Why Are We Interested in a Lunar Based Solar Power System (LSPS)?

• General Features of Extraterrestrial Solar Power Systems
  – The Sun is a dependable energy source that supplies high quality energy
  – Concept utilizes passive and low mass equipment to collect and generate electricity
  – Can be operated while repairs are made
Why Are We Interested in a Lunar Based Solar Power System (LSPS)? (cont.)

• Why the Moon vs. GEO?
  – Stable and predictable platform (low gravity, no wind, few moonquakes)
  – The Moon contains all the materials needed for solar cells and structures (reduces transportation over SPS)
  – Less intrusive than GEO positioning
  – Improved worker safety
Solar Energy From Space

Solar Power Satellites
• Pioneered by Peter Glaser
• Originally proposed 1968
• Subjected to scrutiny by NASA, DOE, and National Academy of Sciences

Lunar Power System
• Pioneered by David Criswell
• Originally proposed 1985
• Subjected to analysis by NASA and U. of Houston
Lunar Power System Concept

- 6 sites 50 GW(Earth) each
- 83 km antenna aperture
- 5400 sq km antenna area
- cosine factor = 6
- lunar surface area each transmitter 32,400 sq. km

- Thermal control surface
- Solid-state microwave power amp, 1.9 kWf

- Microwave reflector
- Iron-coated lunar glass net

- 50 million xmtas per site

(67% of surface area used for power collection)

- Solar cell ridges generate nearly constant output at all sun angles.
- Ridges are thermally glazed regolith with amorphous silicon photovoltaics deposited.

After Woodcock, 1989
Concerns About the LSPS

- Lunar base only receives solar energy 50% of the time (need multiple collection bases)
- Rotation of the Earth means multiple receiving stations are required
- Fixed collectors do not collect optimum solar flux
- Si cells are about 1/3 the efficiency of GaAs cells
- Larger transmitting distance requires bigger transmitting antenna
The Rotation of the Moon and Earth Requires Multiple Collection and Receiving Units

- 29 day orbit
- Lunar power station (inactive)
- Direction of incident solar radiation
  - Lunar altitude ≈ 380,000 km
- Microwave power beam
- Earth rectenna (inactive)
  - 120°
  - 24 hour rotation

After Kerwin and Arndt, 1985
Evolution of Lunar Power System to Continuous Baseload Power Requires Auxiliary Reflectors at Earth and Moon

Initial Capability ~IGW/2

Moon

1 Site

10's of GW

Orbiting reflectors double output

100's of GW

Continuous power requires microwave reflectors or world-wide interneting

Earth

Earth/Moon

Diurnal

Lunar Site

Not Lighted

23.13 hr cycle

Both Sites Lit

Neither Site Lit

After Woodcock, 1989
The Collection Area of a Lunar Power System Must be Much larger Than That for a SPS

- Factor of 2 because of day/night cycle
- Factor of 2 because of fixed oblique solar incidence angle
- Factor of 3 because Si converters are 1/3 the efficiency of GaAs.

The total area of LSPS is $\approx 12$ times that of a SPS
Transmitting Antenna Sizing Criteria

Coherent Microwaves

\[ D_1D_2 = 2k\lambda H \]

\( \lambda = 12.24 \text{ cm (2.45 GHz)} \)
\( k = 1.4 \) (typically)
\( H = 37,000 \text{ km (GEO)} \)
\( = 380,000 \text{ km (Moon)} \)

For \( D_2 = 12 \text{ km} \)
\( D_1 \approx 1 \text{ km (GEO)} \)
\( D_2 \approx 11 \text{ km (Moon)} \)
LSP SYSTEM

Sunlight (#1)
Source of Power

Power Base (east) (#3)
Converts sunlight to electricity and then to beams of microwaves

Microwave Power Beam (#4)

Orbital Relay (#5)

RECTENNA (#6)
(size exaggerated)
# Lunar Solar Power Reference Design - 20,000 GW<sub>e</sub>-(Criswell 1996)

