TECHNOLOGY DEVELOPMENT STATUS FOR SPACE SOLAR POWER SYSTEMS

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Construction of the SSPS (Space Solar Power Systems) requires 4 major system-level technologies; power generation, wireless power transmission, large space structure, and space transportation, each in an extremely large scale. All technologies except wireless power transmission have been already put into practical use in a certain scale. Wireless power transmission has been demonstrated at the 10 kW level in the field experiments. The major problem associated with the SSPS is to apply the technologies to the huge system at GW level in power, km level in size, and several ten thousands of tons in weight. Also it is requested to make its power price be competitive with that of existing power generation systems on the ground. This paper reviews the current status of each system-level technology and evaluates the technology development scenario required for the commercial SSPS to be realized in the mid-2030's.

I. INTRODUCTION

Since the first SSPS concept was proposed by Peter Glaser in 1968, a lot of engineering studies have been conducted so far for more than 40 years. The initial extensive effort was exerted by NASA and DOE in the 1970's. The NASA reference model was an important output from the study. However, the study was terminated early in the 1980's, because the technologies that time were regarded as premature for the commercial system. In the mid-1990's, the concept was re-evaluated by NASA based on the updated technologies. New modular concepts, such as the "Sun Tower", were investigated as the more practical model than the NASA reference model.

After the NASA re-evaluation study ended in the early 2000's, there has been certain progress in the technology of photovoltaic cells, semiconductors, space structure, and space transportation in the past 10 years. Recently, a new roadmap towards commercial SSPS in the mid-2030 was generated. We are now ready to assess the scenario for technology development based on the updated technologies and the updated SSPS roadmap.

In section II, the current technology level and target level for SSPS are reviewed for the 4 system-level technologies. The SSPS roadmap developed by JAXA is introduced in section III, which is essentially equivalent to the international roadmap for Space Solar Power generated by a study team of the International Academy of Astronautics [1], targeting the pilot plants in 10-15 years. In section IV, a development scenario to fill the technology gap between the current level and target level is discussed in accordance with the roadmap.

II. SYSTEM-LEVEL TECHNOLOGIES

II.I Power Generation

The technologies for photovoltaic cells have been greatly improved recently, especially for efficiency and cost. The commercial competition in the green energy requirement has brought the rapid technology advancement. However, for SSPS application, specific weight (W/g) and radiation resistance are also important, considering the space transportation cost and harsh space environment. Since these requirements come only from the space community, motivation for progress is not so strong in the industrial level, which requires research efforts in the SSPS community. Table 1 shows the technology level at present and target level for SSPS use.

II.II Power Transmission

Microwave frequency for SSPS use has been selected in a range of 1-10 GHz, compromising between antenna size and atmospheric attenuation.

Table 1 Photovoltaic Cells Technology

	Current	SSPS Target
Conversion Efficiency	15-30 %	35-40 %
Specific Weight	10-100 g/W	1 g/W
Life in Space	10 years	30-40 years
Cost	4-6 $/W	1-0.5 $/W

Frequencies at 2.45 GHz or 5.8 GHz in the industrial, scientific and medical (ISM) radio bands have been the potential candidate. Current SSPS models tend to adopts 5.8 GHz considering the recent progress in C-band RF technologies. Table 2 shows the technology level at present and in the future for SSPS use.

As for the microwave generator, tubes such as magnetron, klystron, and TWT have been proposed for the SPS use because the power conversion efficiency is reasonably high more than 70 % at low cost. Semiconductor amplifier is getting a stronger candidate as the power efficiency has been considerably improved to 60-70 % with low cost expectation. It is believed 80 % or more will be achieved in the near future.

