Online Journal of Space Communication

Volume 11
Issue 18 *International SunSat Design Competitions (Fall 2013 / Summer 2016)*

Article 4

October 2021

SunSat Design Competition 2014-2015 First Place Winner – Team CAST: Multi-Rotary Joints SPS

Xinbin Hou

Meng Li

Lili Niu

Lu Zhou

Ying Chen

See next page for additional authors

SunSat Design Competition 2014-2015 First Place Winner – Team CAST: Multi-Rotary Joints SPS

Authors

Xinbin Hou, Meng Li, Lili Niu, Lu Zhou, Ying Chen, Zhengai Cheng, and Haipeng Ji

Multi-Rotary Joints SPS

China Academy of Space Technology, Beijing, China

Hou Xinbin, Li Meng, Niu Lili, Zhou Lu, Chen Ying, Cheng Zhengai, Jia Haipeng

ABSTRACT

Space Power Satellite (SPS) is a huge spacecraft designed to collect solar energy in space for supplying electric power to the electric grid on the ground. The SPS concept was first proposed by Dr. Peter Glaser in 1968.

Various studies on SPS in various countries have been produced over the past forty years. Today, there are multiple variations on this early concept, both in innovation and in optimization. Because of the huge size, immense mass and high power of these SPS installations, there are many technological difficulties.

Here, a new Multi-Rotary Joints SPS (MR-SPS) concept is proposed. The large solar array is taken apart to illustrate the many small solar sub-arrays, and to show that each solar sub-array has two middle-power rotary joints. The extreme technical difficulty of high-power rotary joints is simplified by many middle-power rotary joints. The single-point failure problem existing in traditional SPS concept is also solved.

At the same time, the modular solar arrays can be more easily assembled in GEO where the power can best be generated and continuously transmitted. Based on our new concept, a whole system full-life NPV analysis method has been developed to evaluate the economics. Our primary results show that the investment is near 30 billion US dollars, with development and transportation costs representing the main portions. When the price of power and the development and construction costs are fixed, the cost of capital becomes an important parameter in influencing the NPV.

Click here to see the China Academy of Space Technology's (CAST) video: Multi-Rotary Joints SPS - 2015 SunSat Design Competition

TECHNICAL BRIEF

INTRODUCTION

Solar Power Satellite (SPS), a great idea invented by the honored father of SPS Dr. Peter Glaser, is gaining greater attention as an important future energy source.

It has been over forty years since the first SPS concept was proposed, but not a single experimental system has yet been developed. We expect that tens of years will be needed to realize a commercial GW class SPS. The main reason: it will be very difficult to build, launch and operate an SPS.

Firstly, it must be assembled in space and that's a key problem. Its weight, area and volume will be restricted seriously by the launch capability. Maintenance will also be difficult. Secondly, SPS will represent an incredible complex space macro-engineering project. It's structure will be large. For a GW-class SPS system, the area will be several km square; it's weight will be ten thousand tons. Thirdly, the amount of energy that must be managed will be too high. For a commercial SPS, the generated electric power in space will be over 2 GW; the voltage will be thousands of volts. Power management and distribution (PMAD) in space will be a huge challenge.

Fig.1. MR-SPS Concept.

Multi-Rotary joints SPS (MR-SPS) is a huge Solar Power Satellite located in Geostationary Earth Orbit. Multiple independent solar sub-arrays are used to point to the Sun, continuously and steadily converting solar energy to electric power (Fig.1).

Each sub-array can transmit electric power to the cables installed on the main structure by their own two independent rotary joints. The main structure and the transmitting antenna are connected together and there is no relative motion between them. The electric power is transmitted to the antenna by the cables along the structure trusses and is converted to microwave energy by microwave generators. The space antenna transmits high power microwave energy to an Earth-based rectenna that converts it to electric power. This power is either used locally or relayed onto the terrestrial electrical grid for continuous consumer access. (Typical quantities of electrical power are estimated at 1 GW.)

The SPS system proposed includes a Solar Energy Collection and Conversion (SECC) sub-system, a Power Transmission and Management (PTM) sub-system, a Microwave Power Transmission (MPT) sub-system, a Structure sub-system, an Attitude and Orbit Control (AOC) sub-system, a Thermal Management (TM) sub-system, and an Information and System Operation Management (ISRM) sub-system. Our MR-SPS includes three primary parts: solar array, microwave transmitting antenna and main structure. The SPS platform devices, including AOC, TM and ISRM devices, are installed on the solar arrays, microwave transmitting antennas and the main structure.

