A Modular Space Solar Power Pathfinder Mission in Low Earth Orbit

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Overview

- Space Solar Power
- Motivation
- Roadmaps and Previous Demonstration Proposals
- Prospective Requirements
- Limitations & Risks
- Possible Development Path
SPECTRUM ALLOCATION IS A CRITICAL PREREQUISITE FOR WIRELESS POWER TRANSMISSION & SPACE SOLAR POWER
1. Sunlight collected in space

2. Energy sent wirelessly to Earth

3. Energy received at ground receiver

4. Energy consumed
Motivation

• Implementing Space Solar Power would be a huge undertaking

• Being able to show technological readiness through an interim or precursor development is likely critical for success

• One of the steps along the way could be a demonstration mission in Low Earth Orbit (LEO)
2000 NASA SSP Road Map

2007 National Security Space Office Report Roadmap

Space Solar Power System (SSPS)
Strategic Concept for Near-Term Action

Geo-stationary Earth Orbit (GEO) SSPS

Low Earth Orbit (LEO) Experiments & Demos

Terrestrial Tests & Applications

Systems Studies

“Quick-Look” Study(ies)

Seismic Monitoring

ISS-based & Free-Flying Tech.

WPT Experiment(s)

SSPS Ground Demo(s)

Enabling Technology R&D (e.g., Ground Apps.)

Design Studies

SEPS Demonstration(s)

SPSS LEO Demo (c. 2012)

SSPS GEO Pilot (c. 2016)

SPS Deployment

Immediate Future 2008

Near-Term (Part I) 2009-2011

Near-Term (Part II) 2012-2014

Mid-term 2015-2017

Low Cost ETO R&D

New ETO Phase A/B

New ETO DDT&E

RLV Operations

Japanese SSP Roadmap

#1 STEP
Technology Demonstration Satellite (LEO)
- Power transmission
- Effect on Ionosphere
- Beam control technology
- Two-dimensional panel deployment
- Gravity stabilization

#2 STEP
Prototype System (LEO)
- Robotic assembly
- High power control
- High power transmission

#3 STEP
Pilot System (GEO)
- All required technical validation
- Operation test
- Start partial service

#4 STEP
Commercial System (GEO)
- 1GW
- 250MW
- 10MW
- 100KW

Demonstration on Orbit
Pilot Plant
Commercialization

From: http://www.jspacesystems.or.jp/en_project_sspso/
SPS 2000

- Originated in 1987 with the Japanese Institute of Space and Astronautical Science
- Proposed a LEO spacecraft in an equatorial orbit to transmit 10 MW at 2.45 GHz
- A Final Report was published in 2001
- Reasons it was not realized include difficulties in securing funding and lack of maturity of space robotics for assembly
### SSP Integrating Demonstrations Identified by NRL Study in 2008

<table>
<thead>
<tr>
<th>Demo concept</th>
<th>Technology Advanced</th>
<th>Cost range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground-based demonstration of robotic assembly of space structures</td>
<td>SS&amp;A</td>
<td>$2M-$20M</td>
</tr>
<tr>
<td>A large structure robotic construction demo in space</td>
<td>SS&amp;A</td>
<td>$80M-$400M</td>
</tr>
<tr>
<td>An international collaboration LEO free-flyer demonstrator hosting one or more SBSP technology demonstrations and experiments.</td>
<td>PV, WPT, SS&amp;A</td>
<td>$40M-$1B</td>
</tr>
<tr>
<td>Freeflyer Concept A</td>
<td>PV, WPT, SS&amp;A</td>
<td>$100M-$500M</td>
</tr>
<tr>
<td>Freeflyer Concept B</td>
<td>PV, WPT, SS&amp;A</td>
<td>$60M-$400M</td>
</tr>
<tr>
<td>Microwave power beaming from the International Space Station, using its existing solar arrays</td>
<td>WPT</td>
<td>$40M-$80M*</td>
</tr>
<tr>
<td>Demonstrations employing high altitude lighter-than-air vehicles.</td>
<td>PV, WPT</td>
<td>$5M-$30M</td>
</tr>
<tr>
<td>Earth to LEO microwave power beaming</td>
<td>WPT, SS&amp;A</td>
<td>$80M-$300M</td>
</tr>
<tr>
<td>Laser or microwave terrestrial power beaming demonstrations</td>
<td>WPT</td>
<td>$1M-$50M</td>
</tr>
</tbody>
</table>

SS&A = Space Structures and Assembly  
PV = Photovoltaics  
WPT = Wireless Power Transfer  
*shuttle or other launch provided
**NOTIONAL SCHEMATIC OF CONCEPT “A” INTEGRATING EXPERIMENT**
Space-Based Solar Technology Demonstration Mission - Notional Total Cost $350M

**PRAM**
Photovoltaic Radio-frequency conversion Antenna Module

- Such modules would likely employ Fresnel solar flux concentration

**ESA**
Electronically Steered Antenna

**SGLS antenna**
Large structure deployment boom for gravity gradient attitude control

**Laser power beam**
Inflatable ESA (Electronically Steered Antenna)

**Electric thrusters**

**LED beacon**

**Retrodirective microwave pilot beam antenna**

**Inflatable rectenna structure**

**Thin film concentrator**

**Second thin film concentrator or solar thermal demo**

**POWER RECEIVER SPACECRAFT VIEWED FROM -Z DIRECTION**

**POWER TRANSMITTER SPACECRAFT VIEWED FROM +Z DIRECTION**

**POWER RECEIVER SPACECRAFT VIEWED FROM +Z DIRECTION**

**US PRAM**

**JAXA PRAM**

**PRAM** = Photovoltaic Radio-frequency conversion Antenna Module
NRL Notional Concept B

NOTIONAL SCHEMATIC OF CONCEPT “B” INTEGRATING EXPERIMENT – Space-Based Solar Technology Demonstration Mission - Notional Total Cost $100M-$250M depending on number of modules and launcher

Electron emitter for electrodynamic propulsion in LEO

Large structure deployment boom for gravity gradient attitude control

Array of photovoltaic DC-to-RF antenna element modules

POWER TRANSMITTER SPACECRAFT VIEWED FROM -Z DIRECTION

Additional demo concepts were also conceived during the study
International Space Station

