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Space Solar Power development in China and MR-SPS

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China Academy of Space Technology(CAST)

- The biggest satellite manufacturer in China, the headquarter is in Beijing. CAST is the main contractor of many important space projects,
  - The manned space engineering project
  - The lunar and deep space exploration project
  - The Beidou(Compass) navigation satellite system
  - Communication satellite,Earth observer satellite...
- Qian Xuesen Lab is the leader of SPS research project in China from 2006.



Contents

1. SPS activities in China

1. 1 Early activities

- In 1992， researchers from China（including Prof. Ming LI, the Vice president of CAST） attended the International Space University in Japan. The research topic was SSP.

1. SPS activities in China

- In 1996，Prof. Guoxin Li, a space energy expert presented “The Chinese View Concerning Power From Space Prospects for the 21st Century” in the 47th IAC in Beijing.

IAF-96-R.2.01

The Chinese View Concerning Power From Space Prospects For The 21st Century

The 1996 Peter E. Glaser Lecture

Li Guo-Xin

Shanghai Institute of Space Power-sources, Shanghai,China

47th International Astronautical Congress
October 7-11, 1996/Beijing, China

1. SPS activities in China

1. 2 Recent seminars and conferences in China

- In 2006，a small Solar Power Satellite Development Workshop was held by CAST in Beijing.
- In 2010, the first Solar Power Satellite Technology Development Seminar was held in Beijing. Twelve academicians attended the conference. Over fifty papers have been presented and over 100 delegates attended the seminar.
- In 2017, the second Solar Power Satellite Technology Development Seminar was held in Beijing. Over 200 delegates attended the seminar.
- In 2018, the first Committee of Space Solar Power Symposium was held in Harbin.
- The second WPT symposium was held in Shanghai last month. Three types of WPT technologies (MPT, LPT, and electromagnetic induction) are demonstrated.

1. SPS activities in China

XiangShan Science Conference

The Opportunity and Challenge of SPS Development (2014.5)

- Xiangshan science conference is the famous high-level national science conference in China. Over fifty invitation scholars from different fields, including energy, aerospace, power, attended the conference.

- Three topics:

  (1) The key technologies of SPS development.

  (2) The science and technology issues of high power conversion and transmission.

  (3) The analysis of environment and policy of SPS development.

- Conclusion:

  For China, SPS is an important way to obtain the renewable energy. Long term study of science and technology innovation and new concepts are needed to realize the SPS.

1. SPS activities in China

- In 2010，the CAST delegate attended SICES2010 (The Shichuan International Clean Energy Summit) in Cheng Du.

- In the summit, we met and talked with some famous experts in the world, including Ralph H.Nansen, Richard M.Dickinson, Peter Sage, Feng Hsu, etc.

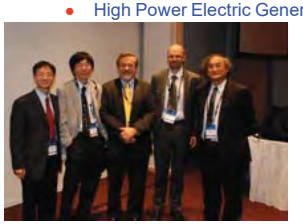
1. SPS activities in China

- In 2011，China Energy and Environment Summit (CEES) 2011 was held in Beijing. Some important persons attended the conference.
- Prof. Xiji Wang, the most famous aerospace expert in China, presented the conference keynote paper "Development Prediction and Countermeasures of Space Solar Power Technology".
- Dr. APJ Abdul Kalam, the former president of India, delivered a video speech. Mark Hopkins of NSS gave a presentation.

1. SPS activities in China

1. 3 Participating in Space Power Symposium of IAC

- From 2011, many papers were presented in Space Power Symposium.
  - Analysis and Comparison of Various SPS Concepts. 62nd IAC,2011.
  - Space Station—The Strategic Opportunity for the Development of SPS in China. 63rd IAC,2012.
  - PETER GLASER KEYNOTE PAPER：Space Solar Power—The great energy evolution of human being in 21st Century .64th IAC,2013.
  - Proposal on a SPS WPT Demonstration Experiment Satellite. 65th IAC,2014.
  - In-orbit assembly mission for the Space Solar Power Station. 66th IAC,2015.
  - Optimal Design of Rectenna Array in MPT System for SSPS. 67th IAC,2016.
  - High Power Electric Power Generation, Transmission and Management of MR-SPS. 68th IAC,2017.
  - High Power Electric Generation and WPT Demonstration in Space for SPS . 69th IAC,2018.



IAC2011, South Africa

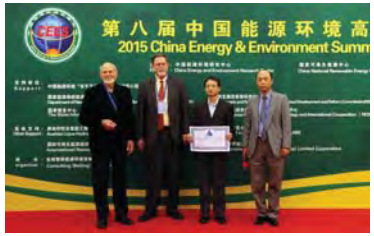
IAC2013, China

IAC2017, Australia

1. SPS activities in China

1. 4 Attending ISDC(annual conference of National Space Society) Space Solar Power Session.

- Space Solar Power Activities in China. 2015.
- Multi-Rotary Joints SPS. 2015.
- Concept and technology of SSPS developments in China. 2016.
- China`s efforts towards developing Space Solar Power. 2016.
- On new developments of Space Solar Power Station (SSPS) of China. 2017.
- Space Solar Power Station and its key materials in China. 2017.
- Space Solar Power development in China. 2018.



The MR-SPS concept won the first place in 2015 Sunsat competition.

1. SPS activities in China

1. 5 Attending space solar power workshop in Dubai in 2016.

In 2016, EXPO2020 organizer held the "NEW BASELOAD ENERGY FOR THE WORLD" workshop in Dubai. CAST experts were invited to attend this workshop.

We believe Space Solar Power, when it is understood as Baseload Energy, can play a key role in achieving Clean, Abundant and Affordable Energy for the world.

1. 6 Attending space solar power workshop in Korea in 2017.

In Nov. 2011，KARI held the “International Workshop for Space Based Solar Power” in seoul. Prof. Shinohara and me were invited to attend this workshop.

Korea is being interested in Space Solar Power more and more and has found a SPS Society including tens of VIPs. The Second workshop will be held next Feb.

1.6 Some important visiting events

- In 2012, Mr. Abdul Kalam, visited CAST and proposed collaboration with China on Space Solar Power.
- In 2013, a delegation from Lavochkin Association in Russia visited CAST and talked about the collaboration in the field of SPS.
- In recent years, top WPT expert in the world, professor Shinohara visited Shichuan Univerisity and CAST Xi’an. He give a short term lecture this Aug.

Lavochkin Association delegation

President Kalam

Professor Shinohara

1.7 Committee of Space Solar Power

- We are applying for “Committee of Space Solar Power” of Chinese Society of Astronautics. Wait for being approved.
  - Three research group:
    - Space Solar Power concept and system
    - Wireless power transmission technology
    - Space high voltage electric power technology
  - 37 organizations
    - University
    - Research institution
    - Company
  - 90 members
    - 12 academicians
    - Other important researchers and suporters

1.8 Others

- In 2009，“Report of the URSI Inter-Commission Working Group on SPS（White Paper）” in Chinese was authorized formally by URSI and published in 2013.