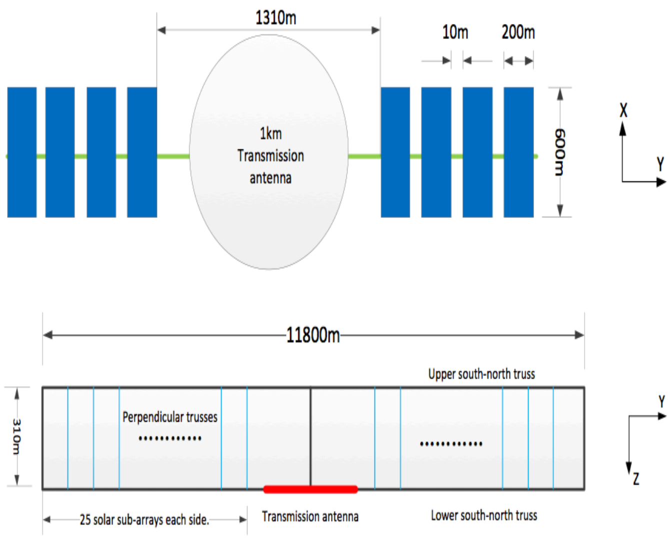


Fig.2. Configuration of MR-SPS.

Fig.2 shows the configuration and size of a typical 1 GW MR-SPS concept. The solar array is composed of 50 solar sub-arrays. The space between solar sub-arrays is 10 m and the space between the two solar sub-arrays beside the antenna is 1,310 m to avoid the effect of eclipse on the antenna. So the whole length of an SPS is 11,800 m.

Considering atmosphere transparency, 5.8 GHz is selected as the frequency for microwave transmission. Because of the high energy density and long transmitting distance, an antenna with 1,000 m diameter is selected.

The main structure connects the solar array and the microwave transmitting antenna. The upper south-north truss supports the solar sub-arrays and the solar sub-arrays rotate around the truss in orbit to point to the Sun. The lower south-north truss supports the microwave transmitting antenna and there is no relative motion between them. The upper south-north truss and the lower south-north truss are connected by many perpendicular trusses.

System Efficiency

The whole energy conversion and transmission efficiency chain of a SPS is shown in Table 1.

Factors	Efficiency	System efficiency
Solar energy collection and conversion（0.29）		
Solar cell	0.40	0.4
Error of Sun-pointing	0.99	0.396
Gapof solar cells	0.85	0.336
Angle of sunlight	0.958	0.322
Space environmenteffect	0.90	0.290
Power transmission and management（0.854）		
Voltage conversion in solar array	0.95	0.276
Transmission	0.95	0.262
Voltage conversion in antenna	0.95	0.249
Consumed by service devices	0.999	0.248
Microwave power conversion and emitting（0.833）		
Microwave generator	0.85	0.211
Microwave regulation	0.98	0.207
Microwave power transmission		
Microwave transmission	0.90	0.186
Microwave power receiving and conversion（0.765）		
Receiving antenna	0.9	0.168
Rectifier circuits	0.85	0.143
Electric power regulation（0.97）		
Electric power collection	0.98	0.140
Voltage conversion	0.99	0.138

Table 1. The efficiency chain of MR-SPS.

Solar Energy Collection and Conversion

The function of the SECC sub-system is to collect and convert space solar energy into electric power. According to the configuration and the efficiency chain, our SECC sub-system will supply 2 GW electric power for MPT sub-system. The whole SECC sub-system includes 50 solar sub-arrays. Each solar sub-array is composed of 12 solar array modules that are divided into two lines and each line includes 6 modules and the whole area is about 0.12 km2. The structure of the solar sub-array is a 200 m × 600 m crisscross truss structure. The 200 m truss connects the rotary joints in two ends and the 600 m truss connects 12 solar array modules. The power generated by each module is transmitted first to the rotary joint and then is relayed to the microwave transmitting antenna by the cables installed on the main structure of the SPS.

A solar array module is composed of a thin-film solar array, trusses and deployment mechanisms. It is folded before launch and is deploys automatically in orbit. Its size is 100 m × 100 m and its weigh is about 3 tons. The high efficiency thin-film GaAs cell is selected and an efficiency of over 40% is expected. Considering the gaps between cells, the output power of a solar array module is about 4 MW. So, the output power of the whole SECC sub-system is about 2.4 GW and the weight is about 1800 tons.

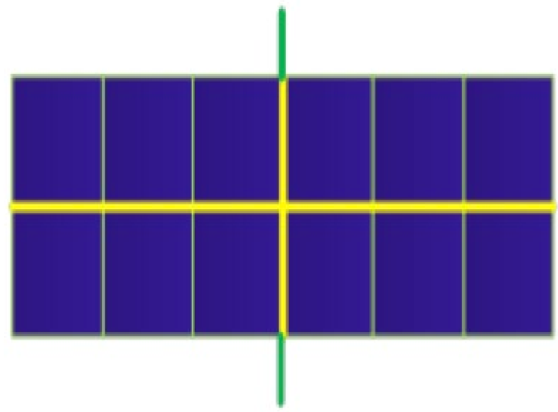


Fig.3. Configuration of a solar sub-array.

