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Re-evaluation of the cost of Solar Power Satellites (SPS) with new structures

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Abstract

In this project, we conducted research on a new structure for tethered SPS (Space Power Satellites) and clarified the related technical issues. We examined the new structure from the perspective of thermal control and investigated the feasibility of the structure. Additionally, we considered the economic benefits of adopting this structure. It was found that the new structure exceeded the allowable temperature range of the onboard equipment. Therefore, we investigated thermal countermeasures. From an economic standpoint, adopting the new structure resulted in approximately a 98% reduction in spacecraft costs. Furthermore, the total weight was reduced by 84%, leading to a significant decrease in transportation costs.
Keywords: SPS, Hybrid structure, weight, cost

Acronyms/Abbreviations

SPS: Solar Power Satellite
JAXA: Japan Aerospace Exploration Agency
MPPT: Maximum Power Point Tracking
DCDC: Direct Current to Direct Current Converter
OBC: On-Board Computer
TCM: Trajectory Correction Maneuver

1. Introduction

Global warming and climate change have made the development of sustainable energy resources an urgent priority. Renewable energy is a promising solution to these problems; however, traditional technologies such as wind and solar power are dependent on weather and sunlight conditions, which limits the stability of energy supply. In contrast, Solar Power Satellites (SPS), which can constantly utilize sunlight in space, are attracting attention as a groundbreaking technology that enables stable energy supply.[1] However, the realization of SPS faces challenges such as transportation costs and technical issues.

In conventional integrated power generation and transmission panels, efforts have been made to reduce costs through panel thinning for weight reduction. However, this has resulted in challenges related to structural deformation and thermal management. For instance, to maintain the accuracy of microwave power transmission, it is necessary to keep panel deformation within a specific range; otherwise, there is a risk of reduced transmission efficiency. Additionally, because the power generation surface and the transmission surface are the same, it is difficult to achieve uniform heat dissipation, which could affect the performance of the onboard equipment.

In this study, we propose an improved structure for integrated power generation and transmission panels to address these issues of deformation and thermal management. In this new design, the panel is divided into a bulk structure that includes onboard equipment and a thin film structure that excludes such equipment. This achieves both weight reduction and enhanced thermal control and deformation suppression.

This improvement has resulted in a 84% reduction in the total weight of the structure. Furthermore, the reduction in weight decreases the number of transportation trips required, and it also reduces material costs of the structure itself. The new structure proposed in this study is expected to be a significant step towards the realization of SPS. Moving forward, further experimental verification and cost analysis will be necessary to overcome the specific challenges toward practical implementation.

2. The traditional tethered SPS model

2.1. Summary of the traditional tethered SPS

The concept of the Solar Power Satellite (SPS), first proposed by Peter E. Glaser in 1968, has since been researched by many countries, and various models have been considered. Among these, the tethered SPS, proposed about 15 years ago, is a representative model developed by the Unmanned Space Experiment Free Flyer (now J-spacesystems).[1]

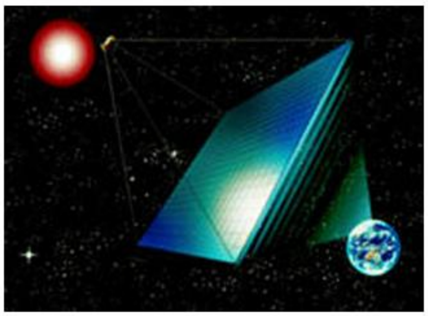

Fig. 1. Illustration of tethered SPS

2.2. Structure of tethered SPS

The most significant feature of the tethered SPS is its modular structure, which ensures robustness, cost-effectiveness, and ease of assembly. This system consists of 38,000 panels that perform both power generation and power transmission functions, with each panel operating independently. Each unit is suspended by four tethers from the bus system, and by combining 625 of these units, a massive wireless power transmission system covering approximately 2.5 square kilometers is formed. The simple and robust design achieves both low cost and high reliability.[2,3]

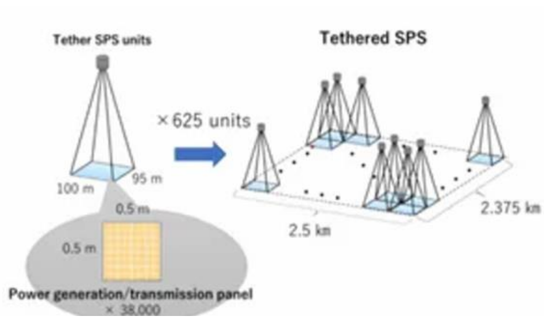

Fig. 2. Illustration of structure of tethered SPS

2.3. Equipment of power generation/transmission panels

The power generation and transmission panels are divided into three main sections: the power generation section, the direction finding section, and the power transmission section.

