A new concept of solar power satellite: Tethered-SPS

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Abstract

Tethered solar power satellite (Tethered-SPS) consisting of a large panel with a capability of power generation/transmission and a bus system which are connected by multi-wires is proposed as an innovative solar power satellite (SPS). The power generation/transmission panel is composed of a huge number of perfectly equivalent power modules. The electric power generated by the solar cells at the surface of each module is converted to the microwave power in the same module. Since the modules are controlled by the bus system using wireless LAN, no wired signal/power interfaces are required between the modules. The attitude in which the microwave transmission antenna is directed to the ground is maintained by the gravity gradient force. The tethered panel is composed of individual tethered subpanels which are loosely connected to each other. This configuration enables an evolutionary construction in which the function of the SPS grows as the construction proceeds. A scale model of the tethered subpanel can be used for the first step demonstration experiment of the SPS in the near future.

Keywords: Solar power satellite; Space tether; Microwave power transmission

1. Introduction

Since the NASA/DOE study of the solar power satellite (SPS) in the 1970s, various types of the SPS have been proposed in Japan, the United States, Europe, and Russia. Typical examples are summarized in Table 1. The NASA/DOE reference model has a simple configuration consisting of single large solar array panel, a microwave transmitting antenna, and a rotary joint connecting the panel and the antenna, which is quite similar to the Glaser’s original idea [8]. But the reference model has technical difficulties in the rotary joint mechanism and power collection. The rotary joint mechanism requires a power transmission mechanism of GW level through a movable contact. There is no practical technology for the rotary joint mechanism without a serious power loss. The mechanism is essentially fragile because one-point failure could lead to a total loss of the SPS function. For the power collection, the power transmission line of GW level from the solar array panel to the microwave transmitter requires a huge amount of conductor or a super-conduction system to avoid a serious Joule loss, but both are non-practical for SPS. A system with movable reflective
mirrors combined with the power generation/transmission panel (sandwich panel) has been proposed as a potential configuration to overcome the difficulties in the NASA/DOE reference model. In this configuration, both the rotary joint mechanism and the high-current transmission line can be deleted. By condensing the sunlight on the power generation/transmission panel, the size of the panel can be reduced. However, the system combined with the light-reflector and the power generation/transmission panel requires complicated configuration and highly challenging technologies for the attitude control and stabilization of the rotating large mirror, and another challenging technology for heat rejection from the power generation/transmission panel if the light is condensed. Furthermore, the movable system even without the power transmission still has a fatal problem to be damaged mechanically by a single point failure. One of the reasons why the past SPS concept has not been accepted as a realistic energy system for more than 30 years since Glaser’s first idea is due to lack of technical feasibility and robustness. Many SPS models have advertised the achievable cost competitive with that of the existing energy system, but investors have no confidence in the cost analysis because it is based on the highly challenging technologies or fanciful schemes.

As an opposite approach to the past efforts, we have investigated a simple, technically feasible, and practical configuration SPS which consists of a large power generation/transmission panel suspended by multi-tether wires from a bus system above the panel. An artist conception of the tethered solar power satellite (Tethered-SPS) is shown in Fig. 1. This concept was first developed by a study team organized by Institute for Unmanned Space Experiment Free Flyer (USEF) in 2001 and 2002 [9]. The essential technologies required for this concept are the deployment of the long tether of 10 km scale and the large panel of km scale in orbit. The basic parts of these technologies have been already verified in space. Space tether has been deployed up to 20 km 3 times in the 1990s [10].
panel deployment in km scale has not been demonstrated yet, but the solar array panels of $4.6 \times 32\, \text{m}$ on the International Space Station were successfully deployed in 2000. As is described later, the size of a unit panel of the Tethered-SPS is $100 \times 95\, \text{m}$, which is achievable in the near future based on the current technologies. The attitude is stabilized automatically by the gravity gradient force in the tether configuration without any active attitude control. Since this system has no mechanism to track the sun for the power generation, the total power efficiency is 36% lower than that for the NASA/DOE reference model or other sun-pointing-type SPS even when the solar cells are attached to both upper and lower sides of the panel. However, the simple configuration resolves almost all the technical difficulties in the past SPS models. No rotation mechanism in a large-scale makes this system highly robust and stable. Since the light condenser is not used for the power generation, a large-scale power generation area of km size is required, but the heat generated in the panel can be released into the space without any active thermal control. The power generation/transmission panel consists of perfectly equivalent modules, which will greatly contribute to the low-cost production, simple testing, and high-quality assurance. Another innovative feature of the module is cableless interface with the bus system and other modules using wireless LAN system, which leads to simple deployment, integration, and maintenance. The Tethered-SPS is an assembly of equivalent miniature Tethered-SPS elements. This configuration makes it possible to verify the function of the SPS phase by phase during the integration. In most of the past SPS models, the concept of the phased construction has not been considered, but is very important for the large space infrastructure. The miniature tethered element, a part of the practical SPS, can be used for the demonstration experiment in the near future. This strategy gives a straightforward scenario for the evolutional development from the demonstration model to the commercial SPS in the technology road map.