Chair: Hiroshi Matsumoto

- A new book is being writing and will be published next year.

Contents

2. SPS researches in China

Since 2008, some research projects have been supported by China National Space Administration(CNSA), National Natural Science Foundation of China(NSFC) and China Academy of Science(CAS). There are more and more research groups engaged on SPS research in China.

- Strategy research on SPS
- SPS system research
- Key technology research on SPS(for example, WPT)
- Fundamental research on SPS

2. SPS researches in China

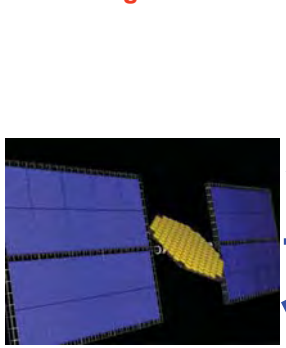
2.1 Strategy research on SPS

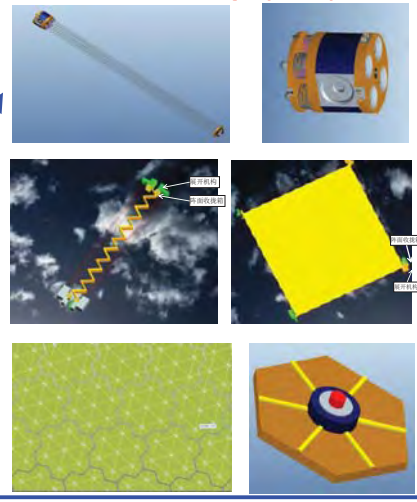
- In 2014, a special expert team(37 experts, Chair is Prof. Ming Li) on SPS strategy research was established by CNSA.
- 7 Senior consultants(academician) includes: Xiji Wang, Guirong Min, Lehao Long, Shizhong Yang, Baoyan Duan, Changchun Ge, Jizhen Liu.
- Participating experts: 130 experts from 16 departments and 49 organizations.
- The development plan and roadmap of SPS were proposed by the expert team and the strategy research will been carried on continually.

2. SPS researches in China

2.2 System research

- **Integrated SPS——the traditional concept (2012)**





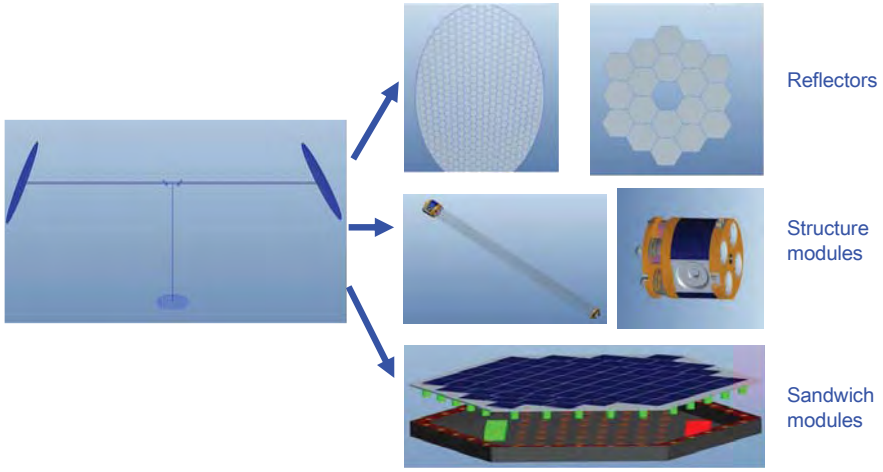
Structure modules

Deployed Solar array modules

Transmission antenna modules

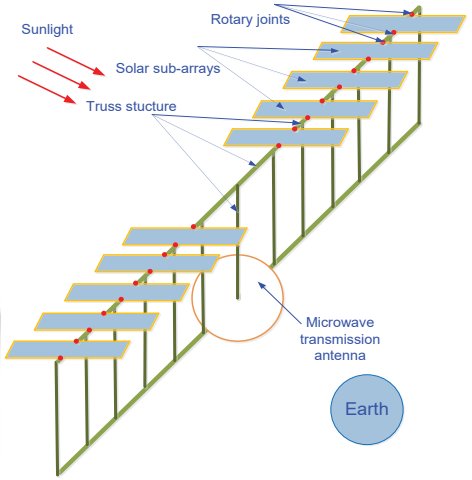
2. SPS researches in China

- Concentrator SPS——the popular concept (2013)



2. SPS researches in China

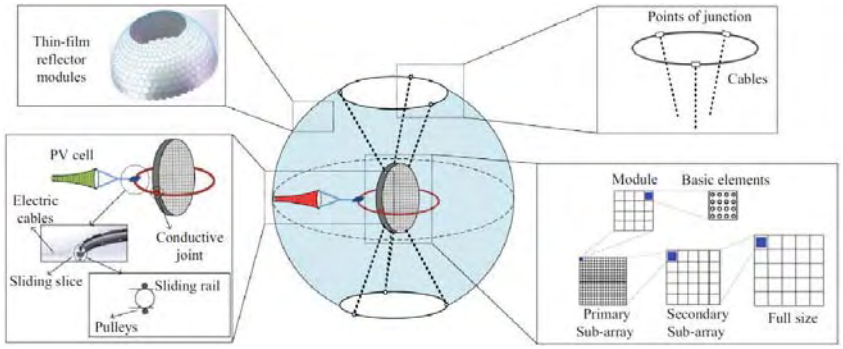
- Multi-Rotary joints SPS (MR-SPS)——a new concept (2014)



- Modularization
- Multiple rotary joints

2. SPS researches in China

- SSPS-OMEGA——a novel concept by Xidian University (2014)

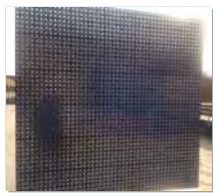


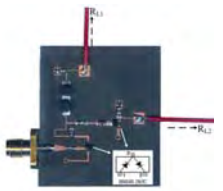
A novel design project for space solar power station(SSPS-OMEGA). Acta Astronautica, 2016,121: 51-58

2. SPS researches in China

2.3 key technologies research

- Microwave WPT
  - MPT has been considered to be the better choice for high power transmission for the advantage of high efficiency.
  - A group leaded by Prof. Huang from Sichuan university has investigated MPT several years. They realized high power combining based on magnetron technology and Some experiments showed that the highest microwave to DC conversion efficiency is over 70% for 5.8GHz.
  - A group leaded by Prof. Yang from ChongQing university is investigating the feasibility to supply power for aeroboat by MPT.