In the power generation section, solar cells convert sunlight into electricity, which is efficiently managed by Maximum Power Point Tracking (MPPT). The generated power is supplied to onboard equipment through DC-DC converters and other components.

In the power transmission section, RF signals, whose phase is adjusted by phase shifters, are amplified and transmitted from antennas. This design allows efficient energy transmission throughout the system.

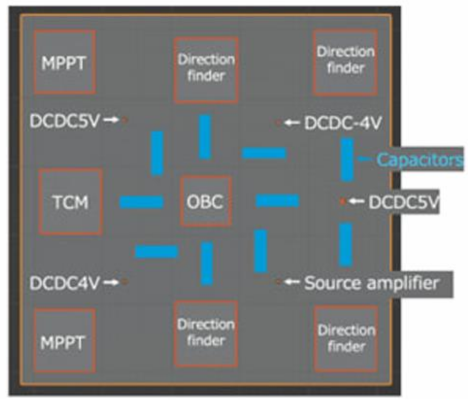

Fig. 3. On-board equipment layout

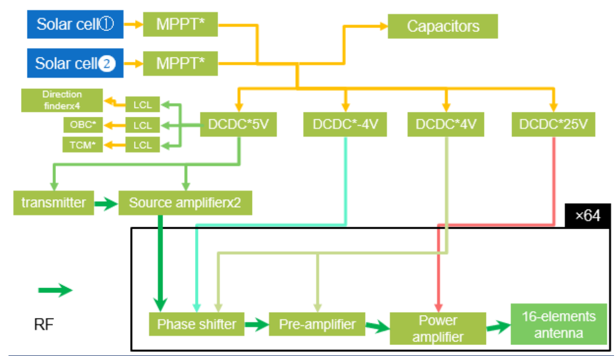

Fig. 4. Equipment Configuration for SPS

3. Hybrid structure

3.1. Overview of the Hybrid Structure

The hybrid structure is a new SPS design that combines bulk and thin-film structures in a 1:3 ratio. In the traditional SPS model, 50 cm square and 7 cm thick integrated power generation/transmission panels were used as the basic structure, with 23.75 million panels combined to form the system. Each panel was equipped with solar cells on both sides, transmission antennas on the Earth-facing side, and internal equipment such as microwave phase control amplifiers, direction detectors, voltage regulators, and distributors.

In the new hybrid structure, some of these onboard devices are consolidated into a few panels, while the other panels are changed to a thin-film structure that consists only of solar cells and transmission antennas.

The panels with consolidated devices are referred to as bulk structures. This design achieves thinner panels and reduced weight.

Fig. 5. Bulk structure

Fig. 6. Thin-film structure

3.2. Thermal Analysis

A thermal analysis was conducted to evaluate the impact of the thin-film structure on temperature changes, and to assess the potential for heat concentration due to the consolidation of devices in the bulk structure. The analysis was performed using Patran (pre/post-processing) and Nastran (solver).

3.3. Results

As a result of the analysis on the conventional structure, it was confirmed that all devices, except for the DCDC converters, remained within the allowable temperature range. To bring the DCDC converters within the allowable temperature range, the following thermal countermeasures were implemented. First, an aluminum honeycomb structure was added for heat dissipation. Next, a high-emissivity coating (glass layer) was applied to enhance heat radiation. Lastly, heaters were installed to stabilize the temperature of the solar cells. As a result, all onboard equipment remained within the allowable temperature range. Therefore, this structure enhances the feasibility of SPS and reduces potential long-term risks.

