



Space-Based Solar Power Satellite Construction: A Review

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Abstract:

This paper being with an introduction to the Microwave wireless power transmission technology has the potential to significantly enhance the endurance and range of unmanned systems, offering broad applications across various fields. One promising area is the Internet of Things (IoT), where this technology can effectively address the challenge of powering numerous devices, ensuring they remain operational without frequent battery changes or wired connections. Additionally, by integrating vehicle-mounted microwave power transmission, we can efficiently power swarms of unmanned aerial vehicles (UAVs), helping to establish an interconnected power network between air and ground systems.

In this study, we developed a comprehensive technical index system and test evaluation methods that are crucial for advancing this technology. We analyzed the structure and functioning of a microwave wireless power transmission system, identifying key technical evaluation criteria for each component, including signal generators, power amplifiers, transceiver antennas, and rectifier circuits. To ensure robust development, we also established detailed test evaluation methods, outlining the necessary equipment, procedures, and processes. These efforts aim to provide a solid technical foundation that will drive the progress and practical application of microwave wireless power transmission systems.

Keywords:

Space-based solar power, microwave transmission, antenna Receiver, satellite network, renewable energy, wireless power transfer.

A Network of Satellites that Collect and Transmit Electrical Power from Space to Earth

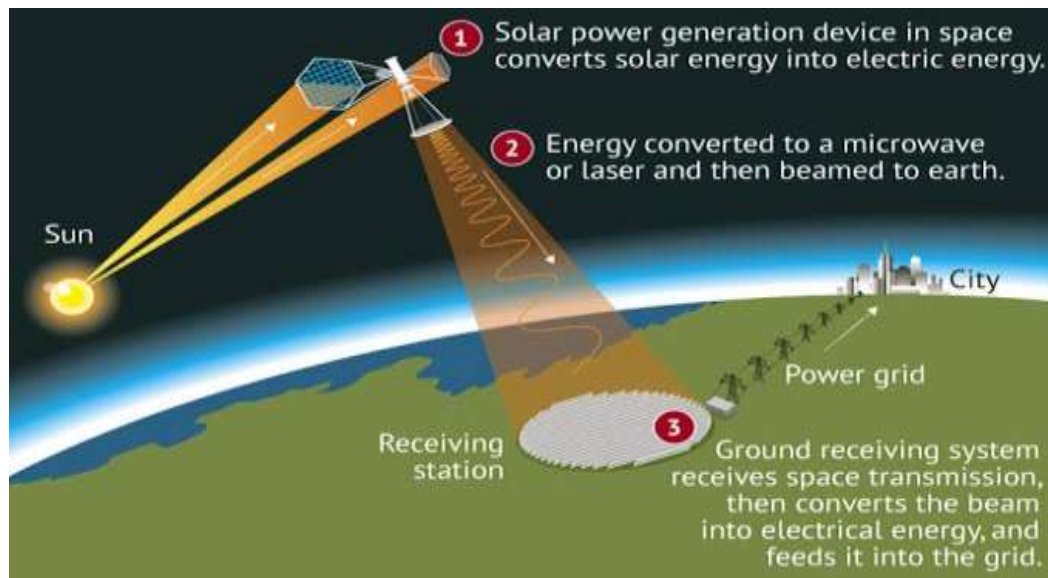


Figure. 1

1. Introduction:

The increasing demand for clean, renewable energy sources drives interest in space-based solar power (SBSP). Unlike terrestrial solar power systems, SBSP can harness uninterrupted solar energy due to the absence of atmospheric interference and nighttime. This paper presents a comprehensive analysis of constructing a satellite network to collect and transmit electrical power from space to Earth. The primary objectives are to evaluate the technical and economic feasibility, identify potential challenges, and propose solutions for successful implementation. [1]

The basic layout of a microwave wireless power transmission system is illustrated in Figure 2. It shows the key components: A DC energy source, a microwave power generator (which includes a signal generator and a power amplifier), a transmitting antenna, free space, a rectifying antenna (Absorb and rectify the incident microwave beam), and a DC load. [2]