2. Tethered-SPS

Fig. 2 illustrates the concept of the Tethered-SPS which is capable of 1.2 GW power supply maximum and 0.75 GW average on the ground. It is composed of a power generation/transmission panel of $2.0 \times 1.9\, \text{km}$ suspended by multi-wires deployed from a bus system which is located at $10\, \text{km}$ upward. The panel consists of 400 subpanels of $100 \times 95\, \text{m}$ with 0.1 m thickness. Each subpanel has 9500 power generation/transmission modules of $1 \times 1\, \text{m}$ size. In each power module, the electric power generated by the solar cells is converted to the microwave power and no power line interface exists between the modules. Fig. 3 shows the concept of the power generation/transmission module. The power module has thin film solar cells both on the upper and lower planes. The microwave transmitting antennas are on the lower plane. The module contains a power processor, microwave circuits, and their controller. Each module transmits a microwave power of 420W maximum. The power conversion efficiencies for the solar
Table 2
Summary of Tethered-SPS

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Power generation/transmission panel suspended by 441 wires</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel size</td>
<td>$2.0 \text{ km} \times 1.9 \text{ km} \times 0.1 \text{ m}$</td>
</tr>
<tr>
<td>Tether wire length</td>
<td>10 km approx.</td>
</tr>
<tr>
<td>Total weight</td>
<td>20,000 MT</td>
</tr>
<tr>
<td>Panel</td>
<td>19,000 MT</td>
</tr>
<tr>
<td>Bus</td>
<td>1000 MT</td>
</tr>
<tr>
<td>Subpanel</td>
<td>Power generation/transmission panel suspended by four wires</td>
</tr>
<tr>
<td>Size</td>
<td>$100 \text{ m} \times 95 \text{ m} \times 0.1 \text{ m}$</td>
</tr>
<tr>
<td>Total number/panel</td>
<td>400</td>
</tr>
<tr>
<td>Structural unit panel</td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>$10 \text{ m} \times 1 \text{ m} \times 0.1 \text{ m}$</td>
</tr>
<tr>
<td>Total number/subpanel</td>
<td>950</td>
</tr>
<tr>
<td>Module</td>
<td>Power generation/transmission capability</td>
</tr>
<tr>
<td>Power generation</td>
<td>490 W maximum</td>
</tr>
<tr>
<td>Power transmission</td>
<td>420 W maximum</td>
</tr>
<tr>
<td>Size</td>
<td>$1 \text{ m} \times 1 \text{ m} \times 0.1 \text{ m}$</td>
</tr>
<tr>
<td>Total number/subpanel</td>
<td>9500</td>
</tr>
<tr>
<td>Microwave</td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>5.8 GHz</td>
</tr>
<tr>
<td>Output power</td>
<td>1.2 GW maximum, 0.75 GW on average</td>
</tr>
</tbody>
</table>

cells and the DC to RF converter are assumed to be 35% and 85%, respectively. The weight of the module is 5 kg or the specific power of the module is 0.08 W/g (12 g/W). These values are beyond the existing technologies by factor two for the power conversion efficiencies and approximately 10 times for the specific power, but are considered to be realizable in 20–30 years based on the potential progress of the photovoltaic and monolithic microwave integrated circuit (MMIC) technologies. There is no wired signal interface between the power modules. The control signal and frequency/phase standard for each module are provided from the bus system by the wireless LAN. The system characteristics of the 1 GW-class Tethered-SPS are summarized in Table 2.