Table 1. Results of Thermal Analysis

	Result(℃) (low)	Result(℃) (high)	Permissible Temperature(℃)
MPPT	-24.5	-23.2	-40~85
Capacitor	-18.7	-18.7	-20~85
DCDC(5V)	-16.2	-16.2	-40~125
DCDC(25V)	-20.6	-20.6	-40~125
DCDC(4V)	-16.2	-16.2	-40~125
DCDC(4V)	-8.5	-8.5	-40~125
OBC	-28.6	-27.2	-40~80
TCM	-26.3	-25.8	-40~85
Direction Detector	-29.9	-26.2	-40~85
Transmitter Amp	-29.6	-29.6	-40~85
Phase control amplifier	42.5	71.5	-40~85
Power generation surface solar cells (bulk)	-30.2	-22.2	-140~125
Power generation surface solar cells (thin-film)	-27.2	5.9	-140~125
Power transmission surface solar cells	-25.2	54.9	-140~125

4. Comparison of weight and cost

This comparison focuses solely on the power generation and transmission system, excluding the tether and bus components. In this section, we clarify the advantages of the hybrid structure through a comparison of weight and cost.

4.1. Weight Comparison

The hybrid structure achieves significant weight reduction compared to the traditional SPS structure due to several key factors. First, by optimizing the selection of onboard equipment, certain components were consolidated or eliminated, leading to an overall reduction in system weight. Additionally, the use of less aluminum in the structural components contributed to further weight reduction.

In the traditional structure, the total weight was 88,000 tons, whereas the hybrid structure reduces this to 14,000 tons, achieving an approximate 84% reduction in weight.

4.2. Cost Reduction

By reducing weight, significant cost savings are expected in both transportation and manufacturing. The lighter system reduces the number of launches required, improving transportation efficiency. Additionally, manufacturing costs are lowered, particularly due to the reduced use of aluminum.

As a result, the cost per module of the spacecraft can be reduced by 243.88 million USD compared to the conventional model. This contributes to overall cost reductions for the entire SPS.

4.3. Comparison with Other Power Generation Methods

SPS can be better understood by comparing it with thermal, nuclear, and solar power generation methods.

Thermal power relies on fossil fuels, offering stable energy but with high sensitivity to fuel price fluctuations. The generation cost is 0.047～0.067USD per kWh, and it produces significant CO_2 emissions, contributing to global warming.

Nuclear power has a generation cost of around 0.067USD per kWh and does not emit CO_2. However, it involves high costs for waste management and safety measures, with concerns over radioactive waste and accident risks.

Solar power is a renewable energy source with a relatively low cost of 0.034～0.047USD per kWh, but its supply is heavily dependent on weather and day-night cycles, leading to stability issues.

4.4. Advantages of SPS

SPS has several advantages over the above-mentioned power generation methods. First, while the generation cost is estimated to be approximately 1.675USD per kWh with the hybrid structure, which is higher than other methods, SPS offers significant environmental benefits by not emitting any CO_2. As technology advances, particularly in reducing the cost of electronic components, SPS could potentially generate power at a cost comparable to, or even lower than, other generation methods in the future.

5. Future challenges

5.1. Further Thinning of the Bulk Structure

The current power generation cost of SPS has not decreased sufficiently, so further thinning of the bulk structure is essential for additional cost reduction. In particular, the current model uses 6mm aluminium heat dissipation plates, which increase both weight and volume. To address this issue, the development of lighter and thinner heat dissipation plates with high self-radiation capabilities is necessary.

5.2. Considerations for Deformation

The current analysis evaluates the temperature at which the equipment is expected to reach its maximum due to direct sunlight. However, in actual SPS operations, the amount of sunlight varies over time, so deformation caused by temperature changes over time must also be considered.

6. Conclusions

This study demonstrated that the Solar Power Satellite (SPS) adopting a hybrid structure has thepotential to achieve significant weight and cost reductions compared to traditional designs. Specifically, the weight reduction improves transportation efficiency, contributing to an overall reduction in costs. Additionally, through thermal analysis, the structural feasibility of SPS was confirmed, indicating that the system can operate stably in the space environment.

Furthermore, by comparing SPS with other power generation methods, we clarified the environmental advantages of SPS. Since SPS emits no CO_2, it has a significantly smaller impact on global warming compared to thermal and nuclear power generation, making it a strong contender as a clean energy source. While the current cost of power generation is higher than that of other methods, future technological advancements are expected to lead to further cost reductions.

Key challenges moving forward include exploring deployment methods to reduce the number of launches, further thinning the bulk structure, and optimizing the circuit design for onboard equipment. Addressing these challenges will further enhance the feasibility of SPS, potentially enabling it to provide energy at costs comparable to or lower than other power generation methods.

In conclusion, SPS holds great promise as a next-generation energy supply technology. By minimizing environmental impact and providing sustainable energy, SPS has the potential to play a significant role in the future of clean energy development.

Fig. 7. Future vision

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