Here is how it all works: The DC energy source powers the entire system. The signal generator produces low-power microwave signals, which are then amplified by the power amplifier to create high-power microwave signals. These signals are sent to the transmitting antenna, which converts the high-power microwave energy into

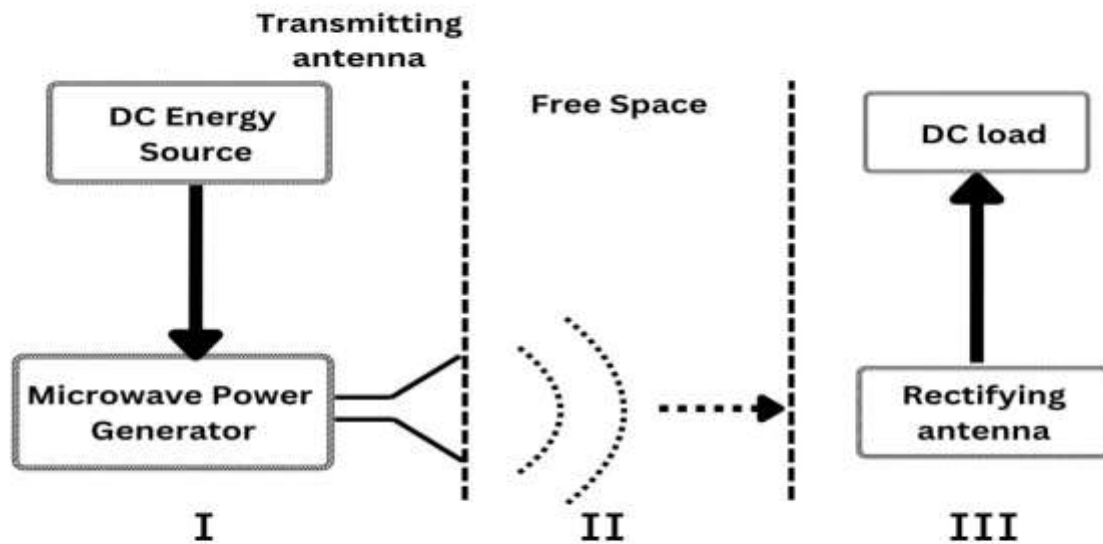


Figure. 2

electromagnetic waves that travel through free space.[3]

In essence, this system efficiently transmits power wirelessly by converting electrical energy into microwaves, sending them through the air, and then converting them back into usable electrical energy at the receiving end.

On the receiving end, the receiving antenna picks up these microwave signals and converts them back into electromagnetic waves. These signals are then sent to the rectifying circuit. The receiving antenna and rectifying circuit are usually combined into a single unit called a rectenna. The rectifying circuit uses the non-linear properties of a rectifier diode to convert the received microwave energy into direct current (DC) energy, which can then be used to power the connected load. [4]

2. Literature Review:

Historical Concept: -

The invention of solar panels for space use is credited to the American engineer Hans Ziegler. He was part of the team that developed the first solar-powered satellite, Vanguard 1, which was launched by the United States in 1958. This satellite used solar cells to generate power, marking the first successful application of solar panels in space. The technology has since become crucial for powering spacecraft and satellites.[5]

The concept of SBSP has evolved significantly since its inception in the 1960s. Key studies and projects include:

NASA's SPS Alpha

A conceptual design for a modular, phased-array system of satellites designed to collect solar energy and beam it to Earth via microwaves. This project demonstrated the potential for large-scale, space-based solar arrays and highlighted the need for further research into efficient energy transmission.[6]

JAXA's SSPS (Space Solar Power System)

Japan's space agency has been actively researching SBSP, focusing on developing efficient microwave transmission technologies and designing lightweight, modular satellite systems.

Recent advancements in solid-state electronics and materials science have improved the efficiency of photovoltaic panels and microwave transmission systems, making SBSP increasingly viable. Key challenges identified in previous research include high initial costs, technical complexity, and regulatory hurdles.[6]

Why do we use Microwaves?