2. SPS researches in China

Laser WPT

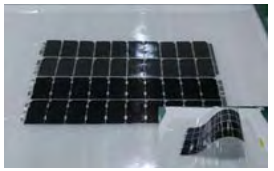
- LPT has the advantage of small transmitter and small receiver. With the advance of efficiencies, LPT will be a better choice for low & middle power transmission.
- A Group in CAST demonstrated the key technology of laser power transmission between two airships. The distance is about 100m. The 808nm laser(48%) and the GaAs solar cell(45%) was adapted. The maximum 13.43W electric power was received and the transfer efficiency was 16.08%.
- A Group from BIT has investigated solar pumped laser LPT several years. The convert efficiency from sunlight to laser has achieved 3%.The convert efficiency from laser to electric power has achieved over 50% in 808nm.




2. SPS researches in China

Advantage solar cells and large scale solar array

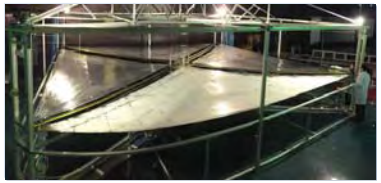
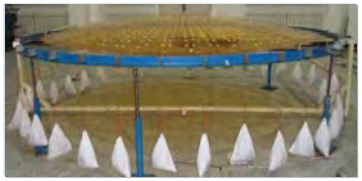
- High efficiency light weight solar cell is very important for SPS. Thin-film GaAs solar cell should be the best candidate.
- The laboratory efficiency of thin-film GaAs solar cell has been over 30% in China.
- Large scale thin-film solar array will be the trend for high power solar array. Over 100m^2 thin-film solar array technology is being developed in China.


2. SPS researches in China

Deployable space structures

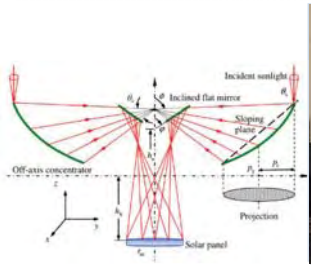
- SPS needs huge deployable space structures, such as solar array, concentrator and antenna.
- A 8×8m solar sail prototype has been developed in CAST.
- A Group from Xidian University has investigated some kinds of deployable large size thin-film antenna.
- Some researches from Harbin Institute of Technology, Zhejiang University, are investigating some kinds of deployable truss structures.

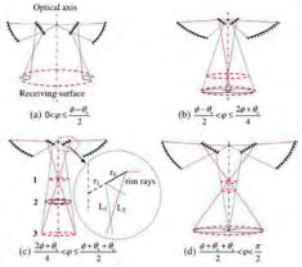



2. SPS researches in China

Concentrator analysis

- A Group leaded by Prof. Xia from Harbin Institute of Technology, cooperating with CAST, has investigated the optical character of the symmetrical two-stage concentrator.
- Monte-Carlo ray tracing method (MCRTM) was used in the analysis and a software was developed.
- Base on this method, “Flexible Adjustment Model for SPS ALPHA: Optical Solution” won the first place in the student SPS competition in 2017 in IAC.





2. SPS researches in China

2.4 Correlative development

- CZ-9, Chinese Heavy Lunch are developing. The payload will be over 100 tons(LEO).
- A new National Science and Technology Major Project——Space vehicle servicing and maintenance system on orbit is set up.
- High power electric propulsion(over 10kW) are being developed in CAST.
- These correlative projects will lay the foundation for the development of SPS.

Total length /m	100
Maximal diameter /m	10
Diameter of fairing /m	10
Total mass /ton	3000
LEO payload /ton	100
GTO payload /ton	46

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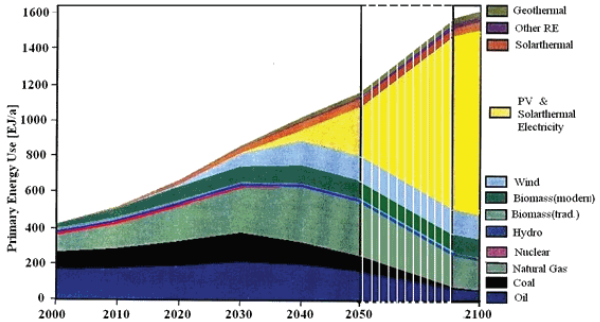
3. Top issues about SPS

Issue 1: When fossil energy is run out or forbidden, can the existing renewable energy technologies match the energy consumption in the future?

In the future, 60% of energy demand will rely on solar power, that means traditional solar terrestrial power station must be combined with enough power storage systems to provide the baseload power.

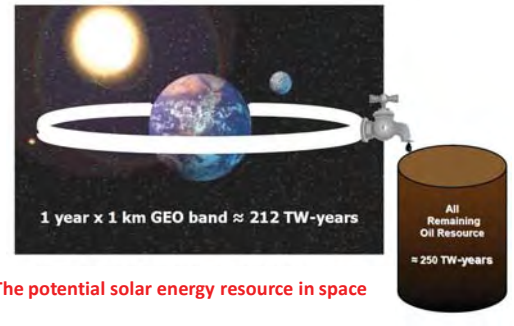


The forecasted world's energy consumption structure

3. Top issues about SPS

Issue 2: How about the potential capacity of SPS?

Assume to deploy one SPS each 0.1°(73km gap) in GEO. Then 3600 SPSs can be deployed and the whole capacity will be 3600GW for 1GW SPS.



The potential solar energy resource in space

How to increase the capacity:

- Increase the power of single SPS.
- Shorten the gap of adjacent SPSs.
- Utilize other orbit but GEO.

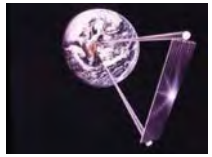
Space - Based Solar Power As an Opportunity for Strategic Security. National Security Space Office. 2007.10

3. Top issues about SPS

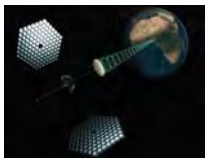
Issue 3: Should the continuous energy transmission be the basic character of SPS?

One of the most important advantage of SPS is continuous power supply, so continuous energy transmit should be a necessary character.

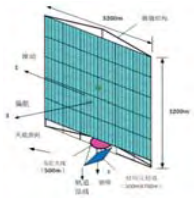
Continuous transmission needs the solar arrays or reflectors track the Sun and the transmitter point to the Earth. It will impact on the configuration and the key technologies of SPS greatly.



Solar arrays rotate.



Reflectors rotate.

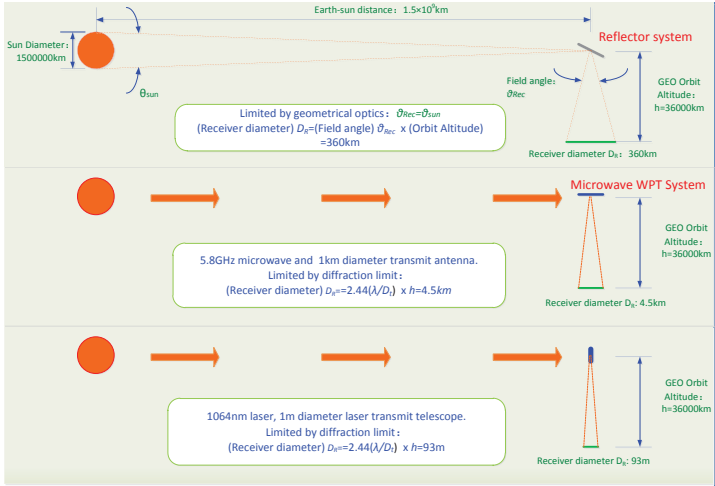


Reflector antenna rotates.

