Wireless Power Transmission Options for Space Solar Power

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Space Solar Power (SSP), combined with Wireless Power Transmission (WPT), offers the far-term potential to solve major energy problems on Earth. In this presentation, two basic WPT options, using radio waves and light waves, are considered for both long-term and near-term SSP applications. In the long-term, we aspire to beam energy to Earth from geostationary Earth orbit (GEO), or even further distances in space. Accordingly, radio- and light- wave WPT options are compared through a wide range of criteria, each showing certain strengths.

In the near-term, we plan to beam power over more moderate distances, but still stretch the limits of today’s technology. For the near-term, a 100 kWe-class “Power Plug” Satellite and a 10 kWe-class Lunar Polar Solar Power outpost are considered as the first steps in using these WPT options for SSP. By using SSP and WPT technology in near-term space science and exploration missions, we gain experience needed for sound decisions in designing and developing larger systems to send power from Space to Earth.
Wireless Power Transmission Options for Space Solar Power

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Wireless Power Transmission Options for Space Solar Power

• Far Term Space Systems to beam power to Earth
  – Radio-Wave WPT System
  – Light-Wave Systems

• Near term Technology Flight Demonstrations
  – Model System Concept 1A: 100 kWe satellite
  – Model System Concept 1B: 10 kWe lunar system
Global Power Consumption

Remote Sensing of Current Global Power Consumption:
A Composite Satellite Photograph of the Earth at Night
Initial Photovoltaic / Microwave SPS
GEO Sun Tower Conceptual Design

- "Sun-Tower" Design based on NASA Fresh Look Study
- Transmitter Diameter: 500 meters
- Vertical "Backbone" Length: 15.3 km (gravity gradient)
- Identical Satellite Elements: 355 segments (solar arrays)
- Autonomous Segment Ops: 1) Solar Electric Propulsion from Low Earth Orbit 2) System Assembly in Geosynchronous orbit
- Large Rectenna Receivers: Power production on Earth
**Photovoltaic / Laser-Photovoltaic SPS**

**GEO Sun Tower-Like Concept**

Solar Panel Segment
Dimensions: 260 m x 36 m

Lasers and Optics
PMAD

Deployable Radiator

8 Ion Thrusters
Avionics

Full Sun Tower Portion
- 1530 modules
- 55 km long
- Backbone can be eliminated

Multiple beams
Synergy Between Sunlight and Laser-PV WPT for Terrestrial Photo-Voltaic Power Production

- Large photo-voltaic (PV) power plants in Earth’s major deserts (Mojave, Sahara, Gobi, etc.) receive & convert light from 2 sources:
  1) Directly from the Sun, and
  2) Via WPT from SSP systems

- Laser light is transmitted and converted more efficiently than sun-light
  - Wavelength is selected for good atmospheric transmissivity
  - Efficient Light Emitting Diode wavelengths match common PV band-gaps

- Gravity gradient-stabilized SPSs are in peak insolation at ~6 AM and ~6 PM, with shadowing or cosine loss at mid-day and midnight
  - Heavy, complex gimbaled arrays add little extra power at these times
  - Both sides of rigid (not gimbaled) solar arrays can be light-sensitive
    - Back-side produces less power due to occlusion by wires
    - Translucent substrate (e.g., Kapton) also reduces back-side power levels
  - Even gimbaled arrays suffer a loss of power around noon and midnight

- The combination of ambient sunlight plus laser illumination combines, at the terrestrial PV array, to match the daily electricity demand pattern
**Sunlight + Laser-PV WPT = ~ Power Requirement**

**Photo-Voltaic (PV) Power Station Receives Both**

- **PV Power from Sunlight**
- **PV Power from WPT-Light**
- **Total Power at PV Receiver**

