UPDATED TECHNOLOGY ROAD MAP FOR SOLAR ENERGY FROM SPACE

S.Sasaki, K.Tanaka, and K.Maki
ISAS/JAXA, sasaki@isas.jaxa.jp

Advanced Mission Research Group
ARD/JAXA

The government commitment to SSPS (Space Solar Power Systems) research in Japan was initiated by the basic plan for space policy in 2009. According to the requirements of the policy, we have updated the technology road map towards the commercial SSPS. It consists of three major phases; research phase, development phase, and commercial phase. In the research phase before the end of 2010's, the critical technologies, especially for wireless power transmission, will be verified both on ground and in the low earth orbit. In the development phase, initially 100 kW-class verification and then plant-level demonstration up to 200 MW, will be conducted in the 2020's. The first commercial SSPS, 1GW class in the geostationary orbit, will come up in mid-2030's.

I. INTRODUCTION

The global problem, combined with CO_2 issue and shortage of natural energy resources, needs to be resolved in the latter half of this century for human sustainability. Considering the climate inertia and the leading time for new energy infrastructure, the "solar energy from space" needs to be realized in the time frame 2030-2040. Referring to the history of nuclear power plant as an innovative energy system shown in Fig.1, it will take 20-25 years for the Space Solar Power Systems (SSPS) from the initial system verification to the first commercial model. The same time frame is considered for the nuclear fusion research. That means we are requested to complete the initial SSPS system verification within 5 years to ensure the first commercial SSPS in operation around 2035.

In 2009, the Japanese government established a new space policy including SSPS. It says "Government will examine the system for the development of space solar power program from a comprehensive point of view in collaboration with related institutions, and also conduct demonstration of technologies for the energy transmission technology in parallel. Based on the result, Government will conduct ample studies, then start technology demonstration project on orbit utilizing "Kibo" or small sized satellites within the next 3 years to confirm the influence in the atmosphere and system

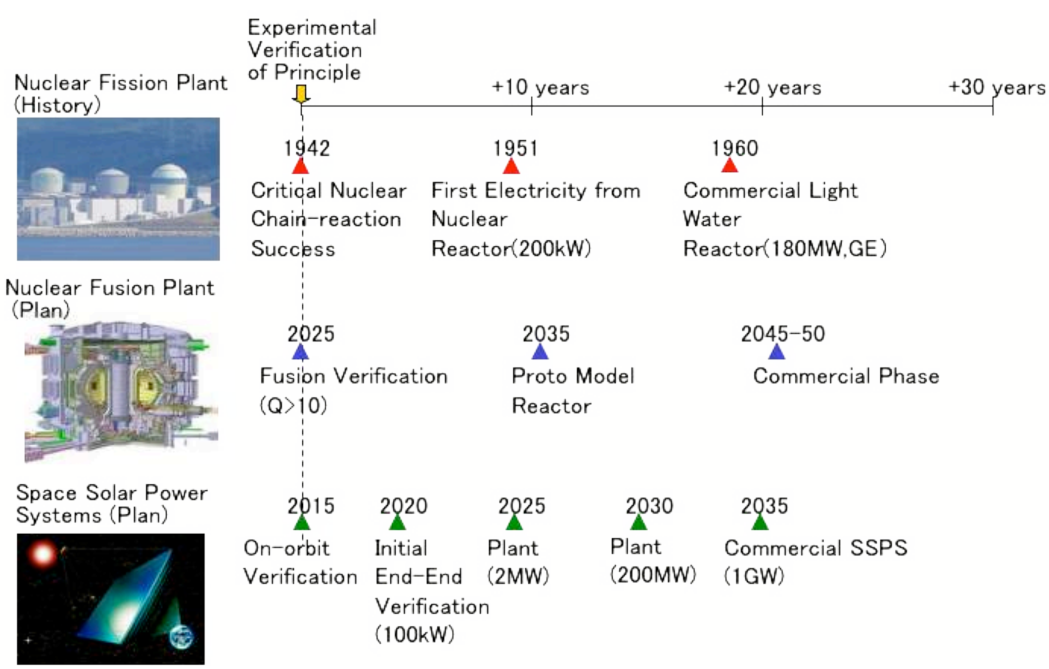
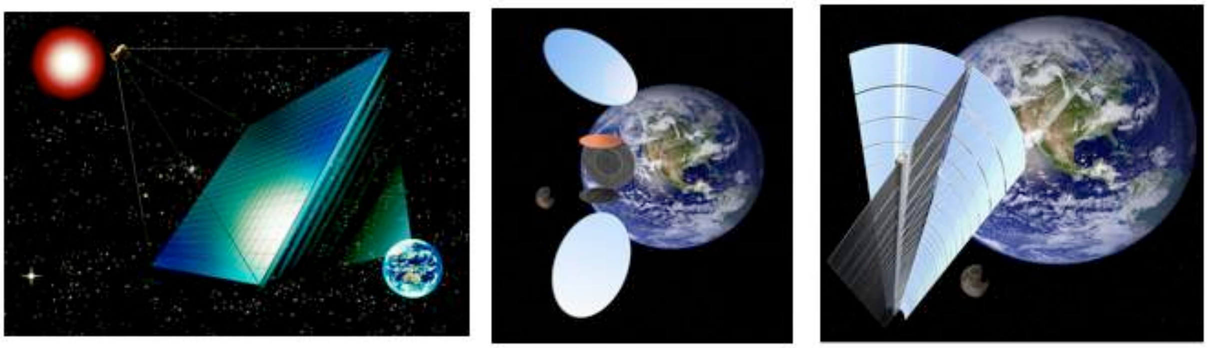