Besides the power efficiency, beam pointing technologies to transmit the microwave power beam precisely to the receiving site are essential for the power transmission. They are peculiar to the wireless power transmission, not covered by the existing communication technologies. A beam angle 100 μrad with a 10 μrad pointing accuracy is required for the 5.8 GHz transmission from an antenna of 2 km square in the geosynchronous orbit to a reception site of 3.5 km diameter on the ground. The transmitting antenna will be assembled by a number of array antenna panels which consist of sub-array antennas. Totally more than 1 billion antennas will be installed. A retro-directive technology with a pilot signal from the ground will be used to control the microwave beam from each antenna panel directing to the ground station. Although each panel is sufficiently stiff for microwave beaming, relative motion between the panels can not be avoided for the large antenna assembly. In order to form a microwave beam precisely focused at the ground station, the phase of microwave from each panel needs to be adjusted between the panels, which requires new technologies.

The microwave power at the receiving site is rectified to provide dc power using arrays of rectifying antenna (rectenna) with Schottky diode. The power conversion efficiency for single rectenna exceeds 80 % in a power range more than 50 mW. However, further research is required to improve the power efficiency for 1 mW class input and rectenna array as a whole.

Table 2 Microwave Power Transmission Technology

	Current	SSPS Target
Conversion Efficiency (DC to RF)	50-70 %	85 %
Conversion Efficiency (RF to DC)	60-80 %	85 %
Specific Weight	50-100 g/W	1-10 g/W
Life in Space	10 years	40 years
Cost	20 $/W	1 $/W

II.III Large Space Structure

The largest structure we have in space is the International Space Station, approximately 110 m by 70 m in length. It was constructed piece by piece by man. The manned construction will not be acceptable for SSPS, considering its cost and the harsh space environment. SSPS construction requires automatic deployment and robot assisted assembly. The maximum size of two dimensional antenna structure automatically constructed in space so far is several tens of meter. For larger structure, innovative technologies are required. As for one dimensional structure, 20 km conductive wire was deployed from the Space Shuttle and 30 km tether wire was reportedly deployed by YES2 ESA satellite. Table 3 shows the technology level at present and in the future for SSPS structure.

II.IV Space Transportation

It has been widely believed that the reusable launch vehicle (RLV) is required for the extremely low cost space transportation requested for SSPS. In the typical scenario for the space transportation for SSPS, the cargo of 50 tons class is transported to the low earth orbit by the RLV, transferred to the OTV (orbit transfer vehicle), and then carried up to the geostationary orbit, as shown in Fig.1. However, the initial research in the world for the RLV, such as

Table 3 Large Space Structure

	Current	SSPS Target
Two-Dimensional (manned)	100 m	1,000-2,000 m
Two-Dimensional (unmanned)	20-30 m	
One-Dimensional	20,000-30,000 m	5,000-10,000 m
Weight	400 tons	10,000-20,000 tons

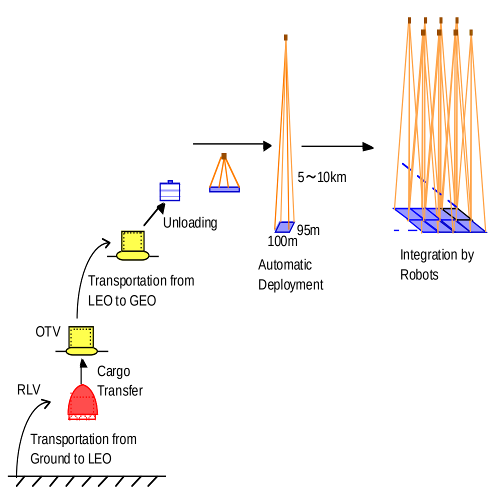


Fig.1 SSPS typical construction scenario.

Table 4 Space Transportation Technology

	Current	SSPS Target
Cargo Weight	30 ton	50 ton
Cargo into Space	Several hundres tons/year	10,000 tons/year
Launch Vehicle	Expendable	Reusable
Transportation Cost (Ground to LEO)	5-10 k$/kg	100 $/kg
Orbit Transfer Vehicle	100 mN Level	100 N Level
Transportation Cost (LEO to GSO)	No reliable data	10-50 $/kg

Space Plane, SSTO (Single Stage to Orbit), and TSTO (Two Stage to Orbit) in the 1990's, were all aborted before 2000. Since then, the efforts have been mainly concentrated on the low cost commercial expendable launch vehicle, such as COTS (Commercial Orbital Transportation Services). Although the efforts for the RLV are now minor in the space transportation community, basic research towards RLV has been continued in the space agencies and universities in the world. One prominent example is the Reusable Sounding Rocket [2] studied since 1990's at the Institute of Space and Astronautical Science (ISAS/JAXA) Japan.