Power Transmission and Management

The primary function of the PTM sub-system is to combine, convert, transmit and distribute the output electric power of the SECC sub-system. A majority of the power is transmitted to the antenna and is distributed to the microwave generators. The remainder of the power is transmitted to and distributed among the platform devices of SPS to maintain normal operation.

Considering the configuration of SPS, a mix of distributed and centralized PTM is adopted. The separated solar sub-arrays transmit the electric power to the cables via 100 rotary joints and these cables are combined and connected to the two electric power interfaces of the antenna. Thereby, the electric power is distributed in the antenna (Fig.4). The whole PTM includes three segments:

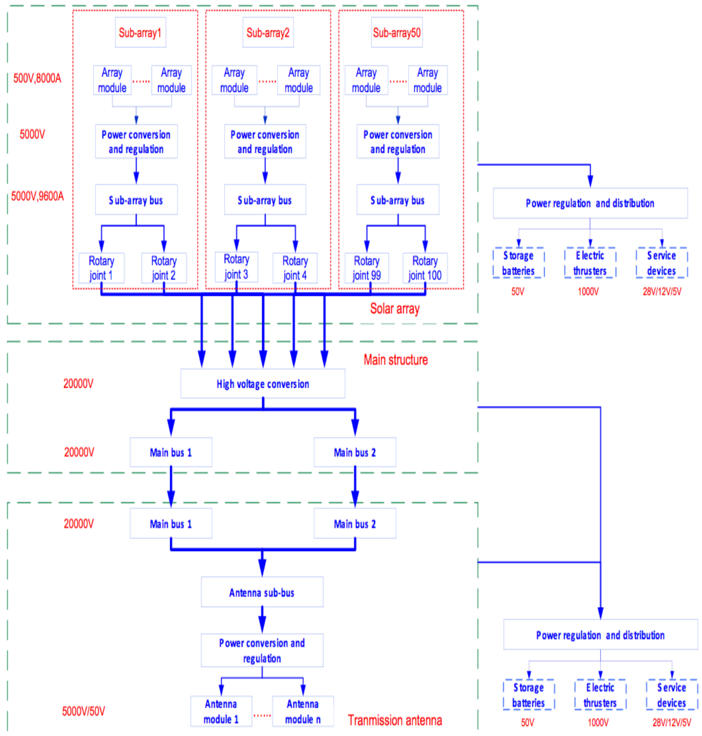


Fig.4. Mix configuration of distributedand centralized PTM.

The first segment is the Power Transmission and Management of the solar array. The function is to convert, regulate and transmit the electric power of solar array modules. A majority of the power is transmitted to the rotary joints. The remainder of the power is distributed to the service devices on the sub-arrays, including to the energy storage equipment needed to supply power during eclipse. The voltage of the output power of solar array modules is 500 V. The power is converted to 5000 V when transmitted to the rotary joints. So, for a solar sub-array, there are two output power buses and each bus is 5000 V, 4800 A.

The second segment is Power Transmission and Management on the main structure. The function is to convert, regulate and transmit the electric power of solar sub-arrays. A majority of the power is supplied to the electric power interfaces of the antenna. A part of the available power is distributed to service devices (including electric thrusters) and the remainder of the power is used for energy storage to supply power for service devices during eclipse. The voltage of output power of solar sub-arrays is 5000 V. The power is converted to 20 kV and is transmitted to the antenna. So, for the antenna, there are two input power buses and each bus is 20 kV, 50 kA.

The third segment is Power Transmission and Management on the antenna. The function is to convert, regulate and transmit the electric power of the antenna. The voltage of input power of the antenna is 20 kV. A majority of the power is converted to 5 kV and is transmitted to the microwave generators to generate microwave. Some of this power is distributed to service devices (including electric thrusters) and the remainder of the power is used for energy storage to supply power for service devices during eclipse.

Microwave Power Transmission

MPT is the most important sub-system of SPS. Considering integration, the microwave power transmission should address both space segment and ground segment requirements. The space segment is composed of the transmitting antenna, microwave generators, microwave phase control circuits and power dividers. The ground segment is composed of rectennas, DC converters and retro-direction beam system. For a SPS, the space segment will be the most important architectural element.