Non rotation concepts.

3. Top issues about SPS

Issue 4: WPT choice, microwave, laser or reflecting the sunlight directly?



Reflector WPT
The size of receiver is extremely large.
Also requires very large reflectors.

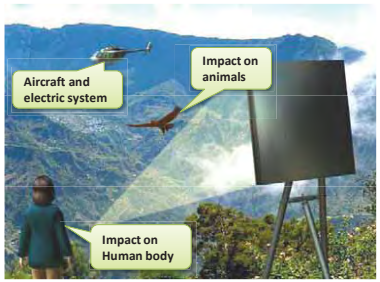
Microwave WPT
The size of receiver is large but acceptable.
Suit for high power transmission.

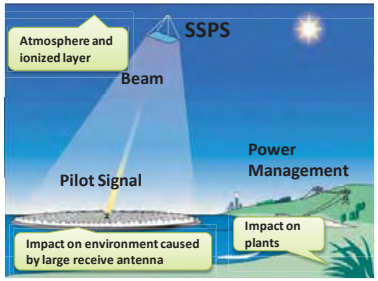
Laser WPT
The size of receiver is small.
Suit for low power transmission.

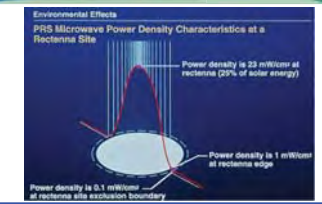
3. Top issues about SPS

Issue 5: How about the safety and the impact on environment during long-term SPS operating?

The safety and the impact need to be studied by the theory analysis and experiment long term.







3. Top issues about SPS

Issue 6: How to lift the launch capacity and cut down the launch cost greatly ? How to assemble and maintain this large scale structure in orbit?

The payload weight needs to be 10 times higher and the launch cost needs to be 10 times lower.

Commercialized operation →

- Heavy Launch Vehicle
- Reusable Launch Vehicle
- Novel Launch Method
- LEO-GEO Orbit Transfer

Large amount of modules are needed to be assembled in orbit. →

Various highly intelligent space robots

Is the in situ manufacturing(Space 3D print) possible?

3. Top issues about SPS

Issue 7: About investment mechanism and commercial operation model.

- How about the economics aspect and benefit pattern of SPS?
- How to attract the commercial capital?
- Which fields are the commercial capital interested in possibly , R&D, manufacture , launch, construction or operation of SPS?
- How to establish positive policies to encourage the commercialization of SPS?

SPACEX

SPACE ENERGY

Hanergy

SOLAREN

POWERSAT CORPORATION

LANDSPACE

3. Top issues about SPS

Issue 8: About international collaboration and correlative policies.

- Can single country afford whole cost during R&D, launch, construction and operation?
- Can international collaboration promote the development of SPS?
- Possible correlative policies
  - United Nations Outer Space Treaty
  - Guide for Space Debris Mitigation
  - International Telecommunication Union(ITU) rules
  - International Civil Aviation Organization (ICAO)rules
  - International Traffic in Arms Regulations
  - ……
- A group in CAST starts to research the frequency and orbit issues related to SPS. They hope to collaborate with international experts on：
  - Proposing a new agenda item related to SPS or WPT.
  - Promoting ITU to study the characteristics of the SPS.
  - Finding a suitable spectrum category for WPT-SPS.

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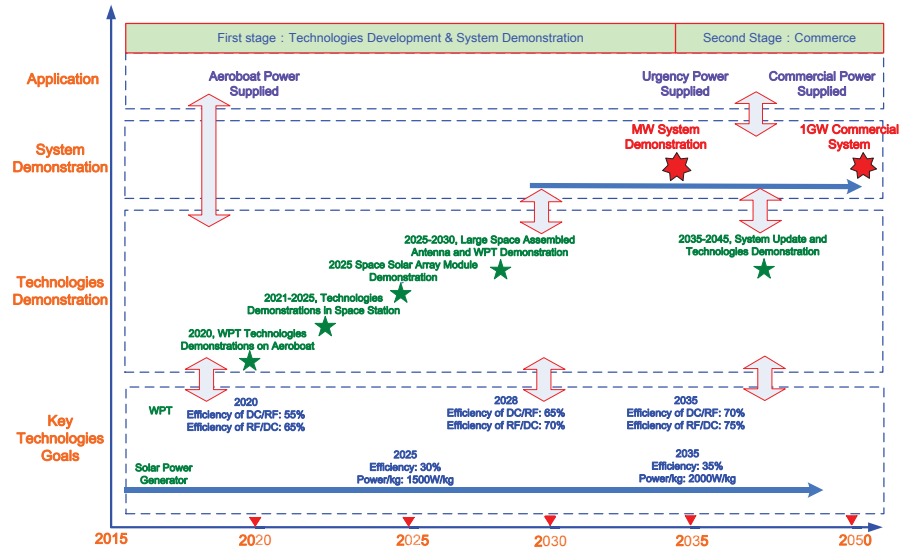
4. Recommended Roadmap on SPS



- **The first stage: SPS R&D, 2015-2035.**

R&D on systems and key technologies, including detail system design and simulation, high power WPT(RF), deployable space structures and control technology, high power space PMAD, etc.

- In 2020, WPT technologies will be demonstrated by an aeroboat.
- Some key technologies are proposed to be demonstrated on the space station during 2021-2025.
- A huge high voltage solar array module will be demonstrated in space in 2025.
- A large antenna will be assembled in space and the MPT will be demonstrated before 2030.
- A MW SPS system will be developed in space before 2035.

- **The second stage: commercial SPS, 2036-2050.**

A GW class SPS system will be developed along with some innovative technologies are verified. The commercial capital will be the main investor.

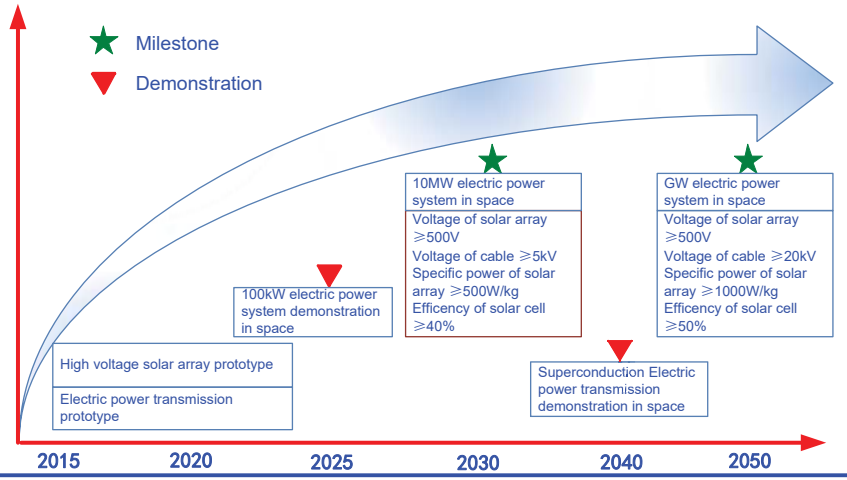
- Some innovative technologies will be developed and demonstrated in space during 2036-2045. The MW SPS system will be updated and maintained.
- A GW class SPS system will be developed based on the MW SPS system demonstration and technologies demonstration.