- Demo was proposed 2008-2009 following the NSSO SBSP report

- A large NASA/DoD-led team with industry and academia looked at number of wireless power transmission options using the ISS:
  - Microwave at various frequencies
  - Laser

- Not realized because of lack of funding
Prospective Requirements

“To extend the successful study of the SPS 2000 for the next century, it is more important to vitalize the requirements for a new system design than to improve the conceptual design itself.”
- Prof. Makoto Nagatomo in SPS 2000 Final Report, 2001

• Provide “meaningful” power
• Employ a similar frequency as for GEO
• Use similar modular elements as for GEO
• Show applicable assembly techniques
• Demonstrate similar elements for receiving stations on the ground
Limitations & Risks

- Intermittent power
- Limited coverage, depending on the orbit
- Orbital debris hazards
- **Spectrum allocation**
Possible Concept Development Path

• Determine requirements for LEO Demo

• Establish modular element standards via an international team

• Employ contributions from multiple countries to spread costs and allay diplomatic concerns
Conclusion

• Japan’s terrestrial wireless power demonstrations of 2015 may show it is now time to focus on space demonstrations

• A LEO space solar power technology demonstration satellite is a possible next step
Who’s Going to Pay for This?
(from 2008 NRL SBSP Report)

- **The National Aeronautics and Space Administration (NASA)**
  - NASA has funded significant SBSP studies and research in the 1970s, 1990s, and 2000s. NRL has performed work for NASA under SBSP related programs, and some of the technologies described in this report were developed in part by such funding.

- **The U.S. Department of Energy (DoE)**
  - The DoE together with NASA funded the comprehensive 1970s study of SBSP. With continued increases in energy costs, DoE may again be in a position to fund SBSP studies and research.

- **The U.S. Department of Defense (DoD)**
  - If sufficient priority is placed on reducing dependence on foreign energy sources and increasing self-sustainability of military installations, DoD may fund SBSP work. The Air Force, Office of Naval Research, DARPA, National Reconnaissance Office (NRO) and other DoD entities have funded science and technology development pertinent to SBSP.

- **International partners**
  - India, Japan, and European countries have expressed explicit interest in spurring SBSP technologies and system development. They comprise another possible source of funding, especially if incentivized by contributions from U.S. sources.

- **The U.S. Department of State or United Nations Office for Outer Space Affairs (UNOOSA)**
  - SBSP offers possible political and humanitarian benefits. Though these agencies might not fund SBSP development directly, they might be employed in mustering political will to fund such activities.

- **Corporate partners**
  - Space and energy industry corporations will likely be hesitant to fund the development of system until the concept has been successfully demonstrated and has a solid business case. Component technologies may be funded by corporate internal research if they also have applicability elsewhere.

- **A new U.S Government entity**
  - It has been observed that because SBSP does not constitute an exploration activity, it does not exactly fall under the purview of NASA, and that since it is a space activity, it likewise does not fall under the purview of the DoE. Perhaps political pressure could result in an agency that would be created to deal with SBSP specifically, much as has been done in Japan and elsewhere.
The Reasons SPS 2000 Was Not Built

• Per email from Susumu Sasaki, 2015-11-21: “The reason why it was not ultimately constructed is that the project was judged to be out of scope of ISAS which was established as a center of academic studies for universities. As a consequence, only a small budget for basic research had been given to the team. Actually the target cost for SPS 2000 was estimated to be 100 M$ or more just for satellite construction (not including launch cost), while the total budget of ISAS was around 200 M$/year that time. The SPS2000 team changed its strategy in mid-1990's to find the budget from other agencies such as MOE (Ministry of Education) or METI (Ministry of Economy, Trade and Industry). But all attempts were not successful. In 2000, the SPS 2000 team published a final report summarizing the SPS 2000 research activities.”

• Per email from Patrick Collins, 2015-11-24: “As I understand it, the single main reason why SPS2000 did not continue was the technical risk of the 100% robotic assembly. As designed, it required successful operation of robots assembling nearly 20 hectares of thin-film solar panels, and a couple of hectares of rigid antenna panels, including docking of a dozen or so different payloads ... Any one of many different possible single failures could have jammed the whole thing! And remembering that, even today, failure of even a relatively simple antenna to deploy mechanically is not unusual (!) I have to agree that the risk was unacceptable.”
References

Carbon-free Energy for Global Resiliency and International Goodwill

Team:
Dr. Paul Jaffe, U.S. Naval Research Laboratory, DOD (Presenter)
Julia Nesheiwat, Bureau of Energy Resources, DOS
Col. Thomas Bongiovi, Joint Staff Logistics Directorate, DOD
Dr. Avram Bar-Cohen, DARPA

Stakeholder Support:
Col. Peter Garretson, Air Command and Staff College, DOD
John Mankins, President, Mankins Space Technology, Inc.
Teresa Smith, Director, Systems Development and Technology Strategy, Northrop Grumman
THE BIG IDEA: Space Solar Power

1. Sunlight collected in space

2. Energy sent wirelessly to Earth

3. Energy received at ground receiver

4. Energy consumed
INNOVATION: The Difference It Will Make for DOD

• Supports ongoing transition away from fossil fuels
• Global transmission increases energy architecture flexibility
• Direct energy delivery reduces logistics burden and minimizes energy resupply risks
INNOVATION: The Difference It Will Make for DOS & USAID

- The ability to provide the developing world aid and reframe diplomacy as a clean energy exporter
- The opportunity to respond quickly to post-disaster energy needs
- Amplification of U.S. leadership in the fight against global warming
The Difference It Will Make for Our Nation and the World

- Reassert U.S. leadership in space, energy, & other technologies
- Create a huge number of new jobs
- Inspire STEM interest with clear societal benefits
- Open the door to space resource utilization & enhance exploration
- Rekindle the spirit that America does great things
With our international partners:

- **2015-2017**  
  $10M  
  • Project Management Office lays groundwork: planning, ground demonstrations, technology

- **2017-2020**  
  $200M  
  • Space demonstrations from low earth orbit

- **2020-2025**  
  $10B  
  • Pilot plant in geosynchronous orbit
CRITICAL ASSUMPTIONS FOR FEASIBILITY:

• **LEGAL:** Spectrum allocation for wireless power transmission can be secured
  – Japan has started this process with the International Telecommunications Union