Another important trend in the space transportation system is the sub-orbital RLV for space tourism, such as Spaceship 2. The technology gap from the sub-orbital flight to the orbital flight is considered very large, but the sub-orbital flight technologies could lead to breakthrough in the orbital RLV.

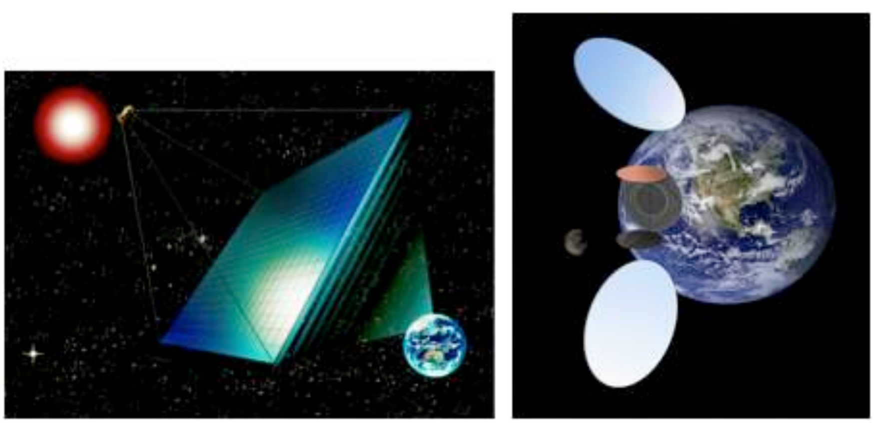
The OTV for SSPS will be a 100 tons class spaceship with a 100 Newton class electric propulsion system of MW class power. A cluster of several Newton thruster will be used for the large propulsion system. Such a large OTV has not been well studied yet. It requires a serious study, but it will be an assembly of current and near future technologies, not requiring critical innovation as compared with the orbital RLV.

Table 4 shows the technology level for the space transportation at present and in the future for SSPS construction.

III. SSPS DEVELOPMENT ROAD MAP

There are two commercial microwave-type SSPS currently studied in Japan; basic model and advanced model. They are illustrated in Fig.2. The basic model is the Tethered-SPS in which the power generation/ transmission panel is suspended by tether wires and stabilized by the gravity gradient force, which was studied by USEF (recently re-organized as Japan Space Systems). The earth-pointing configuration is very simple, and the technical feasibility is high, but the power collection rate is not so high, 64 % as compared with sun-pointing type SSPS. The advanced model is a combination of reflective mirrors with power generation solar array and microwave transmitter. It utilizes the formation flight of reflective mirrors and power generation/transmission complex, which was studied by JAXA. The configuration is complicated, requiring highly challenging technologies, but the power collection rate is almost 100 %. The basic model will be realized initially in the commercial phase and the advanced model will be later constructed when the technologies associated with the sun-pointing system are well established.

In 2009, the Japanese government established a new space policy for SSPS. It requires demonstration of SSPS technologies first on ground and then on orbit within several years. It also expects to have SSPS prospects for practical application within the next 10 years, comparing with the progress of the renewable energy development on earth. This means we will enter the SSPS development phase around 2020, if



(a) Basic Model (Earth-pointing) (b) Advanced Model (Sun-pointing)

Fig.2 Commercial microwave-type SSPS currently studied in Japan [3].