Fig.1 Development time frame for nuclear fission plant and fusion plant as compared with SSPS.



(a) Microwave Basic Model (USEF) (b) Microwave Advanced Model (JAXA) (c) Laser Model (JAXA)

Fig.2 Typical SSPS commercial models currently studied in Japan [1].

check". The policy has been reviewed and reevaluated in 2011, but the fundamental stance has not been changed.

In Japan, there are three types of commercial SSPS currently proposed; microwave-type basic model, microwave-type advanced model, and laser-type model, as shown 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 has been studied by USEF (Institute for Unmanned Space Experiment Free Flyer). 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 has been studied by JAXA. The laser-type model is a combination of focusing mirrors, a crystal laser exciter, optics, and a heat radiator, which has been studied by JAXA.

2. TECHNOLOGY ROAD MAP

The road map to accommodate the requirements of the Japanese space policy is shown in Fig.3. We just started development of the wireless power transmission demonstration systems on the ground at 1 kW level both for microwave and laser. The ground demonstration will be completed by the end of 2012. Based on the design of the ground demonstration system, a small scale microwave power transmission experiment in orbit will

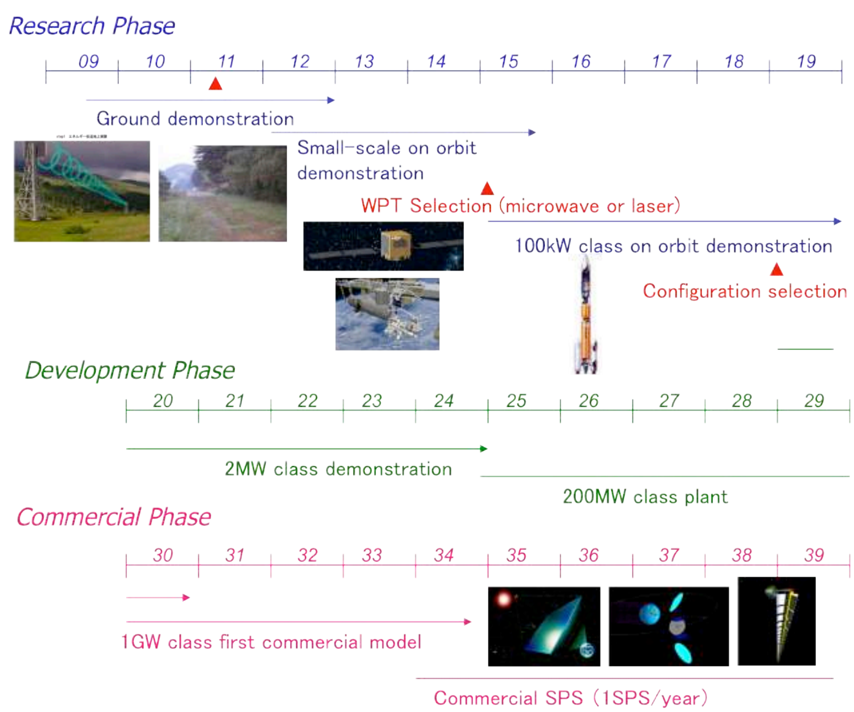


Fig.3 Road map for commercial SSPS.

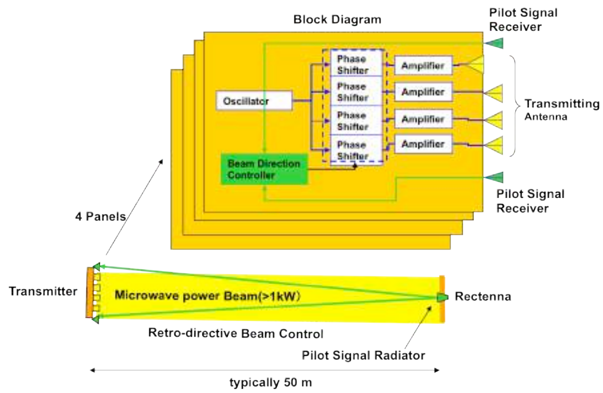


Fig.4 Microwave power transmission experiment on the ground

be conducted around 2015. If the technologies for the laser power transmission and the large scale panel deployment are ready for the space experiment, they will be also demonstrated in the same time frame. Small satellites and/or JEM (Japanese Experiment Module) on the International Space Station are the possible platform for the demonstration experiments. After completion of the demonstration experiments on the ground and in space, we will select the microwave or laser for the wireless power transmission