• **FINANCIAL:** Figures of merit will meet thresholds of economic attractiveness
  – Trends strongly suggest this is within reach
MEASUREMENTS TO TRACK PROGRESS:
Simplified “Levelized Cost of Energy” (in $/kWh) for Space Solar Power:

\[
\text{Launch cost} ($/\text{kg}) + \text{Satellite cost} \ ($/\text{kg}) = \frac{\text{Power per unit mass} (\text{W/kg}) \times \text{Lifetime (years)}}{15\text{$/kWh}}
\]
WITHIN TEN YEARS

Satellite cost ($/kg)

20x Reduction

Power/mass (W/kg)

>50x Increase

Less than 10¢/kWh, assuming no reductions in launch cost
NEXT STEPS:  
(1) Stand Up Organization and Partnerships

Assistant Secretary of Defense for Research and Engineering

Under Secretary for Economic Growth, Energy and Environment

Office of Energy & Infrastructure Programs

Space Solar Power Steering Committee

- Project Management / Technical Lead: DOD
  - Global Integrated System Engineering Team

- Domestic & International Partnership Lead: DOS & USAID
  - EU, Japan, India, etc.
NEXT STEPS:
(2) Small Bets for Gathering Data and Learning

• Perform terrestrial high-power, long distance wireless power transmission demonstration with the international team

• Test spaceborne power collection & transmission hardware using the International Space Station
NEXT STEPS:

(3) Long-term Bets for Implementation

• Low-Earth orbit solar & transmission pathfinder mission with receivers in developing countries

• Geosynchronous orbit pilot plant operational capability
If we act, we can empower a more prosperous and secure World
Carbon-free Energy for Global Resiliency and International Goodwill

Team:
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NRL Space Background

NRL’s Long and Diverse History in Space

- Over 100 Satellites more than 40 Launches for National, DoD, and Civil Sponsors on a Variety of Vehicles
- 3 Major Space Systems Transitioned to Industry

Extensive Experience With Leader/Follower Acquisition and Industry Transition Approaches
End-to-End Solar Power Satellite Demonstration
Frequently Asked Questions

- Won’t most of the energy be lost in transmission?
  - Not for sufficiently large antennas
- Doesn’t it make more sense to use terrestrial solar and just store energy for when it’s cloudy or night time?
  - In some contexts, yes. But:
    - Large-scale storage is currently limited, inefficient, heavy, difficult, and expensive
    - The energy can’t be transmitted globally
    - SSP is inherently a baseload source without storage
- Will the power transmission beam be dangerous?
  - It depends on how it is implemented. Safe power densities can easily be achieved.
Department of Defense (DOD)

MISSION: The mission of the Department of Defense (DOD) is to provide the military forces needed to deter war and to protect the security of the United States. Since the creation of America's first army in 1775, the Department and its predecessor organizations have evolved into a global presence of three million individuals, stationed in more than 140 countries and dedicated to defending the United States by deterring and defeating aggression and coercion in critical regions. The Department embraces the core values of leadership, professionalism, and technical knowledge. Its employees are dedicated to duty, integrity, ethics, honor, courage, and loyalty.

Themes: ENERGY  NATIONAL DEFENSE  MANAGEMENT
EDUCATION, TRAINING, EMPLOYMENT, AND SOCIAL SERVICES
VETERANS BENEFITS AND SERVICES  GENERAL SCIENCE, SPACE, AND TECHNOLOGY

Strategic Goal: Defeat our Adversaries, Deter War, and Defend the Nation

Strategic Goal: Sustain a Ready Force to Meet Mission Needs

Strategic Goal: Strengthen and Enhance the Health and Effectiveness of the Total Workforce

Strategic Goal: Achieve Dominant Capabilities through Innovation and Technical Excellence

Strategic Goal: Reform and Reshape the Defense Institution
MISSION

Shape and sustain a peaceful, prosperous, just, and democratic world, and foster conditions for stability and progress for the benefit of the American people and people everywhere.

STRATEGIC GOAL 1
Strengthen America’s economic reach and positive economic impact

STRATEGIC GOAL 2
Strengthen America’s foreign policy impact on our strategic challenges

STRATEGIC GOAL 3
Promote the transition to a low-emission, climate-resilient world while expanding global access to sustainable energy

STRATEGIC GOAL 4
Protect core U.S. interests by advancing democracy and human rights and strengthening civil society

STRATEGIC GOAL 5
Modernize the way we do diplomacy and development
NEXT STEPS

1. Assign DOD the technical mission of advancing SSP as critical to avoiding strategic technological surprise, and to lay the groundwork outlined above. Create a stand-alone joint program office.

2. Create a joint entity with leadership by DOS, USAID, and USTDA to build and maintain international partnerships with allies for SSP development including those within the EU, Japan, India, and others.

3. Coordinate via the DOS/USAID/USTDA entity to identify first and second tier partners to form an Intergovernmental Agreement for organizing a framework for contributions of technological development and to identify power-receiving station locations across the world.

4. Have ASDRE engage in partnerships with DOS, USAID, DOE, NASA, DOC, formalized thru a Memorandum of Understanding with the ultimate goal of providing energy to the U.S. and team members and maturing SSP technology

5. Pursue special funding authority through legislative relief process to allow nondefense committees (NASA, Energy) to allocate funding to the SSP program office to develop the pathfinder demonstration mission described above to provide 1-10 MW from low-earth orbit as a precursor to a multi-GW geosynchronous satellite.
Why Investigate Energy Alternatives?

• About 85% of our current energy supply is drawn from exhaustible sources
• Carbon-based sources are linked to global warming

How Would it Work?

