospheric interference, making them more reliable for transmission from space to Earth. The end-to-end efficiency of the full LPT system in current configurations averages around 20%, due to transmission losses influenced by environmental factors like medium absorption and scattering.

The two kinds of SBSP solar satellites can be compared based on the different types of WPT technologies required and the characteristics of the medium they use.

Table 2. Microwave and Laser Transmitting Satellites Comparison

Feature	Microwave Transmitting Satellites	Laser Transmitting Satellites
Transmission Medium	Microwaves	Lasers
Atmospheric Interference	Less affected by atmospheric conditions	More affected by atmospheric conditions
Beam Divergence	Higher divergence, requiring larger rectennas	Low divergence, more focused
Ground Receiver	Rectennas (large area required)	Photovoltaic receivers (smaller area)
Energy Density	Lower energy density	Higher energy density
Targeting Precision	Moderate	High
Use Case	Suitable for wide area energy distribution	Ideal for targeted energy applications

- *Earth-Based Solar Photovoltaic Technologies and Cabled Wire Transmission*

Solar Photovoltaic (PV) Panels installed on ground is another method of generating power for space microgrid system. Solar PV panels operate by converting sunlight directly into electricity, making them a well-tested technology that provides a relatively straightforward approach to energy generation in space. Solar PV panels use photovoltaic cells that absorb photons from sunlight and convert them into electrical energy through the photovoltaic effect, which provides a dependable source of power as long as sunlight is available.

To transmit the energy generated by PV panels, cabled wire systems are often employed. These transmission cables can be installed on the surface or underground to protect them from extreme environmental conditions, such as temperature fluctuations and potential physical damage from micrometeorites.

Solar PV panels are advantageous due to their maturity as a technology, straightforward implementation, and relatively low cost compared to other power generation methods. However, they face significant challenges, particularly the susceptibility to efficiency drops during extended periods of darkness. Additionally, the presence of atmosphere can significantly reduce the amount of solar energy captured by panels on the ground compared to space. For example, NASA reported about 23% percent of solar energy would be absorbed by the Earth's atmosphere.

- *Nuclear Fission-based Power Technologies and Cabled Wire Transmission*

The Kilopower Reactor Using Stirling TechnologY (KRUSTY) is a nuclear fission reactor proposed as an alternative to solar power according to Diptish S., et al. (2021). Its independence on environmental conditions make it an alternative solution for long-term or base-load power needs in extraterrestrial habitats.

KRUSTY system operates by utilizing nuclear fission to generate heat within a solid block of highly enriched uranium. This heat is then transferred via sodium heat pipes to Stirling engines that convert thermal energy into electricity. The sodium heat pipes provide redundancy in heat transport, enhancing the overall reliability of the system. Even if one or more heat pipes fail, the reactor can continue functioning at reduced power levels, ensuring a consistent energy supply. Power generated by the KRUSTY reactor is transmitted using direct cabled connections to different parts of the settlement. According to Gibson M., et al. (2018), KRUSTY is completed and tested at the Nevada National Security Site in a space-simulated environment.

KRUSTY can provide higher energy density compared to solar power, making them suitable for supporting energy-intensive activities. However, the use of radioactive materials presents challenges, such as the need for safe handling, transportation, and storage.

- *Comparison of Generation and Transmission Systems*

Given the unique advantages and challenges of each system shown in Table 3, hybrid power systems might be a promising approach for space microgrid development that worth to research further. Hybrid systems can combine different power generation methods, such as SBSP and nuclear fission reactors, to provide a more resilient and flexible power supply.

Table 3. Power Generation Technologies With Transmission Methods Comparison

Power Generation Method	Advantages of Generation Method	Disadvantages of Generation Method	Trans-mission Method	Advantages of Transmission Method	Disadvantages of Transmission Method	Best Use Stage
Microwave /Laser Transmitting SBSP	Continuous energy supply, eliminates day/night cycle interruptions	Requires sophisticated space infrastructure, high development cost	Wireless Power Trans-mission	Flexible energy delivery, high energy density with precise targeting (laser), less atmospheric impact (microwave)	Large receivers required for microwaves, laser susceptible to atmospheric conditions	Early-stage development, Broad area distribution (microwave) and targeted applications (laser)
Earth-Based Solar PV Panels	Mature technology, relatively low cost, straightforward implementation	Susceptibility to dust, day/night cycle interruptions, installation challenges	Cabled Trans-mission	High efficiency with minimal energy loss, well-suited for stable infrastructure	Requires significant infrastructure for cables, Installation challenges due to terrain, lack of flexibility, vulnerable to physical damage	Settled habitats with permanent infrastructure, Supplementary Energy supply
Nuclear Fission (KRUSTY)	Consistent power output, independent of solar conditions, high reliability	Handling radioactive materials, need for heat dissipation, significant infrastructure requirements				Long-duration energy supply for stable habitats

For example, SBSP can provide energy during periods of sunlight, while nuclear reactors can ensure a consistent supply during lunar nights or Martian dust storms. By integrating WPT with cabled transmission, hybrid systems can optimize energy distribution, using WPT for flexible power delivery and cabled transmission for stable, high-capacity needs.