Key Technologies

- High Power Wireless Power Transmission Technology
- High Power Space Generation and PMAD Technology
- Space Super-Large Light Modular Structure and Control Technology
- Space Super-Large System Assembly and Maintenance
- Low Cost Launch and Space Transportation Technology

Key Technologies Roadmap

Sample: High Power Space Generation and PMAD Technology Roadmap



Fundamental Science Problems

- Coupling Theory of Various Physics Fields in SPS
- Interaction between SPS and Space Environment
- Interaction between High-Power Microwave Transmission and Ionosphere and Atmosphere

Key Materials and Components

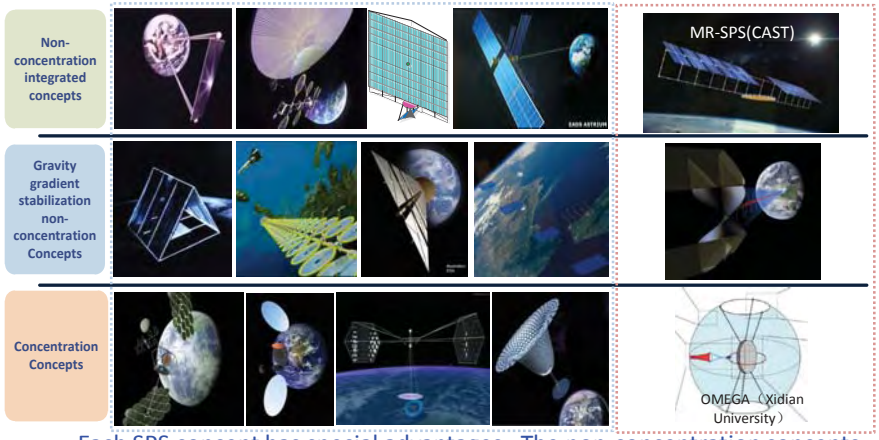
- Ultra-Light Structure Materials
- Light High Electric Conductivity Materials
- Light High Thermal Conductivity Materials
- Long-Life High Reflectivity Film Materials
- High Power Semiconductor Component
- Long-Life High Efficiency High Power Microwave Generator
- High Efficiency Rectifying Device

Contents

Comparison of various SPS concepts

Concept	Orbit	WPT	Configuration	power generation	PMAD
1979 SPS	GEO	microwave	non-concentration	PV	centralized
Sun Tower	GEO	microwave	non-concentration	PV(concentrator)	centralized
Sun Disc	GEO	microwave	non-concentration	PV(thin-film)	centralized
ISC	GEO	microwave	concentration	PV(concentrator)	distributed
Abacus	GEO	microwave	non-concentration	PV(concentrator)	centralized
SPS2000	LEO	microwave	non-concentration	PV	centralized
SPS2001	GEO	microwave	concentration	PV(concentrator)	distributed
Tether SPS	GEO	microwave	non-concentration	PV	distributed
Laser SPS	GEO	laser	concentration		distributed
Sail Tower SPS	GEO	microwave	non-concentration	PV(thin-film)	centralized
Relay SPS	GEO	Laser+ microwave	non-concentration	PV(thin-film)	distributed
SPS-ALPHA	GEO	microwave	concentration	PV	distributed
MR-SPS	GEO	microwave	non-concentration	PV(thin-film)	Centralized+ distributed
SSPS-OMEGA	GEO	microwave	concentration	PV	distributed
CASSIOPeiA	GEO	microwave		PV	distributed

5. Multi-Rotary joints SPS Concept



Each SPS concept has special advantages. The non-concentration concepts have better feasibility and the hardest difficulty is the high-power rotary joint. Concentration concepts are innovative. But the concentration control system are extremely complex and the high heat density make heat control a big problem.

5. Multi-Rotary joints SPS Concept

- **Modularization**
- **Multiple rotary joints**

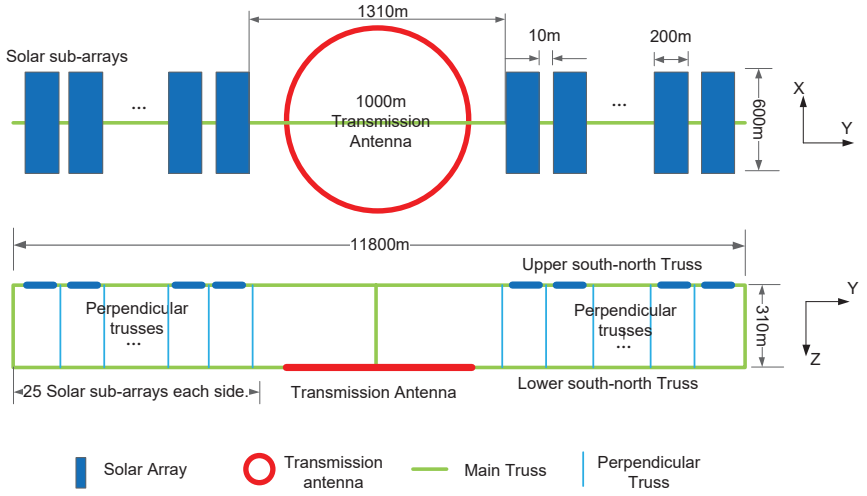
5. Multi-Rotary joints SPS Concept

The technical features of the MR-SPS

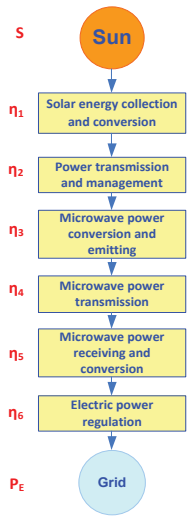
- The huge several sq.km solar array is taken apart many disjunctive solar sub-arrays and each solar sub-array transfers electric power by its own two independent rotary joints. The single point failure problem is avoided that makes SPS more reliable.
- The transferred power of each rotary joint is decreased largely compared with traditional GW class rotary joints. One of the most difficult technologies of platform SPS is solved.
- The modular concept makes the assembly, maintenance, control and expansion of SPS more easily.