**Normalized Output from SPS (Non-Tracking Arrays)**

**Normalized Output from Sun**

**Normalized Total Output**

**Typical Electricity Demand**
## WPT Wavelength Trade for SSP

<table>
<thead>
<tr>
<th>ATTRIBUTE</th>
<th>WPT Using Radio Waves</th>
<th>WPT Using Light Waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture Size</td>
<td>Large, so system must be large</td>
<td>Small; allows flexible system design</td>
</tr>
<tr>
<td>Interference</td>
<td>Radio Frequency Interference</td>
<td>None, except perhaps astronomy</td>
</tr>
<tr>
<td>Attenuation</td>
<td>Penetrates clouds and light rain</td>
<td>Stopped by clouds (need desert area)</td>
</tr>
<tr>
<td>Legal Issues</td>
<td>FCC, NTIA, ITU</td>
<td>ABM treaty, if power density high</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>Rectenna useful for SSP only</td>
<td>PV array for both WPT &amp; solar power</td>
</tr>
<tr>
<td>Dual Use</td>
<td>Crops?; communications?</td>
<td>PV arrays on rooftops; &quot;solar&quot;-sails?</td>
</tr>
<tr>
<td>Perception</td>
<td>Public fears of &quot;cooking&quot;</td>
<td>Government fears of &quot;weapons&quot;</td>
</tr>
<tr>
<td>Safety</td>
<td>Safe (must keep aircraft out of beam)</td>
<td>Safe (WPT light intensity &lt; sunlight)</td>
</tr>
<tr>
<td>Efficiency (space)</td>
<td>High</td>
<td>Improving</td>
</tr>
<tr>
<td>Efficiency (ground)</td>
<td>High</td>
<td>Improving</td>
</tr>
<tr>
<td>Traceability</td>
<td>Heritage to communications &amp; radar</td>
<td>MSC-1 and MSC-2 predecessors</td>
</tr>
<tr>
<td>Power Mgmt &amp; Dist</td>
<td>Heavy, due to centralized WPT</td>
<td>Lightweight; WPT can be distributed</td>
</tr>
</tbody>
</table>

Area of Significant Concern
Intermediate Area
Area of Significant Benefit
MSC-1A: Near Term Demonstration
100 kWe Power Plug Satellite

- Power System derived from existing ISS IEA (Integrated Energy Assembly)
  - IEA is successfully deployed in orbit now
  - IEA includes energy storage (batteries)
  - Current ISS array pair produces 61.5 kWe
  - Advanced PV cells can double IEA power
    - ~120 kWe with derivative array
- MSC-1 demonstrates solar-powered WPT
  - Efficient power generation
    - Light Emitting Diodes (LEDs) achieve >30% conversion efficiency
    - ~36 kW transmitted in light beam
  - Effective heat dissipation via IEA radiators
  - Accurate pointing of beam via reflector

Dimensions:
- 70.8 m
- 11.7 m
ISS with IEA Solar Panels Fully Deployed
Current flight experience with large IEA reduces risk for near-term derivative applications
MSC-1A: Lunar and Mars Power (LAMP) Application
Laser WPT to Photo-Voltaics on the moon or Mars
MSC 1B: Lunar Polar Science Applications

- Technology for Laser-Photo-Voltaic Wireless Power Transmission (Laser-PV WPT) is being developed for lunar polar applications by Boeing and NASA Marshall Space Flight Center.
- A lunar polar mission could demonstrate and validate Laser-PV WPT and other SSP technologies, while enabling access to cold, permanently shadowed craters that are believed to contain ice.
  - Craters may hold frozen water and other volatiles deposited over billions of years, recording prior impact events on the moon (& Earth).
  - A photo-voltaic-powered rover could use sunlight, when available, and laser light, when required, to explore a large area of polar terrain.
- The National Research Council recently found that a mission to the moon’s South Pole-Aitkin Basin should be a high priority for Space Science.
Space Solar Power Technology Demonstration For Lunar Polar Applications

- Craters are COLD: -300°F (-200°C)
- Frost/Snow after Lunar Impacts
- Good for Future Human Uses
- Good for Rocket Propellants

Moon's Orbit

North Pole (SEE BELOW)
Sun Rays are Horizontal at North & South Poles
• NEVER shine into Craters
• ALWAYS shine on Mountain

South Pole (SEE BELOW)

Solar Power Generation on Mountaintop

Direct Communication Link

Wireless Power Transmission for Rover Operations in Shadowed Craters

POSSIBLE ICE DEPOSITS
Summary

- Farther-term micro-wave WPT options are efficient, and can beam power through clouds / light rain, but require large sizes for long distance WPT and a specialized receiver ("rectenna").

- Nearer-term Laser-Photovoltaic WPT options are less efficient, but allow synergistic use of the same photo-voltaic receiver for both terrestrial solar power and SSP.
  - The smaller aperture size also allows smaller (lower cost) initial systems.
  - Laser-Photovoltaic WPT systems open new SSP architecture options.
  - Gravity gradient-stabilized “Sun Tower” SSP satellites may make more sense for laser systems than than for microwave systems, because the receiver also converts sunlight into electricity, to correct for the cosine loss otherwise observed in power production at mid-day.

- Technology flight demonstrations can enable advanced space science and exploration in the near term.
  - “Power Plug” or “LAMP” spacecraft and Lunar Polar Solar Power outpost advance technology for far-term commercial SSP systems, while providing significant value for near-term applications.