The selection of power generation and transmission technologies should be guided by the specific stage and requirements of the settlement. Early-stage, modular settlements may benefit from the flexibility of WPT combined with SBSP, while more established bases could rely on nuclear fission and cabled systems for consistent and stable energy. Hybrid systems would likely to offer a comprehensive solution that balances the strengths and mitigates the weaknesses of individual technologies, providing a robust framework for sustainable energy in space settlements.

- *Underground Wire Transmission*

The transmission cables would connect the receptors to the various loads within the microgrid, and deliver electricity to each household or infrastructure. Besides mostly seen cabled wire, underground transmission cable sessions (UTCS) can be constructed to shield the wires and minimize the risks of being damaged by grit and extreme weather, providing long-term stability. Meanwhile, compared with overhead conductors, UTCS would have a lower loss of transmission and lower resistivity.

Table 4 Simulation results of overhead transmission lines (Khan et al., 2014).

Voltages Level (kv)	Powers in MW		Losses (%)	Voltage drops (kv)
	Sending end power (MW)	Receiving end power (MW)		
230	94.97	93.94	1.10	11.4
345	153.5	152.2	0.53	6.8
500	255	254.2	0.315	5.4
765	361.9	361.2	0.3147	1.3
1100	521.2	521	0.115	-2

High-power gas-insulated underground transmission lines can be incorporated into UTCS. According to Tenzer M., et al. (2016), Gas Insulated Lines (GIL) technology provides high power transmission capability, less resistive losses, a low capacitance, minimized magnetic field, and low demand for maintenance, which suit the environmental needs. GIL enhances safety and resilience in extraterrestrial conditions. Using pressurized gas as an insulating medium (typically a mixture of nitrogen and sulfur hexafluoride) creates an ideal environment for high-voltage transmission by preventing electrical discharges and diluting the risk of power outages. From the stimulation done by Khan D., et al. (2014), a greater increase in the rate of loss reduction, as shown in Table 4 and 5, can be observed for GIL than overhead wire when voltage increases.

Table 5 Simulation results of GIL (Khan et al., 2014).

Voltages Level(kv)	Powers in MW		Losses (%)	Voltage drops (kv)
	Sending end power (MW)	Receiving end power (MW)		
230	160.1	159.3	1.13	2.2
345	159	158.7	0.19	0.1
500	260.7	254.2	0.15	-0.6
765	365.6	365.2	0.11	-2
1100	523.1	522.5	0.114	-4

This is particularly advantageous in space settlements, where minimizing maintenance and ensuring continuous operation are critical due to limited human intervention. GIL systems are designed to operate under extreme conditions, including temperature fluctuations and high levels of radiation, which would be common on other planets.

However, heat dissipation is one of the primary challenges in underground installations, as cables buried underground need effective thermal management to avoid overheating, which can lead to reduced efficiency and system failure.

One solution to address heat dissipation concerns is the use of Fluidized Thermal Backfill (FTB). The research by Quan L., et al. (2019) highlights that applying FTB significantly enhances the thermal performance of buried power cables, particularly in configurations like Flat and Trefoil formations. For instance, with the use of FTB, the ampacity—the maximum electric current a conductor can carry—of Flat and Trefoil formations increased to 1599.3A and 1500.9A, respectively, compared to 1396.4A and 1248.5A without FTB. This increase in ampacity indicates improved heat dissipation, allowing for higher power loads without risking overheating. Additionally, FTB helps maintain lower and more consistent cable temperatures under extreme operating conditions. The maximum cable temperature (Tm) for Flat formation ranges from 319.8K to 332.2K when using FTB, while for Trefoil formation, it ranges from 323.3K to 337.4K. These values are well below the limiting temperature of 363K, ensuring that the system remains within safe operational limits even at high power loads. Flat formations, which have wider spacing between cables, generally perform better in terms of heat dissipation compared to Trefoil formations. The more uniform spacing helps reduce thermal buildup, which is especially beneficial when FTB is used, resulting in lower operating temperatures and improved system reliability.

With GIL technology and FTB incorporated into underground transmission wire systems, space microgrid systems can benefit from both reduced resistive losses and enhanced heat management, ensuring that underground cables can handle high voltages while maintaining thermal stability with protection from environmental hazards.