Space Solar Power Historical Background

• The idea appears in the Asimov story “Reason” from 1941
• Outlined by Peter Glaser in *Science* in 1968
• 34 kW over 1.5 km wireless power demo by NASA in 1975
• The U.S. Department of Energy and NASA spent ~$50M studying SSP between 1978 and 1981
• NASA and other organizations funded small-scale research or published studies from 1994 through today
Space Solar Power Current Activities

- A few companies are pursuing SSP
- Japan and China put several $M into SSP research annually
- Northrop Grumman and Caltech jointly announced in April 2015 an “up to” $17.5M 3-year SSP research effort
- U.S. Gov’t currently has no SSP research programs
Various SSP Conceptual Designs

Peter Glaser GEO concept, circa 1968

Perpendicular to Orbital Plane, circa 1973

NASA/DOE SPS Reference System, circa 1978

Krafft Ehricke Soletta Space Mirrors, circa 1978
Various SSP Conceptual Designs

- NASA/DOE Microwave sandwich concept, circa 1980
- Japanese SPS-2000 LEO concept, circa 1994
- Aerospace Corp. Laser Concept, circa 2002
Various SSP Conceptual Designs

- SolarDisc, circa 1997
- SunTower, circa 1997
- Modular Symmetrical Concentrator, circa 2007
- JAXA modular laser, circa 2008
Various SSP Conceptual Designs

- EADS Astrium laser concept, circa 2011
- SolarHigh, circa 2012
- SPS-ALPHA, circa 2013
- Solaren, circa 2010
- Tin Can SPS, circa 2014

Images © 2014 Peter J. Schubert, used with permission.
Various SSP Conceptual Designs

Hyland Power Star, circa 2014

Team Sunflower Thermal Power Satellite\(^1\), circa 2015

China Academy of Space Technology (CAST)
Multi-Rotary Joints SPS\(^1\), circa 2015

Dickinson Laser to High-Altitude Platform to Microwave, circa 2013

(Or conducting tether)

Etc.….  

\(^1\)Images from Online Journal of Space Communication, Issue No. 18, http://spacejournal.ohio.edu/
The Two Functions a Solar Power Satellite Would Need to Perform

- **Energy Collection:**
  - Photovoltaics (PV)
  - Solar thermal (Heat Engine)
  - Sun-pumped lasers

- **Power Transmission:**
  - Microwave
  - Laser
  - Reflection

For this discussion, focus will be on the most commonly proposed combination, PV/Microwave
Space Solar Power Benefits

• Advantages shared with ground solar:
  – Doesn’t emit greenhouse gases
  – Doesn’t require fuel
  – Doesn’t produce radioactive waste

• Collecting sunlight in space avoids the losses from clouds, night, and the atmosphere

• Satellite coverage would mean energy could be transmitted to a large range of locations

• Could transform the launch and aerospace industry, enabling space resource exploitation
Space Solar Power Challenges

- Requires a tremendous amount of mass to be put in space
- Power transmission beam could cause radio interference on the ground, with aircraft, and with satellites
- The receiving site would need to be large, or the power beam would need to have a high energy density
- Startup costs are likely to be enormous
Important Things To Realize

• Many, many reports and papers have been written about SSP
• People disagree on exactly how to do it
• The size, mass, and number of launches needed for most concepts are huge
Does the Technology Exist?

• At the subsystem level
  – Sunlight-to-electricity conversion has been demonstrated
  – Wireless power transmission has been demonstrated
  – Some SSP-specific hardware has been demonstrated

• A meaningful end-to-end demonstration system from space to earth has NOT been demonstrated to date
Is it Economically Feasible?

• Without a demonstration system, how can costs be accurately determined?

• How can the cost be compared with existing sources and other alternatives?

• Does it offer a compelling advantage over the status quo?
Levelized Cost of Energy (LCOE)

• A means of comparing the cost of energy production across different alternatives, expressed as dollars per watt hour ($/Wh) or an equivalent

• Can we construct a simplified expression that produces the LCOE for space solar power?
Factors that Would Affect SSP Cost

• Cost of launch
  – Depends on number of launches, weight of satellites
• Cost of satellite design and manufacturing
• Cost of materials
• Cost of assembly, operations, and maintenance
• Cost of ground receiving station
• Tax credits or subsidies
• Many others ...
Factors that Would Affect the Amount of Energy Delivered

- Lifetime of the satellite
- Size of the satellite
- Size of the receiving station
- Efficiency of the system
- Others ...
Simplified Levelized Cost of Energy (LCOE) for Space Solar Power

\[
\frac{\text{Cost of launch ($/kg) + Cost of satellite ($/kg)}}{\text{Power per unit mass (W/kg) \times Lifetime of system (years)}}
\]

• This expression gives a result in cents per kilowatt hour, something we can relate to our home electricity bill.
MEASUREMENTS TO TRACK PROGRESS:

Simplified “Levelized Cost of Energy” (in $/kWh) for Space Solar Power:

Launch cost ($/kg) + Satellite cost ($/kg)

Power per unit mass (W/kg) * Lifetime (years)

Today = $15/kWh
Applying Different SSP LCOE Inputs

- Case 1 – Using currently demonstrated values
- Case 2 – 5-year projection, improved W/kg and hardware cost
- Case 3 – 10-year projection, further improved W/kg and hardware cost
- Case 4 – Farther term projection

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass-specific power (W/kg)</td>
<td>5</td>
<td>40</td>
<td>250</td>
<td>500</td>
</tr>
<tr>
<td>Total service life (years)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Cost of launch ($/kg)</td>
<td>2,500</td>
<td>2,500</td>
<td>2,500</td>
<td>2,500</td>
</tr>
<tr>
<td>Cost of space segment ($/kg)</td>
<td>10,000</td>
<td>2,000</td>
<td>500</td>
<td>100</td>
</tr>
</tbody>
</table>

Output

| Levelized cost of energy ($/kWh) | 14.27 | 0.64  | 0.07  | 0.03  |

- No increase in service life or reduced launch costs are assumed
Applying Different SSP LCOE Inputs

- Case 1 – Using currently demonstrated values
- Case 2 – Assuming incremental improvements
- Case 3 – Assuming aggressive improvements
- Case 4 – Assuming revolutionary improvements

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
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<td>Mass-specific power (W/kg)</td>
<td>5</td>
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<td>25</td>
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<td>Cost of launch ($/kg)</td>
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<td>500</td>
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<tr>
<td>Cost of space segment ($/kg)</td>
<td>10,000</td>
<td>5,000</td>
<td>1,000</td>
<td>100</td>
</tr>
<tr>
<td>Output</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Levelized cost of energy ($/kWh)</td>
<td>15.84</td>
<td>1.37</td>
<td>0.07</td>
<td>0.0033</td>
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</tbody>
</table>
## Comparison of Levelized Cost of Energy for Various Means of Power Generation