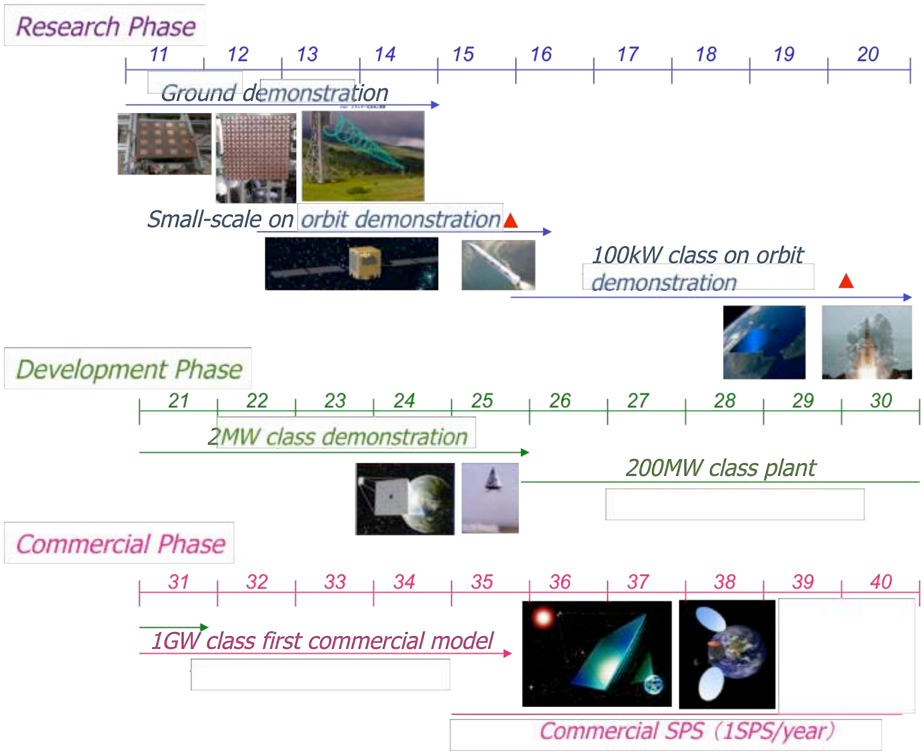


Fig.3 SSPS(SPS) development roadmap to realize commercial model in the mid-2030.

SSPS is accepted as a practical energy source and if the technologies are ready for development. The roadmap we have developed to accommodate the requirements of the space policy is shown in Fig.3.

In the microwave power transmission experiment on the ground, a microwave beam around 1.6 kW from array antenna will be transmitted to a rectenna located typically at 50 m from the transmitter, as illustrated in Fig.4. The microwave beam will be precisely guided using the retro-directive beaming technology with a pilot signal from the rectenna site. This will be the first experiment in the world for kilowatt class power transmission with a high pointing accuracy less than 0.5 degree in a long range up to 50 m.

After completion of the ground microwave power transmission experiment, we will be ready for a small-scale demonstration experiment in orbit. Using the technologies verified in the ground experiment, a microwave power transmission at several kilowatts level from the low earth orbit to the ground will be conducted. The space experiment will demonstrate the beam control technology for several hundred kilometers and verify the power beam transmission through the ionosphere without serious loss of power.

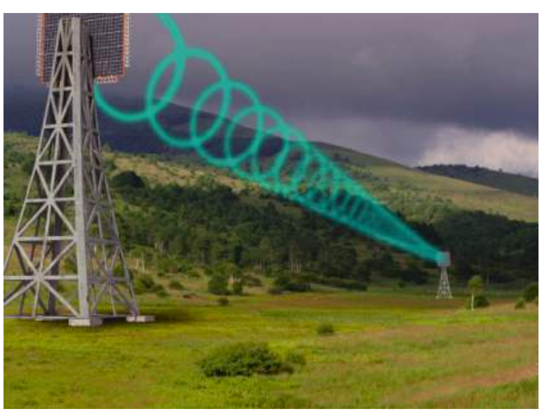


Fig.4 Demonstration experiment on the ground planned for 2014 in Japan.

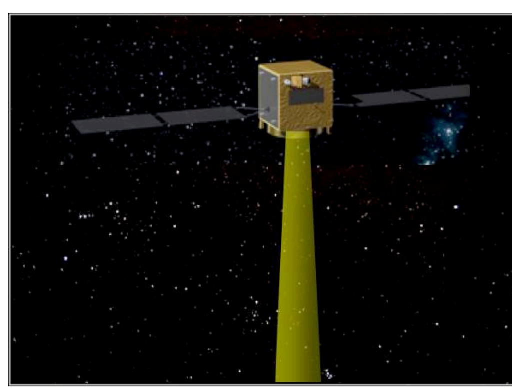


Fig.5 kW class demonstration experiment for microwave power transmission in space.