Power Storage System

Effective power storage systems are essential to maintain a sustainable power supply as they offer flexibility in varying energy storing conditions and discharge requirements within microgrids. Advanced storage technology should be able to store surplus energy during high-production periods with high energy density and release to be successfully operated in unpredictable extreme space environments.

Supercapacitors have the advantage of charging and discharging rapidly, which is beneficial for managing power fluctuations in dynamic space environments. Thus, they can help stabilize energy flow better than traditional power storage systems. When supercapacitors are integrated with wireless power transmission systems, where power input might vary due to atmospheric or orbital conditions, being able to stabilize the system is crucial. Supercapacitors stabilize the system by coordinating the short-term peaks and dips in power generation, for instance, during the transition between daylight and shadowed periods for solar arrays in orbit. Being able to buffer these fluctuations, supercapacitors can provide a smoother energy supply that prevents possible disruptions to essential infrastructure in space settlements, such as life support systems or communication networks.

One significant risk in power storage systems is the possibility of power disruptions caused by varying environmental conditions in space, which can impact both generation and storage stability. To mitigate this risk, supercapacitors are particularly valuable for their ability to absorb sudden peaks or dips in power. In addition, hybrid systems combining supercapacitors with high-capacity battery banks can offer redundancy, reducing the vulnerability of the entire power system to failures by leveraging the complementary properties of different storage technologies. These systems ensure both rapid stabilization and long-term energy storage, thereby decreasing the likelihood of power interruptions that could compromise critical operations, such as communication or life support.

One of the key advantages of supercapacitors in space environments is their durability under extreme conditions. While the traditional batteries would degrade over time due to repeated charging and discharging cycles, supercapacitors retain minimal wear over numerous cycles, making them ideal for long-term use under the condition with limitations of maintenance and replacement.

While supercapacitors excel at rapid energy discharge and short-term stabilization, they do not perform that well in long-duration energy storage as their energy density is lower than that of traditional batteries – meaning that they cannot store large amounts of energy for extended periods. According to Khan H. and Ahmad A. (2024) Supercapacitors have an energy density of 5–20 Wh/kg, while lithium-ion batteries have an energy density of 100–265 Wh/kg. To solve this problem, supercapacitors should be paired with high-capacity battery systems that can store energy for longer durations to build up a hybrid storage system, according to Bocklisch, T. (2015).

Power Conversion and Management Systems

Power conditioning and conversion systems manage the flow of energy to ensure the energy harvested from energy sources is stable to transmit between ports and suitable for use by adjusting the voltage, current, and frequency to adapt to the various needs of the space settlement.

According to Zhu B., et al. (2020), multi-Input-Port bidirectional DC/DC converters allow energy flow in both directions, adding flexibility to the DC space microgrid. While multiple energy storage batteries to the DC bus can be connected at the same time to replace numerous high-cost large-size converters, the bidirectional converter has high voltage conversion gain and low switch voltage stress with controllable power flow to each battery. According to Wang C., et al. (2016), Bidirectional DC-DC converters can be more efficient than traditional DC-DC converters, which typically have an efficiency of around 95%. Bidirectional DC-DC converters can have a peak efficiency of nearly 97.6%.

3.2 Construction Techniques and Special Materials

Creating sustainable power systems is essential for space settlements as building on alternative celestial bodies requires the consideration of extreme temperatures, unpredictable weather conditions, and unsatisfactory atmospheric conditions. Microgrid systems, which provide reliable and adaptable power, are crucial for the sustainability of space habitats. Effective construction methods and materials include modular design, smart grid technologies, and advanced materials for shielding and component fabrication.

Modular Design

Microgrid systems are often constructed using a modular approach which allows for scalability and integration of additional components as energy demands increase. Modular systems can be transported in parts and assembled on-site, which is particularly beneficial for space settlements.

To improve material availability, which is the foundation for construction, in-situ resource utilization (ISRU) should be implemented to better utilize of local resources to reduce the difficulty of transportation and assembling. Lunar regolith, for example, can be utilized to create protective shielding or even used as a construction material for microgrid components. Meanwhile, ISRU techniques require further development for scalability in microgrid applications.

As launching payloads to space cost significantly, modular units must be designed with low-mass, high-strength materials that can withstand subsequent space conditions to minimize weight and costs. Carbon-fiber composites and lightweight alloys are explored as potential materials for microgrid modules to balance durability and mass. Carbon fiber is five times stronger than steel and twice as stiff. Carbon fiber composites can have a tensile strength of 400–500 ksi and are 42% lighter than aluminum of the same thickness. Sayam A., et al. (2022) showed that carbon fiber-reinforced polymer composites (CFRP) has lightweight nature with high strength and higher stiffness. Incorporating carbonaceous nanofillers such as carbon nanotubes (CNTs), graphene, or nanodiamonds can further enhance the mechanical properties of carbon-fiber composites as it would improve interfacial bonding and structural toughness of the carbon-fiber composites. These fillers help distribute loads more effectively and reduce micro-cracking, which is essential in the unpredictable environment of space settlements and would minimize damage of materials during transportation. 3D printing is also a promising way to fabricate carbon-fiber composites, further increasing the feasibility of modular construction on space.