5. Multi-Rotary joints SPS Concept

Configuration



Efficiency Chain

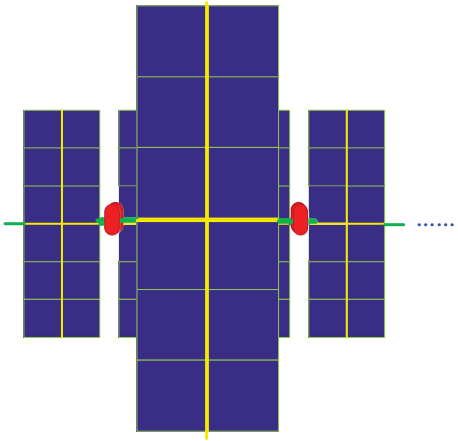


System Efficiency

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
Gap of solar cells	0.85	0.336
Angle of sunlight	0.958	0.322
Space environment effect	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

Solar Energy Collection and Conversion（SECC）

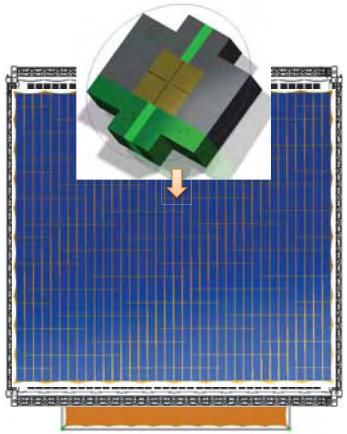
- 25 Solar sub-arrays each side
- solar sub-array
  - 12 solar array modules are divided to two lines and each line includes 6 modules.
  - Whole area: 0.12km^2
- Structure Truss
  - 200m×600m crisscross truss
  - The 200m truss connects the rotary joints in two ends.
  - The 600m truss connects 12 solar array modules.
- Output : 2.4GW
- Weight: 1800 tons.



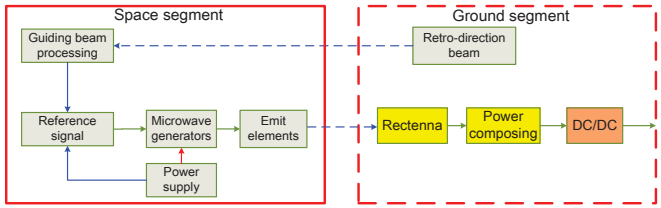
Solar Array Module

A solar array module is composed of a thin-film solar array, trusses and deployment mechanism. Folded before launch, deploys automatically in orbit.

- Size: 100m×100m
- Weigh: 3 tons
- Thin-film solar array: thin-film GaAs cell
- Efficiency: 40%
- Output power: 4MW

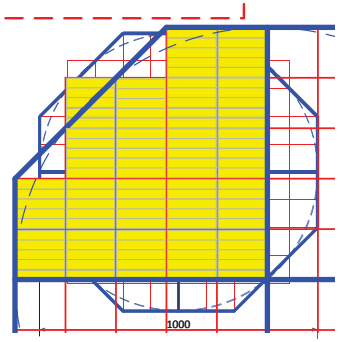


Microwave Power Transmission



Transmitting Antenna

- Ideal shape is a circle of 1km diameter.
- An octagon configuration is adapted.
- Secondary trusses enclose eighty 100m×100m grids.
- Each grid assemble five 20m×100m antenna modules.

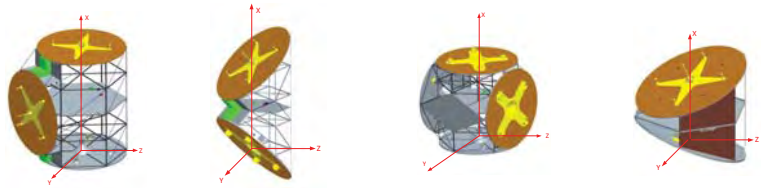


5. Multi-Rotary joints SPS Concept

Structure

- Truss module:

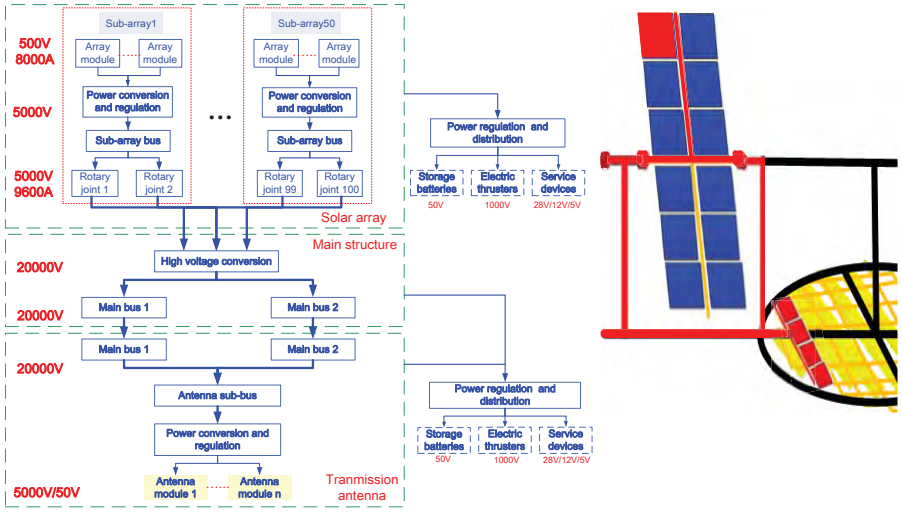
- Joint modules



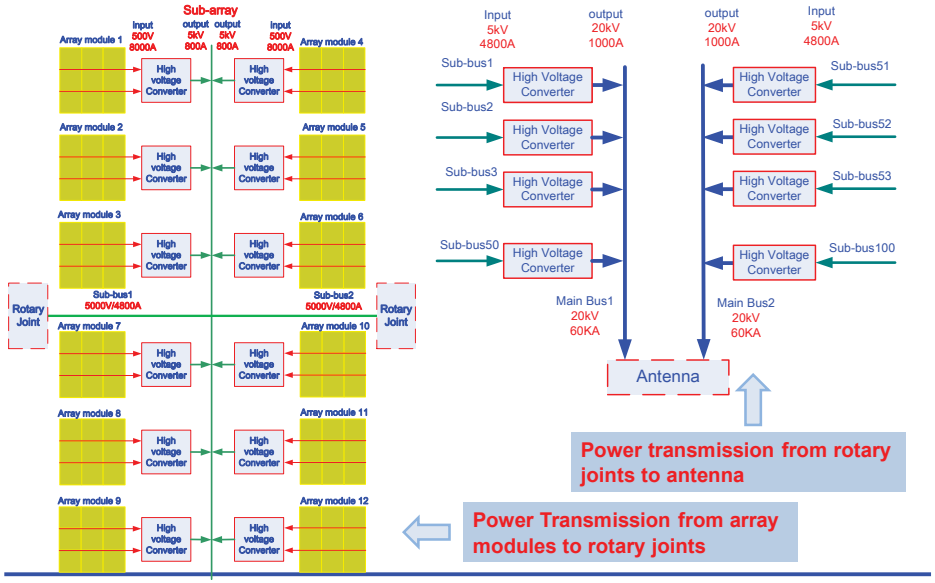
T shape module　L shape module　Cross shape module　135° shape module