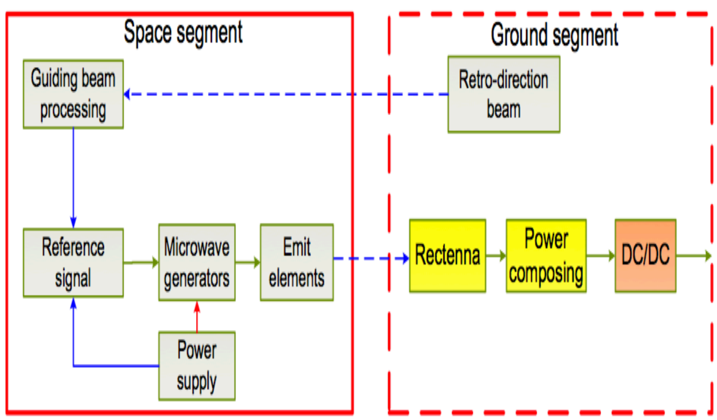
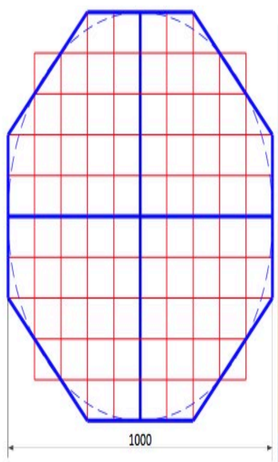


Fig.5. Functional architecture of the MPT.

The microwave generators convert the electric power to microwave power. The microwave power is fed into the antenna by power dividers. The microwave phase control circuits control the phase of all microwave generators to insure high efficiency and high direction precision (0.0005°) of microwave power transmission. The antenna emits power to the rectenna on Earth. The rectenna receives and rectifies microwave power to DC power and then the DC power is transmitted into the grid. The retro-direction beam system emits a guiding beam to the transmitting antenna in space. This beam signal will be received, analyzed and processed to control the phase of microwave generators to achieve high precision direction adjustment.

Considering the requirement of high atmosphere transparency and the size of the transmitting antenna, 5.8 GHz is selected by most SPS conceptual designs. For a special MPT system, the product of the diameter of the transmitting antenna and the diameter of the rectenna is direct proportion to transmission distance while the microwave frequency and energy interception efficiency are fixed. For a SPS in GEO, the distance is about 36000km. When a 1 km diameter transmitting antenna and a 5 km diameter rectenna are selected, the interception efficiency is expected to be larger than 90% using the 5.8 GHz beam.



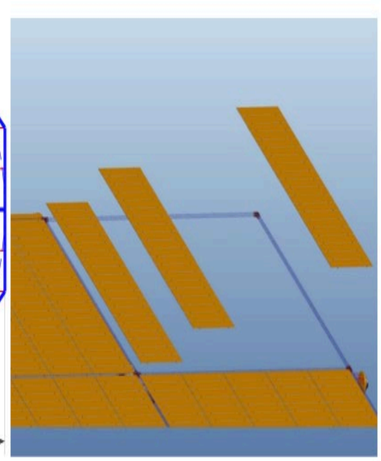


Fig.6. Configuration of transmitting antenna. Fig.7. Antenna modules in a grid.

For the huge 1 km diameter and the high power density (about 2 kW/m2), a flat phase control antenna is selected. The structure of the antenna is composed of many truss modules, presented in Fig.6. The broken line represents the ideal antenna boundary. The wide lines represent the main sustainment trusses. The thin lines represent the sustainment trusses of antenna modules and form eighty 100 m × 100 m grids and each grid can install five 20 m × 100 m antenna modules (Fig.7). An antenna module is composed of 320 array modules and each one includes 6400 emit elements and each one emits about 1.95 W microwave power. So the MPT sub-system includes 128000 array modules in all, i.e. 819200000 emit elements. The microwave phase of a special array module is achieved by processing the received retro-direction beam signal. The phase is input microwave generators, for example Phase Controlled Magnetron.

Other Sub-systems

The main structure of MR-SPS is composed of truss modules and joint modules. For the truss modules, automatic deployment and connection functions are necessary. So a truss module is more similar to a spacecraft including structure, deployable truss, connection mechanism, power supply, GNC, thermal control, TT&C sub-system, and so on.

A truss module includes four deployed trusses and the length of one truss is about 100 m and the weight is about 2-3 tons. The joint modules are used in special connection positions and include four types, i.e. T shape module, L shape module, cross shape module and 135° shape module.

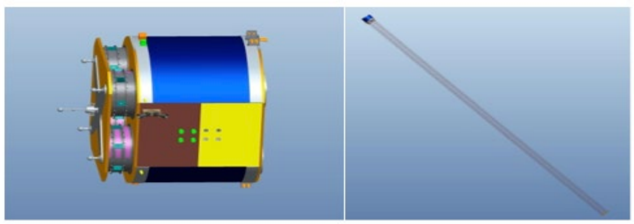


Fig.7. The states of compressed and deployed of atruss module.

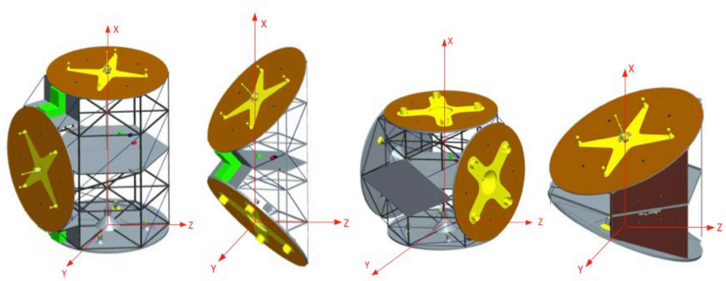


Fig.8. The joint modules.