3. System analysis

3.1. Construction

The tethered subpanel is composed of a $100 \text{ m} \times 95 \text{ m}$ subpanel (47.5 ton) suspended by four wires connected to a bus system (2.5 ton). The $100 \text{ m} \times 95 \text{ m}$ panel 0.1 m thick is regarded as a solid panel with a flatness required for the phase control in the microwave power transmission. The subpanel consists of 950 structural unit panels of $10 \text{ m} \times 1 \text{ m} \times 0.1 \text{ m}$. The overall construction scenario is illustrated in Fig. 4. The structural unit panels are folded in a package of $95 \text{ m} \times 10 \text{ m} \times 10 \text{ m}$ which is a unit cargo transported from the ground to the low earth orbit by reusable launch vehicles (RLV). The cargo is transferred to the orbit transfer vehicle (OTV) in the low earth orbit around 500 km and transported to the geo-synchronous orbit. Delta-V required for the transportation is 4500 m/s. To avoid the degradation of the solar cells by the trapped energetic particles in the radiation belt, the cargo is contained in a radiation shield vessel. If we use a 200 MT OTV equipped with an electric propulsion of 80 N thrust, the cargo is transferred to the geo-synchronous orbit in 4 months. The tethered subpanel is deployed automatically in the geo-synchronous orbit. After the function test of the tethered subpanel is completed, it is integrated to the SPS main body. Docking assistant robots which are manipulated from the ground control center will be required for the integration. Since the SPS main body is an assembly of the functional units, the SPS function of the main body can be verified any time during the construction phase from the low power to the full power.

3.2. System dynamics

The gravity gradient force for the tethered subpanel is 40 g per wire in the geo-synchronized orbit. The gravity gradient force for the complete Tethered-SPS is about
Transportation from low earth orbit to geo-synchronous orbit

150 N, while the sunlight pressure to the 2.0 km × 1.9 km panel is 17 N at maximum. Based on a quasi-static analysis considering the solar light pressure, it has been shown that the variation of the attitude is largest along the pitch axis, but is still less than 0.14° [11]. The inclination of the subpanel due to the temperature difference between the wires is less than 1° for a temperature difference of 30°C in case of Kevlar wire. Since the temperature difference between the tether wires is estimated less than 30°C and the pointing capability of the microwave transmission for each sub-panel is assumed to be ±5°, the inclination control of the subpanel will not be required. However, if the panel control is required for some other reason, the inclination can be easily controlled by adjusting the length of the wires of each tethered subpanel. This technique is usually used for the surface shape control of the primary mirror of the large telescope at the astronomical observatories.

3.3. Power generation

Since the lower plane of the power generation/transmission panel is always faced to the earth by the gravity gradient force, the power generation by the solar cells on the upper and lower panels varies with the local time as the sun angle changes. The average solar power to the panel is 64% of the maximum power, but this number is practically 60%, considering the operational limit of the output voltage of the solar cells and the antenna area in the lower plane. Since the average solar power on the ground is about 10–15% of that in orbit, this system is still able to collect the solar power by 4–6 times more than the ground solar power system, as shown in Fig. 5. While the incident power is too low to drive the microwave circuits near the local
time at 6 and 18 h, the generated power is used to heat the circuits to keep the operational temperature of the module.

3.4. Power transmission

The profile of the microwave intensity for the transmitting antenna has been premised 10 dB Gaussian commonly in the past and current SPS models to concentrate the microwave beam power in the main lobe. For the 10 dB Gaussian taper, the main lobe contains 95% of the total power, while it has about 87% power for the flat distribution. The peak power of the side lobe for the flat distribution is larger by approximately 10 dB than the 10 dB Gaussian distribution. The flat distribution requires a larger rectenna area and evacuation area, approximately twice as compared with that for the 10 dB Gaussian taper to collect the same power. However, the flat distribution has more important advantages. By adopting the flat power distribution, we can use perfectly equivalent modules, which ensures low-cost mass production. For the 10 dB Gaussian taper to collect the same power. If we assume that the efficiency of the solar cell array and the conversion efficiency from DC to RF are 0.35 and 0.85, respectively, the equilibrium temperature is approximately 10°C maximum, which is well within the operating temperature of the commercial parts usually below 80°C. Fig. 7 shows the temperature variation of the upper and lower planes in a day calculated by a simplified thermal model. In the calculation, it is assumed that heaters are activated when the solar radiation to the panel is minimum near the sun angles at 90° or 270°.