5. Multi-Rotary joints SPS Concept

Power Transmission and Management (PTM)



5. Multi-Rotary joints SPS Concept



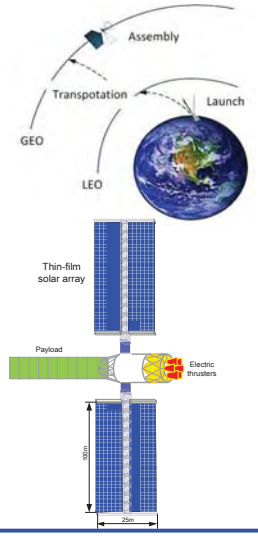
Power transmission from rotary joints to antenna

Power Transmission from array modules to rotary joints

5. Multi-Rotary joints SPS Concept

SPS system	Orbit	GEO
	Delivered power	~1GW
	Efficiency	~13%
	Total mass	~10000t
Solar Energy Collection and Conversion	Solar cell	Thin-film GaAs
	Efficiency	~40%
	Area of solar array	~6km²
	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	12.5 kW
	Mass	4000t
	Diameter of receiving antenna	5km
Power Transmission and Management	Style	Mix of distributed and centralized
	Voltage of main cable	20 kV
	Voltage of solar sub-arrays	5000 V
	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	

Launch and Transportation in Orbit



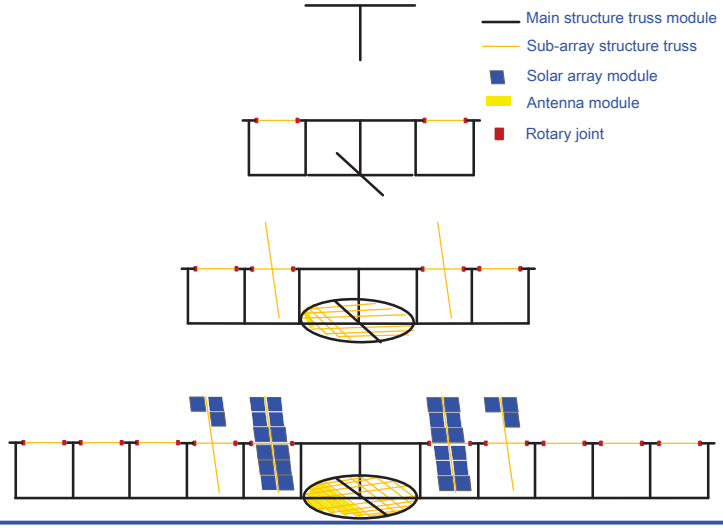
For the SPS, two stages transportation are expected.

- 1st stage: **Earth to LEO** by large reusable space launch vehicle.
- 2nd stage: Transfer from **LEO to GEO** by reusable electric propulsion orbit transfers.

A reusable electric propulsion orbit transfer concept is conceived.

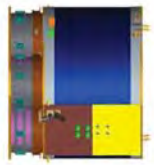
- Dry mass: 10t
- Electric power：1MW
- Thrust：30N
- Specific impulse：4000s

Sequence of Assembly in Orbit



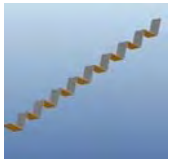
Construction and Assembly in Orbit

- Various modulars:



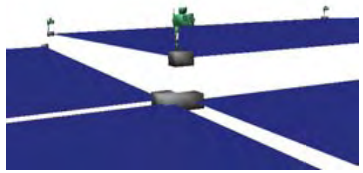
Truss module

Solar array module

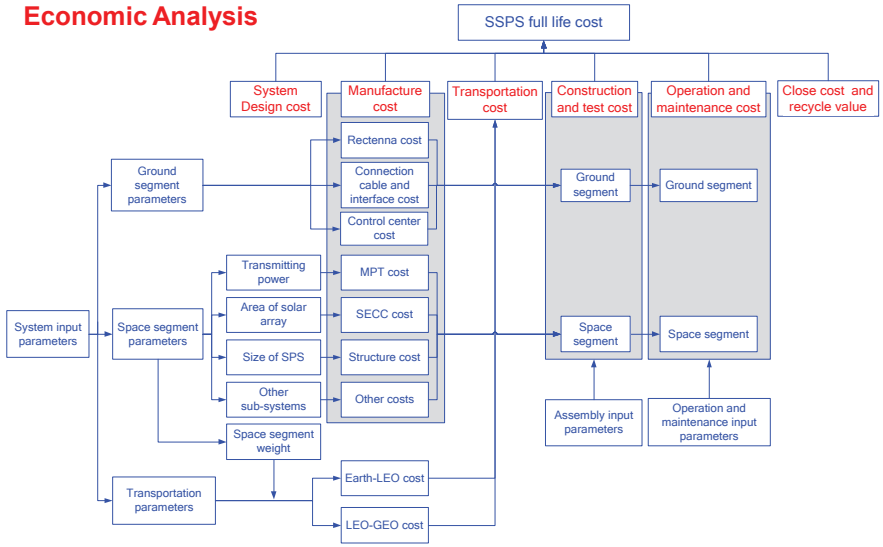


Antenna module

- Multi-robots cooperation:



Economic Analysis



Flow chart of economic analysis of a SSPS

5. Multi-Rotary joints SPS Concept

An example: solar array

- Input parameters
  - Number of solar sub-arrays is 600.
  - Total weight is about 2000 tons.
- Cost of design
  - 5 million $ is assumed.
- Cost of manufacture
  - 1 million $ per ton is assumed.
  - Total cost of manufacture is about 2 billion $.
- Cost of Transportation
  - 0.8 million $ per ton is assumed from Earth to LEO.
  - 0.2 million $ per ton is assumed LEO to GEO.
  - Total cost from Earth to GEO is 1 million $ per ton.
  - Total cost of transportation is about 2 billion $.
- Cost of assembly
  - Number of assembly is 600 times.
  - Cost of assembly is 2 million $ per time.
  - Total cost of assembly is about 1.2 billion $.
- Cost of operation and maintenance
  - Total 100 times of maintenance during
  - 30 years is assumed.
  - 2 million $ each maintenance is assumed.
  - Total cost is about 200 million $.
- Cost of system close and recycle
  - 0.1 million $ per ton is assumed.
  - Total cost is about 200 million $.

5. Multi-Rotary joints SPS Concept

Cost analysis results

Space Segment	Design	Development	Transportation (1000$/kg)	Construction	Operation and Maintenance	Close and Recycle	Total (Million $)
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

Ground Segment	Design	Development	Construction	Operation and maintenance	Close and recycle	Total (Million $)
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

The total cost of a SSPS is about **30 billion US dollars**.