<table>
<thead>
<tr>
<th>Plant Type</th>
<th>Capacity Factor (%)</th>
<th>Levelized Capital Cost</th>
<th>Fixed O&amp;M</th>
<th>Variable O&amp;M (including fuel)</th>
<th>Transmission Investment</th>
<th>Total System Levelized Cost</th>
</tr>
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<tbody>
<tr>
<td>Geothermal</td>
<td>92</td>
<td>3.4</td>
<td>1.2</td>
<td>0.0</td>
<td>0.1</td>
<td>4.8</td>
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<tr>
<td>Natural Gas: Advanced Combined Cycle</td>
<td>87</td>
<td>1.6</td>
<td>0.2</td>
<td>5.4</td>
<td>0.1</td>
<td>7.3</td>
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<tr>
<td>Wind</td>
<td>36</td>
<td>5.8</td>
<td>1.3</td>
<td>0.0</td>
<td>.3</td>
<td>7.4</td>
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<tr>
<td>Natural Gas: Conv. Combined Cycle</td>
<td>87</td>
<td>1.4</td>
<td>0.2</td>
<td>5.8</td>
<td>0.1</td>
<td>7.5</td>
</tr>
<tr>
<td>Hydro</td>
<td>54</td>
<td>7.1</td>
<td>0.4</td>
<td>0.7</td>
<td>0.2</td>
<td>8.4</td>
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<tr>
<td>Conventional Coal</td>
<td>85</td>
<td>6.0</td>
<td>0.4</td>
<td>2.9</td>
<td>0.1</td>
<td>9.5</td>
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<tr>
<td>Advanced Nuclear</td>
<td>90</td>
<td>7.0</td>
<td>1.2</td>
<td>1.2</td>
<td>0.1</td>
<td>9.5</td>
</tr>
<tr>
<td>Advanced Coal with CCS</td>
<td>85</td>
<td>9.7</td>
<td>1.0</td>
<td>3.6</td>
<td>0.1</td>
<td>9.5</td>
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<tr>
<td>Biomass</td>
<td>83</td>
<td>4.7</td>
<td>1.5</td>
<td>3.8</td>
<td>0.1</td>
<td>10.1</td>
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<tr>
<td>Advanced Coal</td>
<td>85</td>
<td>7.7</td>
<td>0.7</td>
<td>3.1</td>
<td>0.1</td>
<td>11.6</td>
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<tr>
<td>Solar PV</td>
<td>25</td>
<td>11.0</td>
<td>1.1</td>
<td>0.0</td>
<td>0.4</td>
<td>12.5</td>
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<tr>
<td>Solar Thermal</td>
<td></td>
<td>20</td>
<td>19.2</td>
<td>4.0</td>
<td>0.6</td>
<td>24.0</td>
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<tr>
<td>Solar Power Satellite Case 1</td>
<td>90</td>
<td>1,584.4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1,584.4</td>
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<tr>
<td>Solar Power Satellite Case 2</td>
<td>90</td>
<td>136.9</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>136.9</td>
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<tr>
<td>Solar Power Satellite Case 3</td>
<td>90</td>
<td>7.1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>7.1</td>
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<td>Solar Power Satellite Case 4</td>
<td>90</td>
<td>0.3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Comparison of JP-8 Cost per Gallon with $/kWh Equivalents and SPS Cases

<table>
<thead>
<tr>
<th>$/(Gallon of JP-8)</th>
<th>$/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.75</td>
<td>0.10</td>
</tr>
<tr>
<td>7.51</td>
<td>0.20</td>
</tr>
<tr>
<td>15.02</td>
<td>0.40</td>
</tr>
<tr>
<td>22.53</td>
<td>0.60</td>
</tr>
<tr>
<td>30.03</td>
<td>0.80</td>
</tr>
<tr>
<td>37.54</td>
<td>1.00</td>
</tr>
<tr>
<td>45.05</td>
<td>1.20</td>
</tr>
<tr>
<td>52.56</td>
<td>1.40</td>
</tr>
<tr>
<td>60.07</td>
<td>1.60</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>450.51</td>
<td>12.00</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Range of reported “Fully Burdened Cost of Fuel” values is $3 to $400 per gallon

SPS Case 1: 15.84
SPS Case 2: 1.37
SPS Case 3: 0.07
Potentially Area for Aerospace Engineers to Contribute

• Spacecraft Subsystems Development:
  – Structures
  – Mechanisms
  – Thermal
• Large Space Structures
• Space Robotics
• Mission Design
Perspective Relative to One Prominent Alternative

- Compare Space Solar Power with another potentially enormous source of energy:
  - Fusion
  - “which has been about ten years away ... for the last 60 years”
- In the U.S., about $30B in inflation-adjusted dollars was spent on fusion research between 1953 & 2012 (about $700M in 2012)
- Over the same ~60 year period, about one thousandth of that amount was spent on space solar power research
Conclusion

• For an “all of the above” energy strategy that balances the development of higher risk / higher payoff options with expanding known sources, more resources should be put into Space Solar Power research

• SSP is a potential opportunity to create huge new markets and applications with benefits for the whole of humanity
Further Exploration

• 2014 Key World Energy Statistics – International Energy Agency

• Do the Math blog -http://physics.ucsd.edu/do-the-math/

• Consider a Spherical Cow – A Course in Environmental Problem Solving, John Harte, 1988, ISBN: 978-0935702583

• National Space Society http://www.nss.org/settlement/ssp/
Further Exploration

• Space-Based Solar Power
  http://physics.ucsd.edu/do-the-math/2012/03/space-based-solar-power/

• Space Solar Power: An Idea Whose Time Will Never Come?