medium. The expected power cost and public acceptance will be the major trade off factors for selection. Using the selected medium, we will demonstrate a 100 kW class SSPS in space around 2020. All basic technologies required for the commercial SSPS will be verified at this stage. The demonstration for the commercial SSPS will be conducted using 2 MW to 200 MW class SSPS plant before 2030. This scenario guaranties the start of construction of the 1 GW class commercial SSPS early in 2030's.

2.1. Research Phase

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. The microwave beam will be precisely guided using the retro-directive

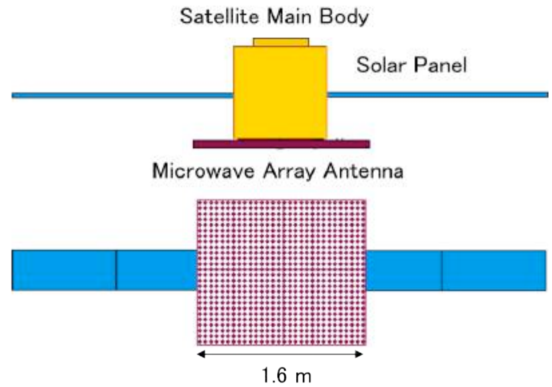


Fig.6 1kWclass demonstration experiment in space.

beaming technology with a pilot signal from the rectenna site (Fig.4). In the laser transmission experiment, a laser beam around 1 kW directly generated by the concentrated solar light will be transmitted to a photovoltaic receiver located at 500 m apart from the transmitter as shown in Fig.5.

After completion of the ground wireless power transmission experiments, we will be ready for a small-scale demonstration experiment in orbit. For the microwave demonstration experiment, power transmission at the kW level from the low earth orbit to the ground will be conducted. The space experiment will demonstrate the beam control technology for several hundred km and verify the power beam transmission through the ionosphere without serious loss of power. The configuration for the microwave transmission experiment from the small satellite is shown in Fig.6. A power generation/transmission panel consisting of 4 modular panels similar to those on the ground demonstration experiment will be used to transmit 3 kW power. If we use the International Space Station for the demonstration experiment, we will be able to have 9 modular panels which is capable of transmitting 6 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 case of the JEM experiment, maximum beam intensity more than 1000 W/m^2 will be