The function of AOC sub-system is to maintain the orbit position and to keep the solar array Sun-pointing and the antenna Earth-pointing. It includes central control computers, node control computers, electric thrusters, momentum wheels, star sensors, Sun sensors, infra-red Earth sensors and gyroscopes.

The sensors send the information concerning the attitude of the SPS to the computers. The control computers send commands to the torquers to control the movement of different parts to maintain correct position and accurate direction. Because the required torque is very large, hundreds of high power electric thrusters and several hundreds of kN·m·s momentum wheels are needed.

Thermal Management is complex for a SPS. There are many deployable structures in a SPS and the whole SPS needs to be assembled in space. Less thermal control is better to avoid possible interference in deployment in space.

Passive thermal control is preferred and is used to maintain the rational temperatures of structures, solar cells and antenna. For high power electric devices, enhanced cooling is needed. For narrow temperature range devices, for example, electric power conversion devices, microwave generators and storage batteries, and active thermal management are needed.

SPS is a huge spacecraft. There is a lot of information that needs to be monitored, obtained, processed and dispensed to maintain normal operation of SPS. When a traditional wire network is adopted, hundreds of km cables are needed that will require assembly in space. So a wireless network Information and System Operation Management sub-system is necessary. Wired networks are adopted in single modules and wireless networks are adopted to communicate between modules.

Launch and Transportation in Orbit

Transportation is a vitally important aspect that determines the technological and economical feasibility of a SPS installation. For a traditional communication satellite in geo-earth orbit (GEO),   there are two stages in transporting the satellite. One stage is to launch the satellite from Earth to geo-transfer orbit (GTO) by the launch rockets, and another stage is to transfer the satellite from GTO to GEO by its own thrusters. For the SPS, two space transportation activities will also be required. One stage is to launch the parts of a SPS from the Earth to LEO by heavy reusable launch vehicles, and another stage is required to transfer the parts of a SPS from low Earth orbit (LEO) to GEO by reusable electric propulsion orbit transfers.

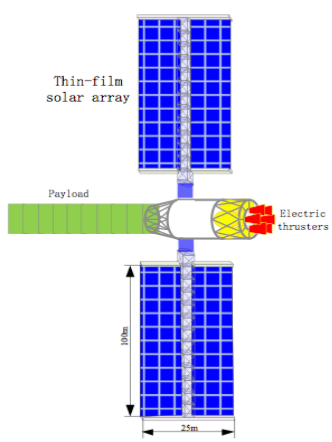


Fig.9. Areusable electric propulsion orbit transfer concept.

The Falcon Heavy can be selected as the heavy reusable launch vehicle. If the payload mass capability is as much as 50 t, then about 200 launches will be needed to launch all the hardware required into LEO.

For further transport from LEO to GEO, a reusable electric propulsion orbit transfer concept is conceived and shown in Figure10. The specifications of the orbit transfer are as follows.

- Initial LEO orbit altitude: 300km
- Dry mass: 10 t
- Electric power：1 MW
- Thrust：30 N
- Specific impulse：4000 s

To illustrate some typical payloads, the transfer times and fuel consumption from LEO to GEO by the reusable electric propulsion orbit transfer are analyzed and shown in Table 2.

payload	Payload mass (kg)	Fuel mass (kg)	Full mass (kg)	fuel consumption (kg)	transfer time (h)	Remain fuel (kg)
The truss modules	56000	7000	73000	4369	1587	2631
The antenna modules	16000	5000	31000	1982	720	2018
The solar array modules	24000	5500	39500	2387	867	3113
Other parts	60000	7000	77000	4329	1655	2671
None	0	1500	11500	935	340	565

Table 2. The transfer times and fuel consumptionsfrom LEO to GEO.

Constructionin Orbit

The modular SPS, composed of truss modules, antenna modules, solar array modules and other modules, is most convenient for assembly in space. The scale and complexity of assembly and maintenance of an SPS will greatly exceed that of the International Space Station (ISS) and will be impossible to be completely assembled by astronauts. Free flying robots operating in a cooperative mode will be necessary new technologies. A possible assembly sequence is shown in Fig.11, where the main structure of SPS is first assembled and then the other modules are assembled on that structure. The assembly of tens of km of electric cables in space is also a huge challenge.