- **Atmospheric Penetration:** Microwaves can pass through the Earth's atmosphere with relatively low attenuation compared to other frequencies, such as visible light or infrared. This makes them suitable for transmitting energy from space to the ground. [7]
- **Efficiency:** Microwaves are efficient for long-distance energy transmission. They offer a good balance between wavelength and power density, which allows for effective and reliable transmission of energy. [8]
- **Beam Directivity:** Microwaves can be focused into a narrow beam, which helps in targeting the energy precisely at the receiving station on the Earth's surface. This high directivity reduces the risk of energy loss and minimizes interference with other systems. [9]
- **Technological Maturity:** The technology for generating, transmitting, and receiving microwaves is well developed and has been used extensively in other applications such as communication and radar. This existing infrastructure and knowledge base make microwaves a practical choice for SBSP.
- **Safety:** Microwaves, when used properly, can be directed in a controlled manner and at power levels that are manageable for safety. The technology can be designed to minimize health risks to humans and wildlife.
- Overall, microwaves strike a good balance between the practical aspects of transmission and the technical feasibility of the systems involved in SBSP.[10]

Energy Generation:

The amount of energy a space solar panel generates depends on several factors, including its size, efficiency, distance from the Sun and angle of solar panel, and the specific mission requirements. However, here's a general overview:

Typical Energy Output:

Modern space solar panels can produce anywhere from 100 watts to several kilowatts of power. For instance, the solar panels on small satellites or CubeSats might generate around 50 to 200 watts, while those on larger spacecraft like the International Space Station (ISS) produce about 84 to 120 kilowatts.

Efficiency:

The efficiency of space solar panels is higher than that of terrestrial panels, often ranging between 25% to 30%. Advanced multi-junction solar cells, which use multiple layers to capture different wavelengths of sunlight, are commonly used in space applications.

Distance from the Sun:

The amount of energy generated decreases with distance from the Sun. For example, solar panels near Earth (1 AU from the Sun) receive about 1,360 watts per square meter, but this value drops significantly for missions to outer planets.

Specific Examples:

- 1) The Juno spacecraft orbiting Jupiter has solar panels that generate about 500 watts of power, despite being five times farther from the Sun than Earth, thanks to its large 60-square-meter solar array.
- 2) The Mars rovers (like Perseverance) generate around 100 to 140 watts from their solar panels on Mars, where sunlight is weaker than on Earth. [11]
- 3) These factors collectively determine how much energy a particular space solar panel can generate in orbit. [11]

Special Solar panel:

Space solar panels differ significantly from home solar panels in several key ways, tailored to the unique demands of the space environment. Here are some of the main differences:

1. Materials and Efficiency:

Space Solar Panels: Uses advanced materials like multi-junction cells, which are often composed of multiple layers of semiconductors (e.g., gallium arsenide, germanium) to capture a broader spectrum of sunlight. This results in higher efficiency, often around 25% to 30% or more.

2. Durability and Lifespan:

Space Solar Panels: Must withstand harsh conditions such as extreme temperatures, radiation, micrometeoroids, and vacuum. They are designed to last for many years (often 15-20 years or more) without maintenance, under these conditions.

3. Weight and Size:

Space Solar Panels: Are designed to be as lightweight as possible to minimize launch costs. They are often made from thin, flexible materials that can be folded or rolled up during launch and then deployed in space.

4. Cost:

Space Solar Panels: Are significantly more expensive due to the specialized materials, manufacturing processes, and stringent testing required to ensure they can survive in space. The cost can be tens to hundreds of times more than home solar panels.

5. Energy Generation per Area:

Space Solar Panels: Are optimized to generate the maximum possible energy from the available sunlight, with no atmospheric interference. This is crucial in space, where the only power source is the Sun.

6. Deployment Mechanism:

Space Solar Panels: Often need complex deployment mechanisms to unfold or extend once in space. These mechanisms must be extremely reliable, as they typically cannot be repaired.

7. Temperature Resistance:

Space Solar Panels: Must endure extreme temperature variations, ranging from the intense heat of direct sunlight to the frigid cold of shadowed space. They are designed with materials that can tolerate these extremes.