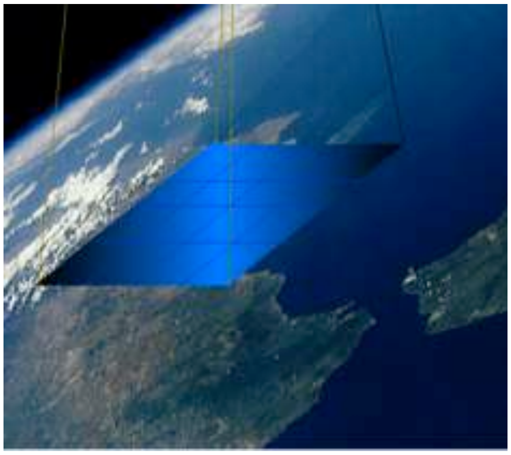


Fig.6 100 kW class microwave transmission experiment in Space.

The concept for the microwave transmission experiment from the small satellite is illustrated in Fig.5. A power transmission panel consisting of several modular panels similar to those on the ground demonstration experiment will be used to transmit several kilowatts power. A small satellite for scientific research is a potential candidate platform for the experiment. The satellite will be launched by the Epsilon rocket which is now under development at ISAS/JAXA. The weight of the satellite will be 500 kg. If we use the International Space Station for the demonstration experiment, we will be able to have more modular panels which is capable of transmitting nearly 10 kW power to the ground. In order to study the nonlinear interaction of the microwave power beam with the ambient plasma, power density more than 100 W/m^2 is required. In the demonstration experiment in the low earth orbit, a maximum beam intensity more than 100 W/m^2 will be realized for several tens of meter in the F-layer of the inosphere.

After the small scale experiment is completed, a 100 kW class demonstration experiment will be conducted using a large rocket, H-II-A or B. It will carry more than 10,000 kg satellite to the low earth orbit. Figure 6 illustrates a 100-400 kW class demonstrator for microwave power transmission. The experiment will verify the end-end SSPS technologies in which an effective power of 10 kW level is obtained on the ground.

After completion of the end-end demonstration experiment, we will be ready for evaluation of SSPS concept as a promising renewable energy source, and also ready to select the target configuration for the commercial SSPS as shown in Fig.2 or possibly other configuration. Based on the space-verified technologies, we will develop the pilot plant of 2 MW and then 200 MW class, the initial practical model towards the commercial SSPS, as is illustrated in

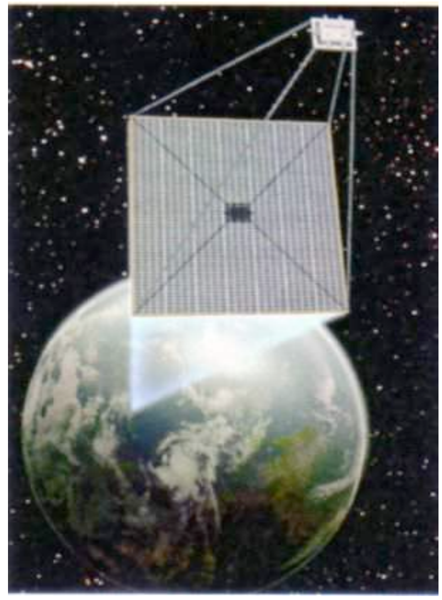


Fig.7 2 MW and 200 MW class pilot plant in the development phase.

Fig.7. In the pilot plant demonstration, the electric power from the rectenna will be supplied to the commercial grids and overall performance will be evaluated.

IV. TECHNOLOGY ASSESSMENT

As is described in section II, the current achievement level for each system-level technology is extremely low as compared with the SSPS target. The scale factor normalized by the target level is currently 1/10,000 for power generation in space, 1/1,000,000 for power transmission, 1/100 for structure size in space, and 1/100 for space transportation capability per year. These gaps need to be filled up step by step towards the commercial SSPS.