• In Defense of Space Solar Power
  http://space.alglobeus.net/papers/FetterResponse.html
<table>
<thead>
<tr>
<th>Parameter</th>
<th>LEO demo</th>
<th>GEO pilot</th>
<th>GEO operational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Flux (W/m²²)</td>
<td>1370</td>
<td>1370</td>
<td>1370</td>
</tr>
<tr>
<td>Concentration factor</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Space Segment conversion eff (combined for PV, RF-DC, etc.)</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Resulting converted flux/m²² at satellite</td>
<td>274</td>
<td>411</td>
<td>411</td>
</tr>
<tr>
<td>Non-Space Segment eff (beam coupling, rectenna eff, atm loss)</td>
<td>0.5</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Power output desired from earth station (MW)</td>
<td>1</td>
<td>120</td>
<td>1,000</td>
</tr>
<tr>
<td>Required collected power (MW)</td>
<td>10</td>
<td>444</td>
<td>3,704</td>
</tr>
<tr>
<td>Required PV area for collection (km²)</td>
<td>0.036</td>
<td>1.081</td>
<td>9.011</td>
</tr>
<tr>
<td>Required PV area for collection (m²²)</td>
<td>36,496</td>
<td>1,081,373</td>
<td>9,011,445</td>
</tr>
<tr>
<td>Radius of solar array (km)</td>
<td>0.108</td>
<td>0.587</td>
<td>1.694</td>
</tr>
<tr>
<td>Assumed solar array thickness (cm)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Assumed array density (kg/m³) Aluminum = 2700</td>
<td>100</td>
<td>55</td>
<td>40</td>
</tr>
<tr>
<td>Volume of array (m³)</td>
<td>365</td>
<td>10,814</td>
<td>90,114</td>
</tr>
<tr>
<td>Mass of array (kg)</td>
<td>36,496</td>
<td>594,755</td>
<td>3,604,578</td>
</tr>
<tr>
<td>Equivalent W/kg for array</td>
<td>27.4</td>
<td>201.8</td>
<td>277.4</td>
</tr>
<tr>
<td>Equivalent kg/m²² for array</td>
<td>1.00</td>
<td>0.55</td>
<td>0.40</td>
</tr>
<tr>
<td>Delta IV EELV Heavy capacity to GEO (kg)</td>
<td>53,000</td>
<td>53,000</td>
<td>53,000</td>
</tr>
<tr>
<td>Number of EELV Heavy launches required for solar array</td>
<td>1</td>
<td>11</td>
<td>68</td>
</tr>
<tr>
<td>Launch rate (per week)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Time to deploy (years)</td>
<td>0.01</td>
<td>0.22</td>
<td>1.31</td>
</tr>
<tr>
<td>Launch cost ($/kg)</td>
<td>2,500</td>
<td>2,500</td>
<td>2,500</td>
</tr>
<tr>
<td>Array launch cost ($)</td>
<td>91,240,876</td>
<td>1,486,888,348</td>
<td>9,011,444,535</td>
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<tr>
<td>Hardware cost ($/kg)</td>
<td>2,000</td>
<td>500</td>
<td>100</td>
</tr>
<tr>
<td>Array hardware cost ($)</td>
<td>72,992,701</td>
<td>297,377,670</td>
<td>360,457,781</td>
</tr>
<tr>
<td>Total array cost ($)</td>
<td>164,233,577</td>
<td>1,784,266,018</td>
<td>9,371,902,316</td>
</tr>
<tr>
<td>Operating life (years)</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Energy produced over operating life (kWh)</td>
<td>175,320,000</td>
<td>21,038,400,000</td>
<td>175,320,000,000</td>
</tr>
<tr>
<td>Cost per kWh (cents/kWh)</td>
<td>$0.94</td>
<td>$0.08</td>
<td>$0.05</td>
</tr>
<tr>
<td>GEO CASE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------------------------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>frequency (GHz):</td>
<td>5.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c = 3 × 10^8 = wavelength × frequency</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>for antennas with a circular aperture</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>π</td>
<td>3.1415927</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Receiving antenna diameter (m)</td>
<td>3000</td>
<td>7,068,583</td>
<td>7.068583471</td>
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<tr>
<td>Transmitting antenna diameter (m)</td>
<td>1200</td>
<td>1,130,973</td>
<td>1.130973355</td>
</tr>
<tr>
<td>wavelength (m)</td>
<td>0.0517241</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Near field test:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>is separation greater than 2 × (diameter of transmit antenna)^2 / wavelength?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>111360000</td>
<td>111,360.00 km</td>
<td></td>
</tr>
<tr>
<td>GEO (km)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>τ = sqrt(AtAr) / (wavelength × separation)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>35786</td>
<td>1.5275167</td>
<td>90%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>efficiency @ 60% for τ = 1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>efficiency @ ~90% for τ = 2.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>efficiency @ 99.63% for τ = 2.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEO CASE</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>---</td>
<td>---</td>
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<td></td>
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<tr>
<td><strong>frequency (GHz):</strong></td>
<td>5.8</td>
<td></td>
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<tr>
<td>for wavelength (m):</td>
<td>0.051724138</td>
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<tr>
<td>$c = 3 \times 10^8 = \text{wavelength} \times \text{frequency}$</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>for antennas with a circular aperture</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\pi$</td>
<td>3.14159</td>
<td></td>
<td></td>
</tr>
<tr>
<td>area ($m^2$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Receiving antenna diameter (m):</strong></td>
<td>300</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>70685.775</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Transmitting antenna diameter (m):</strong></td>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>31415.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>wavelength (m):</strong></td>
<td>0.0517241</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Near field test:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>is separation greater than $2 \times (\text{diameter of transmit antenna})^2 / \text{wavelength}$?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3093333.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3,093.33 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEO (km)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>tau = $\sqrt{At/Ar} / (\text{wavelength} \times \text{separation})$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>901</td>
<td>1.0111666</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>64%</td>
<td></td>
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</tr>
<tr>
<td>efficiency @ 60% for tau = 1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>efficiency @ ~90% for tau = 2.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>efficiency @ 99.63% for tau = 2.4</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Terrestrial solar electricity production

Solar irradiation

1355 W/m² = 100 %

- reduction due to day/night cycle
  = 9 h/24 h = 0.375

- Transmission to earth surface = 0.24

SPS solar electricity production

- PV efficiency 0.2
- Microwave efficiency 0.66
- Transmission to earth surface = 0.8

Atmosphere

- Microwave-electricity conversion = 0.72

- Grid supplied electricity
  = 1.8 % = 24 W/m²

- Grid supplied electricity
  = 7.6 % = 103 W/m²

Figure from 2005 ESA report: “Earth & Space-Based Power Generation Systems - A Comparison Study”
Where Does Energy Come From Today?

World total primary energy supply from 1971 to 2011 by fuel, expressed in Million Tonnes of Oil Equivalents

- **Coal/peat**
- **Oil**
- **Natural gas**
- **Biofuels and waste**
- **Nuclear**
- **Other**

**Other includes geothermal, solar, wind, heat, etc.**

Source: IEA 2013 Key World Energy Statistics
Where Does Energy Come From Today?