These specialized characteristics make space solar panels uniquely suited to the challenges of space, while home solar panels are optimized for cost-effective, durable, and efficient energy production under Earth's conditions. [12]

3. Methodology:

1. Signal Generator:

This study proposes a network of geostationary satellites to collect and transmit electrical power. The methodology involves the following steps:

The key technical specifications for a signal generator in a microwave wireless power transmission system include its operating frequency and efficiency. The operating frequency, often referred to as the “carrier frequency,” is the standard frequency at which the signal generator operates under specified conditions. Efficiency, on the other hand, measures how effectively the signal generator can convert an input DC signal into a microwave signal. [13] From a scientific and practical standpoint, the frequency of electromagnetic waves plays a crucial role in the wireless energy transmission process. Higher frequencies generally result in better signal directionality and reduced spatial attenuation. The loss of energy of a signal), meaning that the energy can be transmitted more effectively over longer distances. In the microwave band, common frequencies used for energy transmission are 2.45 GHz, 5.8 GHz, 35 GHz, or even higher. [13]

Given these factors, it is essential to assess whether the signal generated by the signal generator meets the specific frequency and efficiency requirements for effective microwave power transmission. This ensures that the system operates optimally, with minimal energy loss during transmission.

2. Power amplifier:

The performance of a microwave wireless power transmission system heavily depends on the power amplifier's output power, power gain, and efficiency. The primary role of the power amplifier is to take small signals and boost them into high-power microwave signals. [9]

The power gain, which is a key indicator of the amplifier's performance, is simply the ratio of the output power to the input power. It tells us how much the signal has been amplified. Since the power amplifier is a crucial part of the system, its efficiency directly impacts how effectively the entire system transmits power. If the amplifier is efficient, the system as a whole will perform better.

3. Transceiver antenna:

The performance of a microwave wireless power transmission system heavily relies on the transmitting and receiving antennas, since the link between them is an open loop that cannot be controlled directly. This performance is influenced by how well these antennas are designed and matched. [14]

For both antennas, key technical aspects include:

- Impedance Characteristics: This involves factors like the operating frequency and efficiency of the antennas. [15]
- Directional Characteristics: This includes the antenna's directional pattern and gain. [16]

When the system is used with moving targets, such as unmanned aircraft, the transmitting antenna must adjust its beam direction to follow the target's movement. Additionally, if the receiving equipment is lightweight, like an unmanned aerial vehicle, its design needs to be considered to ensure it can support the required components without being too heavy.

Efficiency is a crucial metric for both antennas. It measures the ratio of the power radiated by the antenna to the power actually fed into it. This is closely tied to the antenna's directional characteristics. Due to losses in free space, the efficiency of the microwave wireless power transmission system is defined by the ratio of the RF energy received by the receiving antenna to the energy sent by the transmitting antenna. [17]

Other important indicators include:

- Operating Range: This refers to the range within which the antenna can effectively direct its beam.
- Power Density: This measures the power received by the antenna relative to its mass and surface area.

These factors together determine how well the system performs and its effectiveness in delivering power wirelessly.

4. Rectifier circuit:

The microwave rectifier circuit plays a crucial role by using the nonlinear properties of a rectifier diode to transform the received microwave energy into direct current (DC) energy, which is then used to power the load. The most important measure of performance for these circuits is power conversion efficiency. This efficiency depends on several factors, including the characteristics of the rectifier diode, the nature of the DC load, and how well the circuit's impedance is matched. In other words, the better these elements work together, the more efficient the conversion of microwave energy to DC energy will be. [17]

5. Microwave wireless energy transfer system:

This outlines the key technical indicators of a microwave wireless power transfer system, which are categorized into three main classes: power, efficiency, and size.

Power Class: This includes the power metrics for the system's main components, such as the power supplied by the DC source, the RF power output by the microwave signal source, the power radiated by the transmitting antenna, the power received by the receiving antenna, and the output power of the rectifier circuit. [18]

Efficiency Class: These indicators measure the efficiency of crucial components in the system. For example, how efficiently the microwave signal source converts DC into an RF signal, the efficiency of both the transmitting and receiving antennas, and the rectification efficiency of converting microwave energy into DC.

Size Class: These indicators assess factors like transmission distance and the lightness of the receiving antenna. Lightness is evaluated by looking at the area power density (power per unit area) and weight power density (power per unit weight).