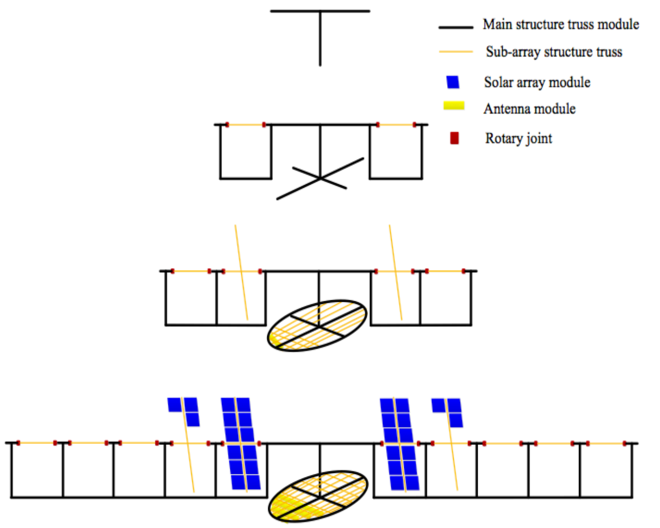


Fig.10. The assembly sequence of a SPS.

Summary of MR-SPS Concept

Based on above introduction, the parameters of a 1GW MR-SPS are summarized in Table 3.

SPS system	Orbit	GEO
	Delivered power	~1GW
	Life time	30years
	Efficiency	~13%
	Total mass	~10000t
Solar Energy Collection and Conversion	Solar cell	Thin-film GaAs
	Efficiency	~40%
	Area of solar array	~6km^2
	Output power	~2.4GW
	Voltage of solar array modules	~500V
	Mass	~2000t
Microwave Power Transmission	Frequency of microwave	5.8GHz
	Efficiency	~54%
	Diameter of transmitting antenna	1000m
	Number of antenna modules	128000
	Transmitting power of an antenna module	12.5kW
	Mass	4000t
	Diameter of receiving antenna	5km
Power Transmission and Management	Style	Mix of distributedand centralized
	Voltage of main cable	20kV
	Voltage of solar sub-arrays	5000V
	Number of rotary joints	100
	Mass	2500t
Structure	Module	Deployed truss
	Mass	1200t
Attitude and Orbit Control	Thrusters	1N electric thruster
	Mass	100t
others	Mass of thermal Management	150t
	Mass of ISRM	50t
Operation mode		Continuous transmission

Table 3. Summary of primary parameters for a 1GW MR-SPS

ECONOMIC BRIEF

Introduction

Solar Power Space Systems (SPSS) are macro-engineering projects and their investment will be enormous. As a commercial electric power system, the net income from selling electric power must be positive throughout the whole life of the installation. It's a long time from system layout to system close, typically exceeding 35 years. The major financial investment will happen in the first several years, while the income will be obtained in the last 30 years. Therefore, a full-life net present value (NPV) analysis is necessary to evaluate the economics of a SPSS.

The Full-life Stages of a SPSS

The economic analysis of a SPSS needs to consider all stages from the beginning to the end of the project. In our present analysis, six phases are considered:

(1) Phase 1: System layout and design. This phase includes development layout and system design before a SSPS is built. In this phase, the human cost is the predominant cost.

(2) Phase 2: Development and manufacture of components. This phase includes the development, manufacture and testing of all components that will be installed on the ground and in space. It is a main requirement during the whole life of a SSPS and needs massive of investment.

(3) Phase 3: Launch and deployment of components. All components will be launched into space and be deployed in GEO in this phase. Large reusable space launch vehicles and reusable electric propulsion orbit transfers will be needed to accomplish the two stages of transportation. This too is a required investment that affects the whole life of an SSPS installation.

(4) Phase 4: Assembly and test. All components will be assembled on the ground and then in space, and the whole SSPS will be tested in each phase. Lots of free flying robots and a space logistics base will be needed to accomplish the assembly. This requirement will be present throughout the whole life of a SSPS and needs a massive investment.

(5) Phase 5: Operation and maintenance. The whole system must operate normally and essential system maintenance, repair and resupply will necessary. Maintenance operations will be needed over a long time and must be budgeted.

(6) Phase 6: System close and recycle. When the system reaches the end of its life, the system must be properly disposed of. Some components will be recycled to construct new systems.

Economic Analysis Method

The flow chart of economic analysis of a SSPS is shown in Fig.12. Firstly, the basic system parameters need to be input and the relative parameters of ground segment and space segment will be chosen and analyzed. From these, the design cost and development cost will be calculated. The transportation cost will be calculated according to the transportation parameters. The construction cost will be calculated according to the assembly parameters. The operation and maintenance cost will be calculated according to those relative parameters. The close cost and recycle value will be estimated. Finally, the full life cost of a SSPS will be calculated by adding all these costs.