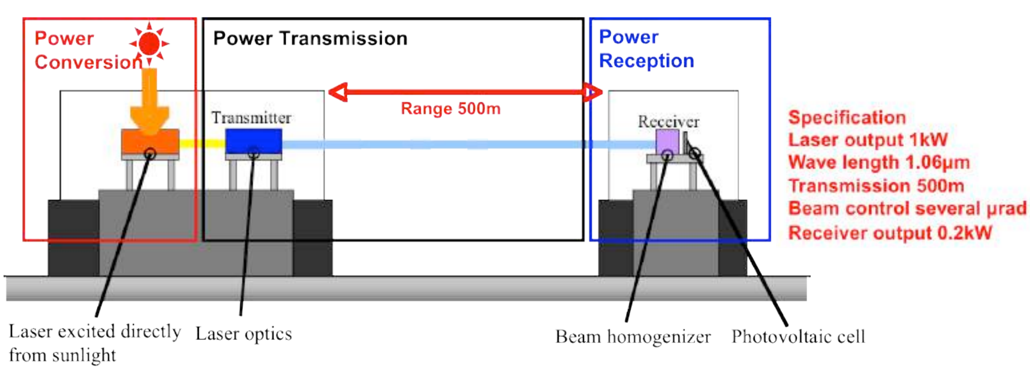


Fig.5 Laser power transmission experiment on the ground.

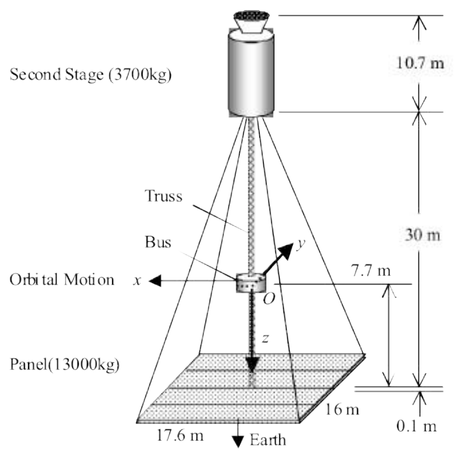


Fig.7 100kWclass demonstration experiment in space.

realized for more than 130 m from spacecraft. Based on the results from the small-scale demonstration experiments in space and laboratory research, we will make a decision on the technology selection, microwave or laser, for the next phase development.

2.2. Development Phase

After the small scale experiments are completed, a 100 kW class demonstration experiment using the selected transmission medium, microwave or laser, will be conducted. Figure 7 shows a 100 kW class demonstrator for microwave 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 experiments, we will 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 200 MW class, the initial practical model towards the commercial SSPS. For the pilot plant demonstrations, the electric power from the rectenna will be supplied to the commercial grids.

Table 1 shows a verification matrix towards the commercial SSPS. In the ground demonstration phase, beam control up to 50-500 m will be verified. In the small scale experiment in orbit, the beam control up to 400 km will be verified. For microwave transmission through the ionosphere, the power density up to 1 kW/m^2 will be verified. At this phase, the wireless power transmission technologies are all verified. In the large scale demonstration phase, 100 kW level, the power reception on ground will be verified, and end-end SSPS technology verification will be completed. In the small plant phase (2MW), one unit of commercial SSPS is constructed, in which the electrical performance, construction scenario, and operation procedure will be fully verified. 200 MW class pilot plant phase is the final demonstration stage for commercialization to verify the over-all technologies using 1/5 scale model.

3. SPACE TRANSPORTATION SYSTEM

The road map shown in Fig.3 is based on several critical assumptions. One of them is a revolutionary development in the field of the space transportation. The transportation cost is currently 5 k$/kg - 10 k$/kg, depending on the transportation system. The cost will be lowered in the near future in the process of commercialization. However, the cost reduction is limited to factor of magnitude, not order of magnitude if we stick to the conventional Expendable Launch Vehicle (ELV). In order to achieve a realistic power cost compatible to that of the ground commercial plant, the transportation cost needs to be reduced down to 1/50 -1/100. To realize such an extremely low transportation cost, we have to develop the Reusable Launch Vehicle (RLV).