When measuring the efficiency of a microwave wireless power transfer system, it's essential to consider not just the overall system efficiency, but also the input and output power and efficiency of each main component. This detailed analysis helps track how energy flows through the system and highlights where losses occur during transmission. By understanding these losses, we can identify the factors that impact system efficiency and find ways to improve it.

The testing process Involves varying specific parameters, such as the DC power input, the distance between the transmitting and receiving antennas, or the characteristics of a particular component, while keeping all other components constant. This approach allows us to isolate and examine the effect of each variable on system efficiency, providing valuable insights for optimizing performance.[19]

Satellite Design:

- Satellites will be equipped with high-efficiency photovoltaic panels capable of capturing solar energy continuously.
- Each satellite will have a phased-array antenna to precisely direct microwave beams to receiving stations on Earth. [20]

Power Transmission:

- Microwave transmission is chosen due to its high efficiency over long distances and established safety protocols.

- A frequency

X-Band (8-12 GHz)

Ku-Band (12-18 GHz)

These two are balancing efficiency and safety.

Simulation Model:

- A simulation model is developed to evaluate the satellite network's efficiency, coverage, and transmission losses. The model considers factors such as orbital mechanics, atmospheric conditions, and antenna alignment. [21]

Economic Analysis:

- A cost-benefit analysis is performed to evaluate the economic viability of the proposed SBSP system, considering factors such as launch costs, satellite construction, and energy pricing. [22]

4. Results:

The simulation results indicate that a network of geostationary satellites can achieve continuous global coverage with a transmission efficiency of approximately 60%. Key findings include: [23]

- Satellite Network Efficiency:

- Optimal spacing and alignment of satellites are critical for maximizing energy collection and minimizing transmission losses. [24]

- Economic Viability:

- While the initial costs are high, the long-term benefits of continuous, renewable energy supply and reduced carbon emissions make SBSP economically attractive.

5. Discussion:

Microwave wireless power transmission is a promising method for transmitting energy over long distances and has the potential for widespread applications. However, despite the maturity of the technology, a comprehensive evaluation system is still lacking, which hinders its further development and application. Currently, evaluations tend to focus mainly on the system's overall transmission efficiency, with less emphasis on the performance of individual components and their applications. This is a significant oversight, as the performance of each component directly influences the system's overall effectiveness, and real-world applications often present challenges that prevent the system from achieving its full potential.

The system primarily consists of key components like the signal generator, power amplifier, transceiver antennas, and rectifier circuits. [26] This paper takes a detailed approach by analyzing the role of each component in the microwave wireless power transmission system, identifying the factors that could impact transmission efficiency. By testing each component within the system, we aim to develop a comprehensive evaluation index that not only assesses the performance of individual parts but also examines how these parts affect the system as a whole. This method provides valuable insights into both component-level and system-wide performance, offering a solid foundation for advancing microwave wireless power transmission technology. [27] [28]

6. Conclusion:

To drive the development of microwave wireless energy transfer systems, extensive research has been undertaken to establish technical benchmarks and testing methods for these systems. This includes analyzing the overall structure of the systems, defining key performance indicators for critical components, and developing corresponding evaluation methods. While significant progress has been made, there are still areas that need further attention.

1. Component Efficiency and Performance: There is a need to delve deeper into the technologies behind signal generators, power amplifiers, and transceiver antennas. By improving the conversion efficiency of these core components, we can enhance the overall performance of microwave wireless energy transmission systems. Additionally, efforts should focus on making these systems more compact, lightweight, adaptable, and electromagnetically compatible.
2. Optimizing the Evaluation System: To effectively measure the performance of microwave wireless energy transmission systems, the current evaluation index system needs refinement. This will help establish a comprehensive framework for testing every aspect of these systems. Developing standards for interface design, transmission frequencies, communication protocols, interoperability, and energy management is also crucial for ensuring system effectiveness.

3. Enhancing Testing and Evaluation Methods: Given the complexity of testing and evaluating microwave wireless energy transmission systems, it is essential to improve the testing tools and define clear testing guidelines. Developing a robust evaluation method will provide the necessary technical support for advancing these systems, ensuring they meet the demands of real-world applications.

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