Contents

6. Key technologies of SPS

6.1 High Power Electric Power Generation, Transmission and Management

Requirements of SPS

- 2GW electric power needs to be generated and transmitted to antenna.
- The high efficiency thin-film GaAs cell is chosen for the ultra-large flexible solar array module. The proposed output voltage of the high voltage solar array is 500V.
- The transmission power of a rotary joint is about 24MW. The transmission power can be reduced further by adding more solar sub-arrays. The voltage will be over 5kV.
- The long distance high voltage (20kV) electric power transmission cable is needed.
- The high voltage, high power converter devices are needed for difference requirement(such as electric thrusters).

Key technologies of electric power generation, transmission and management

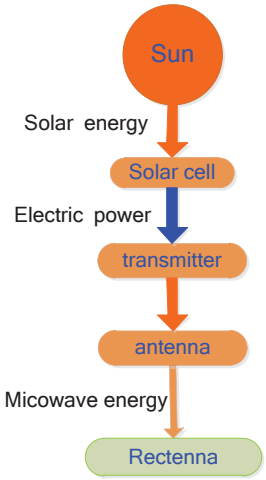
- **High power solar power generation**
  - High efficient, ultra-light and long life thin-film GaAs PV cell.
  - New cover film to prevent electrons accumulation and serious arcing.
- **High voltage electric power transmission**
  - High efficiency converter, switch.
  - Ultra-light cables, high power rotary joint.
- **Special material and component**
  - New high conductive conductor materials.
  - High temperature superconductive material.
  - New lightweight radiation hardening insulation dielectric materials.
  - New generation SiC and GaN power electronics components.
- **Assembly and maintenance of electric power system**

6.2 Wireless Power Transmission

Requirement of WPT on SPS

- Requirement of Efficiency. High efficiency and low energy loss are very important for SPS. The mainly efficiency factors include DC/RF efficiency, transmission efficiency, receiving and rectifing efficiency.
- High power. SPS is a high power space system. The power needed to be transmitted is over GW.
- Long distance. The best running orbit of SPS is GEO. The distance of WPT is 36000km.
- High pointing precision. WPT beam needs to point to the receiver accurately. For 5.8GHz microwave, the requirement of precision is better than 0.0005° that means 300m error.

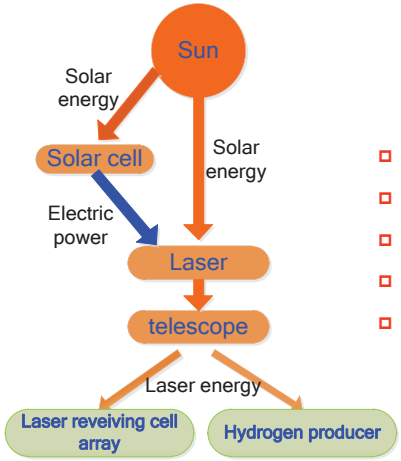
MPT technology



Key technologies

- High power high efficiency transmitter
  - microwave tube(Magnetron)
  - semiconductor amplifier
- Ultra large high power transmit antenna
- Retrodirective target detection
- High precision phase shifter
- High precision beam direction control
- High efficiency rectenna
- High efficiency Cyclotron-Wave rectifier

LPT technology



Key technologies

- High power high efficiency laser
- Direct solar pumping laser
- High power large aperture telescope
- Ultra high precision beam direction control
- High efficiency laser receiving cell

6.3 Space Super-Large Light Modular Structure, Assembly and Control

Requirement on SPS

- The total areas of solar array is about 6km^2.
- The diameter of the antenna is about 1km.
- The total length of the truss structure is over 11km.
- All modules need to be deployed and assemblied in space.
- Most of devices need to be repaired and replaced in space.
- Distribution control method is needed to keep the attitude and the orbit altitude of the SPS.

Key technologies of Structure, Assembly and Control

- Ultra-light structure materials
- Long-life film materials
- New deployed mechanism
- Free flying robot for assembly in space
- Attached robot for assembly in space
- High power electric thruster
- Refueling technology in space
- 3D print in space
- New method for distribution control of large spacecraft
- New method for assembly in space

Contents

- SPS is one of the important potential renewable energy ways in the future for China and the world.
- SPS is a macro-engineering in space. There are still many technology challenges need to be overcome to achieve the economy of delivered power.
- SPS may need tens of years to be developed and it needs continuous support by government and commercial organization.
- The development of SPS will bring the innovation of many advanced space technologies. It can also improve the ability to exploit space resource hugely.
- Widely international collaboration, innovative commercialized pattern and more positive policy are very important.
- The energy revolution of SPS will become realization with the cooperation and effort of the whole world.

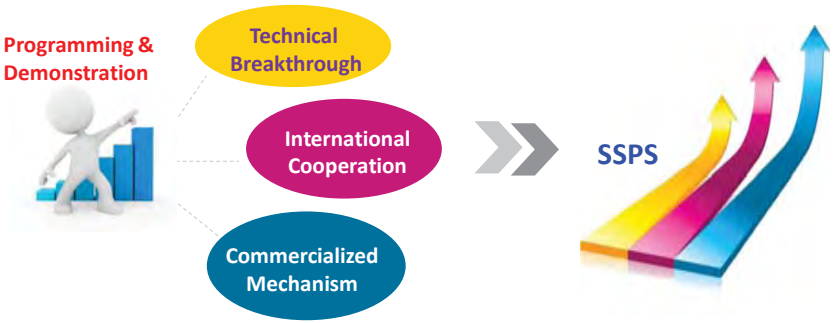
7. Conclusion

- SPS is a macro-engineering in space. There are tens of SPS concepts and each has its own advantages and different technology difficulties. There are still many technologies need to be studied deeply.
- The development of SPS will bring the innovation of many advanced space technologies. It can also improve the ability to exploit space resource hugely.
- MR-SPS is a new non-concentration concept and can provide electricity continuously and steadily in GEO.
- The huge several sq.km solar array is taken apart 50 same solar sub-arrays and each solar sub-array transfers electric power by its own independent rotary joints.
- The high efficiency thin-film GaAs cell is chosen for the ultra-large flexible solar array module. The output voltage is 500V.
- The transmission power of a rotary joint is about 24MW. The transmission power can be reduced further by adding more solar sub-arrays.

7. Conclusion

- The power of solar sub-arrays is transferred to antenna by cables fixed on structure trusses which keep immobile relative to antenna.
- The long distance high voltage (20kV) electric power transmission cable is needed.
- The structure is composed of truss modules and joint modules and is convenient for assembling in space.
- The antenna is composed of truss modules and antenna modules and is convenient for assembling in space.
- Microwave WPT is accepted as a feasible way. Considering the atmospheric attenuation, the size of antenna and the power density, 5.8GHz was chosen to be the frequency.
- Rectenna is chosen as the receiver. The efficiency and cost are two aspects need to be considered mostly. The safety and the impact on environment should be also taken into account.
- The low cost heavy launcher and orbit transfer are the key to lower the cost of SPS.

7. Conclusion



Thank you very much!

Wish close cooperation with 宇宙太陽発電学会

Welcome to CAST

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