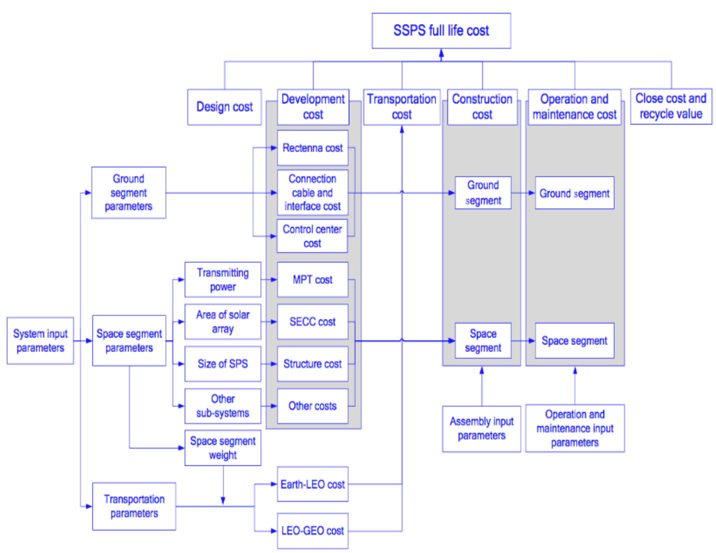


Fig.12. The flow chart of economic analysis of a SSPS.

System Cost Analysis Results

The whole SSPS system includes space segment and ground segment. The space segment includes SECC, PTM, MPT, Structure, AOC, TM, and ISRM sub-system. The primary cost analysis result of space segment is shown in Table 4.

	Design	Development	Transportation (1000$/kg)	Construction	Operation and Maintenance	Close and Recycle	Total
SECC sub-system	5	2000	2000	1200	200	200	5605
PTM sub-system	5	2000	2500	1000	500	250	6255
MPT sub-system	10	3600	4000	800	400	400	9210
Structure sub-system	5	600	1200	550	50	120	2525
AOC sub-system	5	500	100	200	2500	10	3315
TM sub-system	5	150	150	0	150	15	470
ISRM sub-system	10	250	50	100	250	5	665
Total	45	9100	10000	3850	4050	1000	28045

Table 4. The cost analysis result of space segment（million US Dollars).

The ground segment includes rectenna, control center, connecting cables and interfaces. The primary cost analysis result of the ground segment is shown in Table 5.

	Design	Development	Construction	Operation and maintenance	Close and recycle	Total
Rectenna	2	800	120	460	-80	1302
Connect cable and interface	2	25	10	15	-2.5	49.5
Control center	4	10	—	240	-2	252
Total	8	835	130	715	-84.5	1604.5

Table 5. The cost analysis result of ground segment（million US Dollars).

Therefore, the total cost of a SSPS over 30 years is near 30 billion US dollars.

Economic Analysis

The NPV analysis method is adopted to analyze the costs associate with the construction, launch and operation of a SSPS. Some important baseline parameters are assumed as follows.

- Cost of capital: 5%
- Tax rate: 15%
- Lifetime: 30 years
- Period of development and construction: 5 years
- Delivered electric power per year (kW·h): 7884 million
- Power price ($/kW·h): 0.3

Based on the above parameters, the NPV of the SSPS project is $US 2,256.83 million. The following is a sensitivity analysis based on the variations of several parameters, including power price, lifetime, development and construction cost, operation and maintenance cost, tax rate and cost of capital.

Variation value	Power price	Lifetime	Development and construction cost	Operation and maintenance cost	Tax rate	Cost of capital
50%	13,875.76	5,383.50	-8,585.66	955.39	-224.87	-4,435.03
40%	11,454.26	4,855.34	-6,514.87	1,117.97	173.76	-3,352.95
30%	9,032.77	4,243.92	-4,444.08	1,280.55	572.39	-2,199.92
20%	6,611.28	3,536.14	-2,373.29	1,443.13	971.02	-968.10
10%	4,189.78	2,716.79	-302.50	1,605.71	1,369.66	351.32
0%	1,768.29	1,768.29	1,768.29	1,768.29	1,768.29	1,768.29
-10%	-653.21	670.28	3,839.08	1,930.87	2,166.92	3,293.97
-20%	-3,074.70	-600.80	5,909.86	2,093.45	2,565.55	4,941.01
-30%	-5,496.20	-2,072.24	7,980.65	2,256.03	2,964.18	6,723.66
-40%	-7,917.69	-3,775.61	10,051.44	2,418.61	3,362.81	8,658.06
-50%	-10,339.18	-5,747.48	12,122.23	2,581.19	3,761.45	10,762.51

According to the sensitivity analysis results, it's obvious that power price, lifetime, development and construction cost, and cost of capital will greatly influence the NPV, while operations and maintenance costs, and tax rate will influence the NPV lightly.

CONCLUSION

Because SPSS is a macro-engineering project and the investment is near 30 billion US dollars, the development and transportation costs are the main portions. According to our rough analysis, a SPSS shall be a commercially valuable project when the power price is close to 0.3 $/kW·h based on other baseline input parameters. When power price, development and construction cost are fixed, the cost of capital becomes an important parameter to influence the NPV.