2011

- Oil: 31.5%
- Coal/peat: 28.8%
- Natural gas: 21.3%
- Nuclear: 5.1%
- Hydro and waste: 10.0%
- Biofuels: 2.3%
- Other**: 1.0%

**Other includes geothermal, solar, wind, heat, etc.

Source: IEA 2013 Key World Energy Statistics
What are Some Proposed Alternatives?

Renewable Alternative Energy Sources Currently in Use Represent 16.7% of Total Consumption; Balance Consists of Fossil Fuels and Nuclear

Other Comparison Considerations

• Weighting of factors
• Additional factors
  – Dispatchability
  – Technology Dividends
  – Economic Attractiveness
    • Payback Period
    • Operating Expenses
    • Etc...
Segments and Historical Efficiencies

Image from 1980 DOE/NASA report
System Blocks and Estimated Currently Achievable Efficiencies

<table>
<thead>
<tr>
<th>Segment</th>
<th>Efficiency</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photovoltaics</td>
<td>30%</td>
<td>Efficiencies &gt;40% in lab under concentration</td>
</tr>
<tr>
<td>DC-to-RF Conversion</td>
<td>85%</td>
<td>Varies with conversion method &amp; implementation</td>
</tr>
<tr>
<td>Antenna</td>
<td>90%</td>
<td>Includes conduction and scan losses</td>
</tr>
<tr>
<td>Atmospheric Transmission</td>
<td>98%</td>
<td>Weather &amp; frequency dependent</td>
</tr>
<tr>
<td>RF Collection Area</td>
<td>90%</td>
<td>Function of rectenna array size &amp; transmit taper</td>
</tr>
<tr>
<td>Rectenna Elements</td>
<td>91%</td>
<td>Demonstrated at 2.45 GHz</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>17%</strong></td>
<td>Energy is available essentially 24 hours a day, all year round</td>
</tr>
</tbody>
</table>

Satellite

Ground Station
Does the Technology Exist?

• Has anything similar been done previously?

• Determine the “Technology Readiness Level”
  – Used by NASA, Department of Defense, others

# NRL Report Finding 2, SBSP Research Areas

## Highest Priority SBSP Technology Research Areas with Extensive NRL Heritage

<table>
<thead>
<tr>
<th>Technology Area</th>
<th>NRL Precursors</th>
<th>Recommended research</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space Structures</td>
<td>Superstring longeron truss</td>
<td>Beam walker &amp; rolled-up beam deployment mechanism development and demonstration</td>
</tr>
<tr>
<td>Space Robotic Assembly</td>
<td>Satellite for the Universal Modification of Orbits (SUMO), Front-End Robotic</td>
<td>Co-operative robotics, smart skin technology, space robotic structure assembly</td>
</tr>
<tr>
<td></td>
<td>Enabling Near-Term Demonstrations (FREND)</td>
<td></td>
</tr>
<tr>
<td>Space Subsystem Development</td>
<td>W-band transponder, Frangibolt deployment mechanism, atomic clocks for</td>
<td>Photovoltaic RF-conversion antenna module research, a.k.a &quot;sandwich&quot; module</td>
</tr>
<tr>
<td></td>
<td>spaceflight, etc.</td>
<td></td>
</tr>
<tr>
<td>Thermal Management</td>
<td>Two-phase heat pipes, diamond substrate heat Management</td>
<td>SBSP detailed component alternatives thermal analysis, e.g. the &quot;sandwich&quot; module</td>
</tr>
<tr>
<td>Photovoltaics</td>
<td>TacSat-4 solar cell experiment</td>
<td>Photovoltaic collector and concentration experiments</td>
</tr>
<tr>
<td>RF amplifier technology</td>
<td>Multiple beam klystrons, coupled-cavity and helix traveling wave tubes</td>
<td>Phase-controllable, light weight, high-efficiency, multipactor resistant microwave</td>
</tr>
<tr>
<td></td>
<td></td>
<td>sources in the 2kW to 15kW range</td>
</tr>
<tr>
<td>Propulsion</td>
<td>High Performance Xenon Flow System, Electric Propulsion Demonstration Module</td>
<td>Long duration electric propulsion for large structures, LEO to GEO transfer propulsion,</td>
</tr>
<tr>
<td></td>
<td>(EPDM), Advanced Tether Experiment (ATEx)</td>
<td>stationkeeping, LEO electrodynamic Tethers</td>
</tr>
<tr>
<td>Spacecraft Engineering</td>
<td>Clementine, TacSat-1, TacSat-4, WindSat, Upper Stage, Interim Control Module,</td>
<td>In-orbit robotic construction demonstration, SBSP-related technology free-flyer</td>
</tr>
<tr>
<td></td>
<td>etc.</td>
<td>experiments</td>
</tr>
<tr>
<td>Energy Management &amp; Storage</td>
<td>Spacecraft power subsystems, Sodium Sulfur Battery Experiment (NaSBE)</td>
<td>SBSP flight power architecture, Large capacity load-leveling storage capabilities</td>
</tr>
</tbody>
</table>
NRL Report Finding 2, SBSP Research Areas

Other Priority Technology Research Areas

• Mission Concept of Operations Modeling
• Power Transmitting Antenna Systems
• Retrodirective Beam Control
• Power Transmit Amplitude Weighting
• Rectenna Design
• Rectenna Power Management and Distribution (PMAD)
• DC-Optical Conversion
• Optical Receivers
• Terrestrial Power conversion and control
Objective: Resolve trades and execute proof of principle development of an integrated module for converting received light energy into transmitted microwave energy to support terrestrial, marine, and space-borne wireless power transfer applications, with a focus on the space case.

Approach:
- Performed critical trades of photovoltaic, DC-to-RF conversion, and antenna element candidates
- Analyzed thermal challenges and integration schemes
- Developed and integrated a proof of principle Photovoltaic RF-DC converter Antenna element Module (PRAM) unit
- Conducted lab testing and performance characterization
- Executed environmental testing of units

Prospective users of systems employing such modules:
- Forward based troops and other remote energy consumers that require baseload power
- Power companies and cooperatives

PRAMs, a.k.a. “sandwich modules” form a large microwave transmitting aperture
Accomplishments / Achievements

• Completed and tested in space-like conditions the most efficient, highest specific power sandwich conversion modules to date
  • 8% & 7%, ~4x previous record
  • 4.5 W/kg & 5.8 W/kg
• Demonstrated and tested a novel new sandwich module design that addresses thermal concerns
• Provided a meaningful empirical basis for space solar power economic studies
Photovoltaic RF Converter Antenna Element Module Research

Relationship to Other Projects / Organizations

- Our team is a top group nationally and internationally investigating the thermal limitations of sandwich modules, integration challenges, and was the first to target and demonstrate prototype environmental testing. Other groups working with sandwich module development (Kobe University, Kyoto University, Texas A&M University, Caltech/Northrop Grumman, others) are now seeking to improve upon our results.