3D printing is also useful for materials recycling. For example, metallic waste from old structures can be melted down and reformed into new parts using 3D printing. Recycling materials is an essential strategy for the sustainability of space settlements. Construction processes and decommissioned equipment generate waste that can be repurposed to build or repair microgrid components. Modular construction allows for the feasible disassembly and reuse of components. If an outdated or damaged part of the microgrid is no longer required, it can be deconstructed, and its materials can be repurposed. This approach minimizes waste, extends the lifespan of materials, and supports a circular economy within the settlement, contributing to both sustainability and resilience.

Smart Grid Technologies

Implementing smart grid technologies enhances the efficiency and reliability of microgrids. This includes advanced metering infrastructure (AMI), demand response, and automated grid management systems. Smart grids in space can manage power distribution and optimize energy usage based on real-time data.

Advanced Metering Infrastructure (AMI) plays a crucial role in space microgrids by providing real-time monitoring and data collection. However, in the context of space environments, the implementation of AMI faces challenges related to communication reliability and data transmission latency. For example, the harsh conditions of space, such as radiation, dust, and extreme temperature fluctuations, can interfere with communication signals and degrade sensors over time. To mitigate these challenges, AMI devices need to be designed with radiation-hardened components and equipped with redundant communication pathways to ensure uninterrupted data collection and distribution. For instance, sensor arrays must be capable of adapting to sudden temperature swings between -150°C and 120°C, while maintaining accuracy and precision in energy measurements.

4. Discussion

Considering the feasibility of using microgrid systems for isolated and remote power applications on Earth, several aspects of the technologies should be further explored and improved to ensure they can be implemented and greatly utilized in the space environment.

When integrating the Wireless power transfer (WPT) system into a microgrid system, minimizing the loss of energy during the conversion and transmission process is still a major challenge. Microwave-based systems like MAPLE might need to enhance beam precision in order to improve the efficiency of energy transfer from the space-based solar energy resources to the ground receivers that have been limited by beam divergence and atmospheric interference.

Underground Transmission Cable Sessions (UTCS) with gas-insulated lines (GIL) used would protect the cable from the possible extreme environment. However, there are potential construction and installation difficulties, including excavation and cable setting. Lightweight materials and automated construction technology can be further researched to facilitate the implementation of GIL systems for UTCS.

Power conditioning and conversion systems ensure stable energy delivery within the microgrid system. It might encounter challenges including voltage regulation, energy loss, and heat dissipation while the multi-input-port bidirectional DC/DC converters improve the system's flexibility by allowing energy flows in both directions. Future research could be conducted to develop advanced materials and heat management to improve the efficiency and durability of the system in space conditions.

The scalability and adaptability of microgrid systems should be improved as space settlements might expand, leading to greater demand for new energy sources and power. Microgrids can be expanded in scope and strength by adding new energy sources, storage systems, and transmission lines, because their modularity allows it to scale to cope with the growth of energy demand. But at the same time, it is necessary to ensure that the new integrated components are compatible with the original system. In order to better manage the diverse and growing microgrid systems, it is important to develop smart grid systems. With the rapid development of Artificial Intelligence, it is worth researching incorporating AI algorithms in building the smart grid system, for instance, developing models to detect errors to address different conditions using machine learning.

A significant challenge in researching the specific implementation steps for microgrid systems in space settlements is that space microgrid systems are not yet a well-developed technology and lack mature case studies. Space microgrids are still relatively conceptual. This lack of concrete examples makes it difficult to provide detailed step-by-step descriptions of how such systems can be scaled as space settlements grow. For instance, while the potential for adding power generation sources and storage incrementally is promising, the actual logistics of modular expansion, integration of new technologies, and maintaining compatibility with existing infrastructure in the unpredictable space environment remain theoretical. When more technologies are designed for space environment, further specifications of the implementation of microgrid system can be delved deeper.

5. Conclusion

In conclusion, microgrid systems are a well-suited solution for ensuring sustainable power in space settlements. With targeted construction strategies, by integrating advanced technologies like wireless power transmission, advanced energy storage and power management, microgrid systems have fewer limitations than traditional terrestrial power grids in the space environment. Yet challenges—such as optimizing transmission efficiency and addressing construction feasibility — urge further research and advancements of various components that could be utilized in space microgrid systems. As space exploration continues to progress, the development of space microgrids to ensure humanity's long-term survival in space will grow in importance.

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