The history of the efforts for the RLV has shown that

Table 1. SSPS verification matrix towards the commercial SSPS.

Phase / Verification	Ground Demonstration	Small-scale Flight Demonstration	Large-scale Flight Demonstration	Small Plant	Large Plant
	kW Ground	kW Low Earth Orbit	100kW Low Earth Orbit	2MW 1000 km Altitude	200 MW Geostationary Orbit
Beam Control	50-100m	400km	400km	1000km	36000km
Ionosphere/ atmosphere transmission	-	$1kW/m^2$	$1kW/m^2$	$1kW/m^2$	$1kW/m^2$
Power Transmission	(Test Rectenna kW)	-	Small Rectenna 10kW	Large Rectenna 2MW	Large Rectenna 200MW
SPS Total Function	-	-	10kW	2MW	200MW
Power for Practical Use	-	-	-	2MW	200MW

Table 2. SSPS requirements to space transportation system.

Phase	Small scale demonstration	Large scale demonstration	Small plant	Large plant	First commercial model	Commercial
Target year	～2015	～2020	～2025	～2030	～2035	2035～
Orbit	LEO	LEO	1000 km	GEO	GEO	GEO
Power level	1～5kW	100 kW	2 MW	200 MW	1 GW	1 GW
System weight	500 kg	15 tons	50 tons	3000 tons	10000 tons	10000 tons
Construction period	NA	NA	1 year	3 years	5 years	1 year
Payload weight	500 kg	15 tons	10 tons	50 tons	50 tons	50 tons
Launch vehicle	1 ELV LEO	1 ELV LEO	1 RLV 1000km 5 round trips launch/2.4 months	4 RLV 500 km 160 round trips launch/week 4 weeks turn around	8 RLV 500 km 640 round trips launch/3 days 3 weeks turn around	28 RLV 500 km 640 round trips 2 launch every day 2 weeks turn around
Orbit transfer vehicle	NA	NA	NA	17 OTV 500 km-GEO 6 round trips *	40 OTV 500 km-GEO 10 round trips*	200 OTV 500 km-GEO 2 round trips*

* 6 months round trip, fuel 30 tons

the development is quite challenging, but not impossible. It is widely believed its realization will take 10-20 years from now. Towards the low cost reusable transportation system, several efforts are now underway in Japan. One of them is the on-going project for the "reusable sounding rocket" [2] by ISAS/JAXA. SSPS project definitely requires the low cost transportation system, but not now. Table 2 shows the launch vehicle required for each phase. Up to the large scale demonstration experiment at 100 kW class, the existing ELV can be used. However, for the phase of small plant construction starting around 2024, at least one RLV of 10 tons class will be required for transportation of 50 tons cargo. 10 tons class RLV is an initial test model for the standard 50 tons RLV. No OTV is required at this stage, because the small plant SSPS is put into the orbit at 1000 km height. For the large scale plant, 1/5 scale model of commercial model, 4 RLVs from the ground to 500 km altitude and 17 OTVs from 500 km altitude to the geosynchronous orbit are required for the construction starting in 2027. In the commercial era, 28 RLVs and 200 OTVs will be required for construction of 1 GW class SSPS every year.

4. SUMMARY

The updated technology road map towards commercial SSPS that accommodates the requirements from the Japanese space policy has been introduced. The projects for ground demonstration experiments have been already started. They demonstrate the technologies to transmit a kW class microwave beam or a kW class laser beam precisely to the receiving site located at 50-100 m from the transmitter. The technologies verified in the ground experiment will be used to conduct the next-step kW class demonstration experiment from the low earth orbit to the ground. After completion of the small scale demonstration experiment, we will make a 100 kW-class SSPS demonstration experiment in orbit, as the first end-end SSPS verification. The plant level demonstration from 2 MW to 200 MW will be conducted by the end of 2020's, that will contribute in timely manner to solve the global problem, combined with CO_2 issue and shortage of natural energy resources.

References

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[2] Y.Inatani, Recent Progress toward Reusable Sounding Rocket, IAC-10.D2.4.9, 61st International Astronautical Congress, Prague, 2010.