Image Credits

1. Original SPS Concept. Credit: Peter Glaser
2. 1979 SPS Reference System. Credit: NASA/DOE
3. SPS2000 Concept. Credit: ISAS
4. SUNTOWER SPS Concept. Credit: NASA
5. Solar Disc SPS Concept. Credit: NASA
6. Integrated Symmetrical Concentrator (ISC) SPS Concept. Credit: NASA
7. Sail Tower SPS Concept. Credit: ESA
8. SPS2001 Concept. Credit: NASDA (JAXA)
9. Tethered-SPS Concept. Credit: USEF/ JAXA
10. Solar-Pumped Laser SPS Concept. Credit: JAXA
11. Modular Symmetrical Sandwich SPS Concept. Credit: SpaceWorks Engineering, Inc/John Mankins
12. LPT SPS Demonstration Concept. Credit: EADS ASTRIUM
13. Aeroboat Relay SPS Concept. Credit: Lavochkin Association
14. SPS-ALPHA Concept. Credit: Artemis Innovation Management Solutions LLC

REFERENCES

1. **Leonard David,** Peter Glaser, Father of Solar-Power Satellite Idea, Dies at 90. Space.com. 2014. http://www.space.com/26175-peter-glaser-solar-power-satellite-obituary.html

2. **P.E. Glaser**, Power from the Sun: its future, Science 162 (1968) 867-886.

3. **NRC**, Electric Power from Orbit: A Critique of a Satellite Power System, National Academy Press, Washington, D.C., 1981.

4. **Peter E. Glaser, Frank P. Davidson, Katinka Csigi**, Solar Power Satellites: A Space Energy System for Earth, Praxis Publishing Ltd, Chichester, England, 1996.

5. **J.C. Mankins**, A Fresh Look at Space Solar Power: New Architectures, Concepts and Technologies, Acta Astronautica 41(1997) 347–359.

6. **John C. Mankins, Joe Howell**, Overview of the Space Solar Power Exploratory Research and Technology Program, AIAA 2000-3060, 35th Intersociety Energy Conversion Engineering Conference, Las Vegas, Nevada, 24-28th, July 2000.

7. **John C. Mankins**, A Technical Overview of the SUNTOWER Solar Power Satellite Concept, Acta Astronautica 50 (2002) 369–377.

8. **W. Seboldt, M. Klimke, M. Leipold, N. Hanowski**, European Sail Tower SPS Concept, Acta Astronautic,48(2001)785–792.

9. **Susumu Sasaki, Koji Tanaka, Ken Higuchi, Nobukatsu Okuizumi**, A New Concept of Solar Power Satellite: Tethered-SPS, Acta Astronautica 60 (2006)153-165.

10. **S.Sasaki, K.Tanaka, K.Maki**, Updated Technology Road Map for Solar Energy from Space, IAC-11-C3.1.4, 62nd International Astronautical Congress, Cape Town, South Africa, 3-7th, October 2011.

11. **URSI**, Report of the URSI Inter-Commission Working Group on SPS, June 2007.

12. **John C. Mankins**, Space Solar Power—The First International Assessment of Space Solar Power: Opportunities, Issues and Potential Pathways Forward, International Academy of Astronautics, October2011.

13.**V. K. Sysoeva, K. M. Pichkhadze, L. I. Feldman, E. A. Arapov, A. S. Luzyanin**, Concept Development for a Space Solar Power Station, Solar System Research, 46 (2012) 548 - 554.

14. **John C. Mankins**, SPS-ALPHA: The First Practical Solar Power Satellite via Arbitrarily Large Phased Array, Artemis Innovation Management Solutions LLC, September 2012.

15. **John C. Mankins**, The Case for Space Solar Power. Virginia Edition Publishing, Houston, TX, 2014.

16. **Hou Xinbin, Wang Li, GaoJi**, Analysis and Comparison of Various SPS Concepts, IAC-11-C3.1.8, 62nd International Astronautical Congress, Cape Town, South Africa, 3-7th, October 2011.

17. **Hou Xinbin, Wang Li**, Space Station——The Strategic Opportunity for the Development of SPS in China, IAC-12-C3.1.7, 63rd International Astronautical Congress, Naples, Italy, 1-5th, October 2012.

18. **Liu Haitao, Hou Xinbin, Wang Li, Li Ming**, The Experimental Proposal of the Microwave Power Transmission from the Chinese Manned Space Station, IAC-13-C3.2.4, 64th International Astronautical Congress, Beijing, China, September 2013.

19. **Li Ming, Hou Xinbin, Wang Li**, Proposal on a SPS WPT Demonstration Experiment Satellite, IAC-14.C3.1.2, 65th International Astronautical Congress, Toronto, Canada, 3-7th,29 September - 3 October 2014.

20. **Sun Xin, Evelyn Panier, Cornelius Zund, Raul Gutierrez Gomez**, Financial and Organizational Analysis for a Space Solar Power System-A Business Plan to Make Space Solar Power a Reality，Toulouse Business School, May 2009.