- Collaborations currently being investigated for possible formalization through MOUs, MOAs, CRADAs:
  - ARTEMIS Innovation, LLC
    - Follow-on hardware development via NASA NIAC or ARPA-E
  - Solaren Corporation
    - Solaren is currently under contract to provide clean power to PG&E in 2019
    - NRL’s Tech Transfer office has drafted an NDA for Solaren, our discussions with them are ongoing
Photovoltaic RF Converter Antenna Element Module Research Documentation

- Summary of presentations and outreach
  - 2014 International Astronautical Congress
  - MSNBC Interview, March 2014

- Summary of publications

- Awards: Alan Berman Publication Award, 2012 & 2015; IEST Publication Award 2015
Space solar power has been studied for many years in the absence of realistically prototyped components. This research effort critically scrutinized the key challenges and produced, tested, and characterized a proof of principle unit like that employed in several popular concepts.

- **Why NRL?**
  - NRL hosts staff with the unique blend of expertise and knowledge needed to produce meaningful module prototypes

- **Why Navy?**
  - The Navy and DoD’s energy needs, particularly for disadvantaged forward operating bases and combat outposts, demand critical investigation of novel alternatives

- **Why now?**
  - With global warming and energy security as looming threats, the investigation of alternative energy sources is an imperative
Goubau and Schwering Method of Finding Beam Collection Efficiency

\[ \tau = \frac{\sqrt{A_t A_r}}{\lambda D} \]

Using GEO (36,000km), 1500 m Tx diameter, and 2.45 GHz assumptions with a 7.5 km diameter receiving area provides a \( \tau \) of about 2, > 95% collection efficiency.
One-way Sea Level to Zenith Attenuations in Clear Sky Conditions

Zenith Attenuation (dB)

Frequency (GHz)

- Total
- Water Vapor
- Dry Air

1013 hPa pressure
15°C temperature
7.5 g/m³ water vapor density

5.8
2.45
35
94
Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).

Visible Light observable from Earth, with some atmospheric distortion.

Most of the Infrared spectrum absorbed by atmospheric gasses (best observed from space).

Radio Waves observable from Earth.

Long-wavelength Radio Waves blocked.
# SPS Systems Designs Considered in URSI Report

<table>
<thead>
<tr>
<th>Model</th>
<th>Old JAXA model</th>
<th>JAXA1 model</th>
<th>JAXA2 Model</th>
<th>NASA-DOE model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>5.8 GHz</td>
<td>5.8 GHz</td>
<td>5.8 GHz</td>
<td>2.45 GHz</td>
</tr>
<tr>
<td>Diameter of transmitting antenna (TX)</td>
<td>2.6 km</td>
<td>1 km</td>
<td>1.93 km</td>
<td>1 km</td>
</tr>
<tr>
<td>Amplitude taper</td>
<td>10 dB Gaussian</td>
<td>10 dB Gaussian</td>
<td>10 dB Gaussian</td>
<td>10 dB Gaussian</td>
</tr>
<tr>
<td>Output power (beamed to earth)</td>
<td>1.3 GW</td>
<td>1.3 GW</td>
<td>1.3 GW</td>
<td>6.72 GW</td>
</tr>
<tr>
<td>Maximum power density at TX center</td>
<td>63 mW/cm²</td>
<td>420 mW/cm²</td>
<td>114 mW/cm²</td>
<td>2.2 W/cm²</td>
</tr>
<tr>
<td>Minimum power density at TX center</td>
<td>6.3 mW/cm²</td>
<td>42 mW/cm²</td>
<td>11.4 mW/cm²</td>
<td>0.22 W/cm²</td>
</tr>
<tr>
<td>Antenna spacing</td>
<td>0.75 λ</td>
<td>0.75 λ</td>
<td>0.75 λ</td>
<td>0.75 λ</td>
</tr>
<tr>
<td>Power per one antenna (Number of elements)</td>
<td>Max. 0.95 W (3.54 billion)</td>
<td>Max. 6.1W (540 million)</td>
<td>Max. 1.7 W (1,950 million)</td>
<td>Max. 185 W (97 million)</td>
</tr>
<tr>
<td>Rectenna Diameter</td>
<td>2.0 km</td>
<td>3.4 km</td>
<td>2.45 km</td>
<td>10 km</td>
</tr>
<tr>
<td>Maximum Power density at rectenna</td>
<td>180 mW/cm²</td>
<td>26 mW/cm²</td>
<td>100 mW/cm²</td>
<td>23 mW/cm²</td>
</tr>
<tr>
<td>Collection Efficiency</td>
<td>96.5 %</td>
<td>86 %</td>
<td>87 %</td>
<td>89 %</td>
</tr>
</tbody>
</table>
High Volume Changes the Game

Can we achieve 1/10 present capital costs? (Industrial learning curve suggests easily)

Can we achieve < $1500 / kg launch costs? (probably much lower at these launch rates)

Source: Dr. Marty Hoffert
Is low-cost space hardware possible?

**ASSERTION:**
When assessing manufacturing in larger “Lot Sizes,” Space Systems/Subsystems should be cost-estimated according to this type of curve. This suggests a strategic “line of attack” on the challenge of Affordable Space Systems.

From: John C. Mankins
Are launch costs really insoluble?
Who will develop it?

• Because of the absence of a US project and fiscal constraints in Japan and Europe, China appears best positioned to develop SBSP

Whoever takes the lead in the development and utilization of clean and renewable energy and the space and aviation industry will be the world leader.

—Prof. Wang Xiji, Chinese space program pioneer

• Three Conclusions from SPS research

• 空间太阳能电站的三个重要结论

Space power is one of the important potential renewable energy in the future both for China and world. Space power is for China and world.

SPS is an incredible macro-engineering in space. There are still many technology challenges need to overcome.

SPS need more collaboration between different countries and organizations.

空间太阳能电站是一个庞大的工程仍然有许多挑战需要克服。