4. Demonstration experiment

A scale model of the tethered subpanel, a part of the practical SPS shown in Fig. 4 is used for the demonstration experiment. The basic concepts of the power generation/transmission module and tether configuration which play an essential role in the Tethered-SPS are verified in the demonstration experiment. Evolutional relationship from the demonstration experiment to the practical SPS is shown in Fig. 8.

4.1. Demonstration experiment on the ground

A demonstration experiment on the ground using a balloon has been investigated as a precursor experiment to the demonstration experiment in orbit. The amount of the heat radiation depends on the surface area, its thermal and optical properties, and the temperature. In the present configuration in which the panel is composed of the perfectly equivalent and thermally isolated modules, the thermal analysis for one module is sufficient to show the feasibility of the total system. The equilibrium temperature for the module is calculated from the Stefan–Boltzmann’s law. Since both sides of the module are mostly covered by the solar cells, the coefficients, 0.8 and 0.7 are used as the typical values for the solar absorptance and emittance, respectively.
The configuration of the experiment is shown in Fig. 9. A super-pressure balloon of 1000 m³ capacity can lift an experimental system of 800 kg. The balloon is moored to the rectenna site on the ground. The length of the mooring cable is 1 km. It takes about 1 h to deploy and to retract the system, which makes it possible to conduct the experiment in a day. The experiment time for the microwave power transmission will be 2–4 h per day. A tethered power generation/transmission panel of 4 m × 4 m which is a 1/4 scale model of the demonstration model in orbit is used for the experiment. The transmitting power is 17.5 kW. If a rectenna of 30 m diameter is prepared, approximately 7 kW power is obtained on the ground. This experiment is regarded as a systems test to verify the function and operation of the space and ground segments for the demonstration experiment in orbit.

4.2. Demonstration experiment in orbit

The most important subject in the SPS technologies is the verification of the power transmission from the orbit to the ground. The concept of the demonstration experiment is shown in Fig. 10. The main objectives of the experiment are:

1. demonstration of the microwave beam control precisely to the rectenna on the ground from the large panel antenna in orbit,
2. evaluation of the overall power efficiency as an energy system,
3. demonstration of the electromagnetic compatibility with the existing communication infrastructure, and
4. study of the operational procedure of the SPS.
H2A rocket, an advanced type, is considered as the launch vehicle for the demonstration experiment. The subrecurrent orbit at an altitude of 370 km (47 revolutions per 3 days) is selected to compromise the requirements from the microwave power density on the ground and orbit maintenance operation against the air drag. Fig. 11 illustrates the configuration of the experimental system. The system characteristics are summarized in Table 3. The attitude of the system is stabilized by the gravity gradient force of the H2A second stage as an end mass and the power generation/transmission panel which are connected by a truss and four tether wires. The truss is used to support the bus system at the center of the gravity to operate a propulsion system to keep the orbit. The truss also gives a tension to the wires under the low-gravity gradient force for the 30 m scale tether. The truss is peculiar to the demonstration experiment and will not be used for the subpanel of the practical SPS. The panel consists of 88 foldable structural unit panels. The structural unit panel is 0.8 m × 4 m wide and 0.1 m thick. The 80 structural unit panels are used for the power transmission, while the other eight are blank panels to stabilize the yaw motion. The structural
Table 3
Summary of demonstration experiment for Tetherred-SPS