Figure 8 shows the technology gap at each milestone in the roadmap, which suggests the priority in the technology development for each phase. The ground demonstration experiment at the kW level is now underway and the technologies required for the experiment are almost established. The first milestone from now is the kW level transmission experiment from space to ground, currently proposed in the mid-2010's. It requires a progress in the power transmission technology, shown in green in Fig.8. No new advancement in other technologies is required for the first milestone. The microwave power transmission in space environment in a long range more than 100 km requires new technologies. The second milestone is the 100 kW class demonstration in space around in 2020, which requires a large step-up in the power transmission technology as shown in

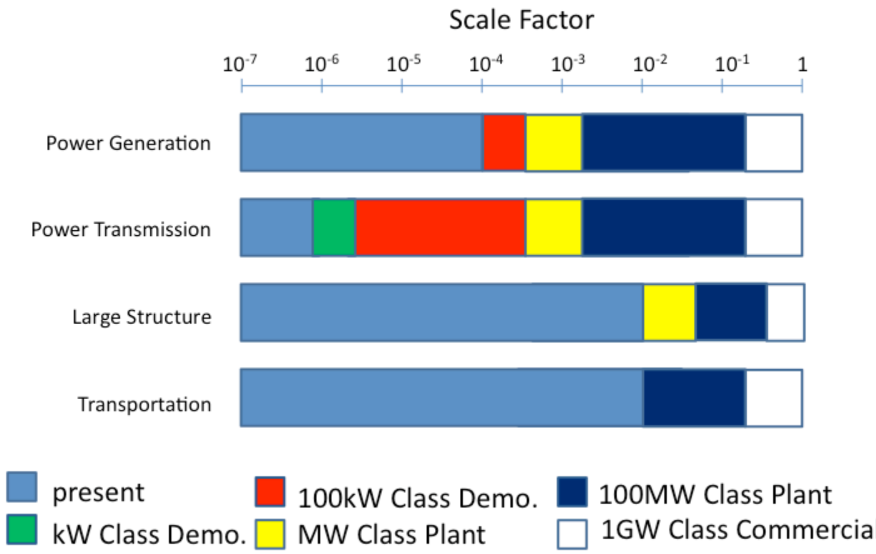


Fig.8 Technology gap at each milestone in the roadmap.

red. It includes the end-end technology of microwave power transmission/reception. For the second milestone, a small step-up is also required for the power generation, which includes the interface between the power generation system and power transmission system. The third milestone is the MW class plant in the mid-2020's, which requires a new progress in yellow for automatic construction of 100 m scale space structure, as well as another big step-up in yellow for power generation and power transmission technology. If we consider the sandwich panel, new technologies are not required for the power generation and transmission at this stage. The 100 MW plant, the fourth milestone around 2030' requires a big advancement in blue for all 4 field technologies. However, among them, the space transportation technology requires the largest innovation as the reusable launch vehicle and the orbit transfer vehicle are eventually required at this phase. For the power generation and power transmission, new technology is not required at this phase, because the increase of the power is achieved just by connecting power modules (100mx100m) at this stage. However, a new technology in the field of space structure to connect the large panels of 100 m scale is required at this stage. After the fourth milestone, the technologies used for the 100 MW class plant are applied straightforward to construction of the 1 GW class commercial model in 2030's.

V. CONCLUSION

Construction of the SSPS requires 4 major system-level technologies; power generation, wireless power transmission, large space structure, and space transportation. We have reviewed the current status of each technology level and necessary progress towards the commercial SSPS. Combined with the roadmap targeting the pilot plants in the mid-2020's and the commercial SSPS in the mid-2030', we have analyzed the advancement of technology required for each milestone of the roadmap. It is concluded that a large progress is required for the power transmission in the first 10 years from now, a new progress is required for the large space structure targeting in the next 10 years, and an innovative advancement for the space transportation is required targeting in the last 5 years.

VI. REFERENCES

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