World Installed capacity -1999-3,180 Gwe

<table>
<thead>
<tr>
<th>Component</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illumination of one cell (geometry)</td>
<td>32%</td>
</tr>
<tr>
<td>Fill factor (ground cell area/base area)</td>
<td>20%</td>
</tr>
<tr>
<td>Solar cell efficiency</td>
<td>10%</td>
</tr>
<tr>
<td>Collection efficiency</td>
<td>90%</td>
</tr>
<tr>
<td>Electricity to microwave</td>
<td>85%</td>
</tr>
<tr>
<td>Transmission to Earth</td>
<td>73%</td>
</tr>
<tr>
<td>Earth atmosphere transmission</td>
<td>98%</td>
</tr>
<tr>
<td>Rectenna collection efficiency</td>
<td>89%</td>
</tr>
<tr>
<td>Microwave power conditioning</td>
<td>88%</td>
</tr>
<tr>
<td>Electric grid conditioning</td>
<td>97%</td>
</tr>
<tr>
<td>Overall efficiency for 1,368 W/m&lt;sup&gt;2&lt;/sup&gt; (electricity to Earth grid/lunar solar watt)</td>
<td>0.266%</td>
</tr>
</tbody>
</table>
• For a 0.266% overall efficiency and to produce 20,000 GW\textsubscript{e}, one would need to cover 15.3% of the lunar surface.
• Number of bases required would be 12 (pairs)
### Lunar Solar Power Reference Design - 20,000 GW<sub>e</sub> - (Criswell 1996) - Continued

<table>
<thead>
<tr>
<th>Category</th>
<th>Details</th>
<th>Amounts</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total regolith handled</strong></td>
<td></td>
<td>2 billion tons/y</td>
</tr>
<tr>
<td><strong>Lunar equipment</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mining</td>
<td></td>
<td>12,739 tons</td>
</tr>
<tr>
<td>processing</td>
<td></td>
<td>428,481 tons</td>
</tr>
<tr>
<td>support</td>
<td></td>
<td>48,171 tons</td>
</tr>
<tr>
<td><strong>Transport to Space</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>from Earth (ave. for 10y ramp-up)</td>
<td></td>
<td>70,314 tons/y</td>
</tr>
<tr>
<td>from Earth (parts, consumables, &gt;10 y)</td>
<td></td>
<td>172,687 tons/y</td>
</tr>
<tr>
<td>from the Moon (LO mirrors)</td>
<td></td>
<td>336,181 tons/y</td>
</tr>
<tr>
<td><strong>People</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>on the Moon</td>
<td></td>
<td>5,000</td>
</tr>
<tr>
<td>in LLO</td>
<td></td>
<td>395</td>
</tr>
<tr>
<td>in LEO</td>
<td></td>
<td>486</td>
</tr>
</tbody>
</table>
Lunar Solar Power Reference Design-20,000 GW<sub>e</sub>-(Criswell 1996)-Continued

<table>
<thead>
<tr>
<th>Costs ($1995 billions)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Space</td>
<td>4,926</td>
</tr>
<tr>
<td>Earth (mainly rectennas)</td>
<td>17,040</td>
</tr>
<tr>
<td>Total</td>
<td>21,966</td>
</tr>
</tbody>
</table>

| Capital Costs                              | 1,098 $/kW<sub>e</sub> |
It is Claimed That the Total mass Investment for Electricity from Solar Energy is Less Than for Terrestrial Systems

<table>
<thead>
<tr>
<th>System</th>
<th>Tons/GW_e</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrestrial Thermal Power Systems</td>
<td>310,000</td>
</tr>
<tr>
<td>Terrestrial Photovoltaic</td>
<td>430,000</td>
</tr>
<tr>
<td>Lunar Solar power System</td>
<td>52,000</td>
</tr>
</tbody>
</table>

After Criswell and Thompson, 1996
What if the SPS was Constructed of material from the Moon?

• First proposed by G. O’Neill, 1974
• General Dynamics and MIT completed the analysis in 1979
• Conclusion was that 90-96% of the SPS mass could come from the Moon
• Would require mass drivers on a Lunar base to send material to a Space Manufacturing Facility
Using Lunar Resources Can Greatly Reduce the Mass Launch Rates From Earth

After G. E. Marvniak and G. K. O'Neil. 1993
Conclusions-LSPS

- The Lunar Solar Power Satellite would require a substantial return to the Moon.
- The LSPS would only make sense if it produced most of the projected electricity use in the World.
- A major factor in the ultimate COE from the LSPS will be the launch costs from Earth.
Solar Power Satellites Could Also Use Lasers For Energy Transmission

Height 35,800 km

Diameter = 42.4 m

Width = 35.8 m

Optics

LPTS-1

Diameter = 0.5 m

Width = 3,560 m

Optics

LPTS-2