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Power generation/transmission panel suspended by four tether wires</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel size</td>
<td>17.6 m × 16 m × 0.1 m</td>
</tr>
<tr>
<td>Tether wire length</td>
<td>30 km approx.</td>
</tr>
<tr>
<td>Total weight</td>
<td>18,100 kg</td>
</tr>
<tr>
<td>Panel</td>
<td>12,600 kg</td>
</tr>
<tr>
<td>Others</td>
<td>5500 kg</td>
</tr>
<tr>
<td>Structural unit panel</td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>4 m × 0.8 m × 0.1 m</td>
</tr>
<tr>
<td>Total number/panel</td>
<td>80</td>
</tr>
<tr>
<td>Module</td>
<td>Power generation/transmission capability</td>
</tr>
<tr>
<td>Power generation</td>
<td>55 W maximum</td>
</tr>
<tr>
<td>Power transmission</td>
<td>700 W maximum</td>
</tr>
<tr>
<td>Size</td>
<td>0.8 m × 0.8 m × 0.1 m</td>
</tr>
<tr>
<td>Total number/structural unit panel</td>
<td>5</td>
</tr>
<tr>
<td>Microwave</td>
<td>Frequency 5.8 GHz</td>
</tr>
<tr>
<td>Output power</td>
<td>280 kW high-power mode, 28 kW to lower-power mode</td>
</tr>
</tbody>
</table>

unit panel contains five power generation/transmission modules of 0.8 m × 0.8 m. There is no electrical wire interface between the power modules. The cylindrical bus system has a control and data management system and a propulsion system to keep the orbit. Either a hydrogen thruster system or an ion engine is considered for the propulsion system. Since the large panel interrupts the direct communication between the bus system and the ground station, a communication relay system will be installed in the part of the panel.

For the microwave power transmission, two kinds of microwave system have been investigated. One is the combination of a phase control magnetron (PCM) and integrated antennas with a phase shifting capability composed of semiconductors. In this configuration, the microwave power of the PCM typically more than 1 kW is divided into the 625 antenna elements in each power module. Another system is the combination of a local oscillator and active integrated antennas (AIA) in each power module. In this configuration, the source signal is amplified by 625 sets of the AIA up to 700 W in total. The former-type module, consisting of a thin film solar array, batteries, a power control unit, a high-voltage converter, a PCM, and integrated antennas, has been designed. Fig. 12 shows the configuration of the components in the power module. The antenna panel is attached to the bottom of the wave guides, while the electrical components are installed on the wave guides. Fig. 13 illustrates the block diagram of the module. The microwave circuit is designed to control the direction of the beam ±10° from the normal line of the panel. The total microwave power injected from the power generation/transmission panel is 280 kW. The microwave power transmission will generate the power density above 100 W/m² for 20 km and above 10 W/m² for 60 km in the ionosphere, as shown in Fig. 14. The interactions between the high-power density microwave and the ionospheric plasma can be studied on a large scale. They are observed by ionosphere sounding instruments both from the spacecraft and the ground. The power density on the ground is estimated as 0.25 W/m², which is well below the standard for public exposure (10 W/m²). Since the power density is too low to be rectified by a single antenna combined with a Schottky diode, it is necessary to use a parabola to concentrate the microwave power [13]. If we have a rectenna area of 500 m in diameter, the output power from the rectenna will be more than 10 kW.

The analysis of the microwave beam pattern transmitted from the panel indicates that the misalignment and the gap between the structural unit panels need to be less than 5° and 10 mm, respectively, from the standpoint of the allowable beam divergence and avoidance of the unnecessary radiation [14]. The analysis of the dynamic motion of the system in orbit has been conducted to find out the orbital and structural conditions to satisfy the requirements from the microwave beaming. The results of the computer simulation have shown that the pitch (pendulum) motion is within 3.5° for the orbit eccentricity less than 0.01 [11], which is in the capability of the beam control (±10°). Based on the linear elastic analysis, the characteristic frequency of the
oscillation of the panel is less than 10 Hz for the realistic range of the stiffness of the panel, truss, and wires. Since the feedback frequency for the beam control of the microwave circuit is expected to be more than 100 Hz, the direction of the beam can be well controlled regardless of the dynamic motion of the panel. The structural unit panels are latched to each other in two dimensions to keep their gaps within 10 mm.

The thermal analysis is conducted for the power module composed of the PCM, batteries, integrated antennas, and the other electric parts. The analysis results show that the temperature is maximum at the PCM, but can be kept below 100°C for the intermittent operation if a thermal capacitor is combined with the PCM.

The orbit analysis shows that the fuel of 500 kg is required for two years mission if we use the hydrazine thruster system. The dominant force to the system is the air drag force to the H2A second stage used as the end mass. The electric propulsion system can be more beneficial considering the amount of the fuel and attitude disturbances during the operation, but additional
The experiment sequence is shown in Fig. 15. For the first 2 min, the microwave beam at 10% of the full power is transmitted to the ground. The onboard computer controls the beam direction without the pilot signal from the ground. When the demonstrator passes over the rectenna site, the microwave beam at the full power is transmitted to the rectenna for 16 s guided by the pilot signal from the rectenna site. The beam direction is changed in ±10° from the normal line of the panel to target the rectenna. After the full power operation, the power transmission at 10% of the full power is performed for another 2 min.

### 5. Summary and conclusion

Tethered-SPS in which a power generation/transmission panel is suspended by multiple wires from a bus system above the panel has been investigated in a conceptual study level. This concept has several advantages, as summarized below:

1. Since the attitude is stabilized automatically by the gravity gradient force, no active attitude control is required.
2. There is no moving structure, which makes the system highly robust and stable. Especially one-point failure mode peculiar to the rotary mechanism is excluded.
3. The tethered system is composed of equivalent tethered subpanels, which enables the phased construction and leads to easy integration and maintenance.
4. The subpanel consists of equivalent power generation/transmission modules, which enables low-cost mass production.
5. There is no wired signal/power interface between the modules, which leads to easy deployment of the subpanel.
6. Active thermal control is not required because of the flat distribution of the transmitting power (10 dB taper configuration will require the active thermal control for the modules near the center of the power generation/transmission panel).
7. A scale model of the tethered subpanel can be used for the demonstration experiment on the ground and in orbit in the near future, which assures the evolutional scenario for the SPS development from the initial demonstration to the commercial SPS.

Especially, (3)–(7) are the innovative points peculiar to the concept of the Tethered-SPS. On the other hand, the Tethered-SPS has several disadvantages in the performance as compared with the past SPS model that has a sun-pointing capability for the constant power.
Beam transmission controlled by an onboard computer

Beam transmission controlled by a pilot signal from the ground (±10°)

Beam transmission controlled by an onboard computer

370 km

Receiving Antenna

900 km

Fig. 16. Sequence of microwave power transmission experiment.

Fig. 17. Combination of the power supplies to meet with the diurnal variation of the power consumption in Japan. The power from the 50 Tethered-SPS (60 GW maximum) is superimposed.

generation. They are summarized as:

(1) The power efficiency is 64%, or practically 60%, as compared with the sun-pointing-type SPS, even if the solar cells are attached to both sides of the power generation/transmission panel.

(2) The power generation changes 100% with the local time as the sun angle changes.
(3) A larger size rectenna is required for the flat distribution of the transmitting power as compared with that for the tapered distribution.

The lower power efficiency of the Tethered-SPS results in higher cost of the power supply. However, the cost of the power from the Tethered-SPS could be still lower than the sun-pointing SPS that requires highly challenging technologies or non-practical technologies. Actually, the cost for the non-existing technologies such as the rotary joint or the large rotating mirrors cannot be estimated. The change of the power supply with the local time for the Tethered-SPS can be accepted for the commercial system in the mixture of varieties of the power resources on the ground, especially in the initial phase of commercialization with a ratio of the SPS power to the total less than 30%. Fig. 17 shows a combination of the power supplies to meet with the diurnal variation of the power consumption in Japan. The power from 50 Tethered-SPS (60 GW maximum) is superimposed on the same chart for reference. SPS can substitute for the power generated by LNG or petroleum, which greatly contributes to the reduction of CO₂. The rectenna size for the flat distribution is relatively larger than that for the tapered one, but the actual size is not so large as compared with the past GW-class SPS using a transmitting antenna typically with 1 km diameter, because the Tethered-SPS has a larger transmitting antenna by approximately twice than the past SPS. In case of the current study model, a rectenna 4 km in diameter can collect 90% of the total power for the flat distribution.

As a conclusion, the Tethered-SPS is a highly practical SPS model, with a number of advantages in the production, integration, construction, and operation as compared with the past SPS models. This model can be used as a realistic reference model to evaluate the cost and CO₂ load as a future energy system for human society, because the technologies employed in this concept are all achievable in the near future. However, the current study still remains at initial conceptual stage. Further studies are required to confirm the technical feasibilities more extensively, especially on the technologies for the microwave transmission and the construction of the large system in orbit.

References