Introduction to Space Solar Power for the
Global Electric Power Utility Market

WiSEE SSP Workshop
November 8, 2013
Baltimore, MD

Darel Preble
President, Space Solar Power Institute
Chair, Space Solar Power Workshop

www.solarsat.org
www.sspi.gatech.edu
Bill Brown, far right and Peter Glaser explain their Solar Power Satellite to school children.
"That's one small step for a man, and one giant leap for mankind."

The **Amplitron** device that transmitted Neil Armstrong’s audio and video TV signal from the Moon, was designed and built by William C. Brown. Bill demonstrated a small helicopter powered by microwave beam using his new invention, the rectifying antenna, or “rectenna” in 1964. Much hardware to enable **microwave power beaming** was designed and built by William C. Brown, the “Father of Microwave Power Transfer”. Blake Marshall earned the first William C. Brown Fellowship in MPT. We are now publishing Bill’s MPT journals.

Thirty seven states, 4 territories, and many countries have Renewable portfolio standards and other initiatives to adopt better energy alternatives.
Energy Bosses Call for End to Subsidies for Wind, Solar Power
Group Includes CEOs From Eni, GDF Suez and E.ON
By Géraldine Amiel (WSJ)
Oct. 11, 2013 - Brussels - Top executives of companies that provide half of Europe's electricity production capacity called on politicians to end "distorting" subsidies for wind and solar power, saying the incentives have led to whopping bills for households and businesses and could cause continent-wide blackouts.

#1 cause of the Arab Spring revolts has been the rising price of food. 40% of our corn goes to make ethanol for gasoline.
Scant Gains on CO2 Emissions, Energy Agency Says

London (WSJ) - The world has made almost no progress over the past 20 years in reducing the carbon content of its energy supplies, despite more than $2 trillion of investment into renewable-energy projects such as wind and solar power, the International Energy Agency said. Carbon-dioxide emissions from each unit of energy consumed have fallen by less than 1% since 1990, largely because of coal's continued dominance as a fuel for electricity generation, the IEA said. As energy consumption has grown, total global emissions of CO2 rose 44% from 1990 to 2010, it said.

http://online.wsj.com/article/SB10001424127887324493704578428591203150334.html
Energy Return On Investment (EROI) is how many BTU’s of energy are brought to market per BTU invested.

Some oil fields in the Mid-East have had EROIs of 100. But different oil fields have markedly different EROI, which can and is dramatically impacting the market outlook for those countries and fields and the market’s response to consumer’s ability to meet market price points. As this “hurdle” is slowly being raised, countries and consumer markets are and will be excluded.

SSP has essentially zero fuel cost for power generation - a prime advantage for SSP. By tapping the sun directly, SSP is expected to be lower in cost (EROI), than anything else on the energy horizon. Next Figure shows EROI for various power generation plants.
Figure 3: (Color online.) EROIs of all energy techniques with economic "threshold".

**Biomass:** Maize, 55 t/ha per year harvested (wet). **Wind:** Location is Northern Schleswig Holstein (2,000 full-load hours). **Coal:** Transportation not included. **Nuclear:** Enrichment 83% centrifuge, 17% diffusion. **PV:** Roof installation. **Solar CSP:** Grid connection to Europe not included.
High oil prices lead to RECESSION

- Economist James Hamilton has shown that oil price spikes connected with 10 out of 11 recent US recessions!

Source: Based on BP 2012 Statistical Review of World Energy data
A favorite slide you did I liked. Could you update this one? Overextended on debt, people are squeezed by rising costs and declining real wages.
Crude oil production vs Brent oil spot price, in US $ - EIA data.
IEA World Energy Outlook projects the global petroleum decline rate at 6.7%!
http://www.guardian.co.uk/business/2008/dec/15/oil-peak-energy-iea
1. **Should be dispatchable, or “baseload”**.

   SSP would be available (in full sun) 99.3% of the year at GeoSynchronous Orbit (GEO). The satellites would be in the Earth’s shadow for up to 72 minutes at local midnight during the period ±22 days of the spring and fall equinox.
2. Zero fuel costs; like hydro, for example, but easy to dispatch than hydro.

SSPs burn no fuel in operation except a tiny amount of station keeping fuel – probably electric ion or plasma drive since electric power is readily available at GEO.
A New Alternative - Space Solar Power (SSP)

3. Low CO$_2$ emission intensity:
Plant-available nitrogen decreases 40 to 50 % under doubled carbon dioxide levels expected ~2050 ... resulting in reduced nutrition from forage and grasses grown under doubled CO$_2$.

Ruminants, including cattle, sheep, oxen, buffalo, deer, etc., the source of nearly all the milk and half the meat the world eats, will gain weight more slowly under doubled CO$_2$. 

Kansas State University  http://spuds.agron.ksu.edu/gainco2.gif
• Nutrition from wheat and rice decline:

• Wheat grown at doubled CO$_2$ declines in protein content by 9-13%. It produces poorer dough of lower extensibility and decreased loaf volume. The quality of flour for bread making degrades.

• The protein content of rice declines under doubled CO$_2$ corresponding temperature increase. Iron and zinc concentrations in rice, important for human nutrition, would be lower.
As our atmospheric CO$_2$ level continues to increase, plant photorespiration decreases and nitrate assimilation in most plant species is severely inhibited. Declines in forest health and food quality that are associated with climate change derive in part from CO$_2$ inhibition of nitrate assimilation that diminishes plant organic N (Nitrogen, and therefore, protein concentration.) levels. This exacerbates damage from insects and other pests as they consume more plant material to meet their nutritional needs.

- “Elevated Carbon Dioxide”, Arnold J. Bloom, Ph. D, Professor and chair, Dept. of Plant Sciences, Univ. of California, Davis.
http://www.plantsciences.ucdavis.edu/Faculty/bloom/bloom.htm
4. Low Water usage.

For the first time in 50 years, Black & Veatch’s annual Strategic Directions in the Electric Utility Industry survey’s 2011 ranked water supply the top environmental concern. Water effluent was also a top five environmental concern.

Competition for water in the next decade is increasing both domestically, and in South Asia and the Middle East where adoption of water as a weapon by states or terrorists will become more likely. (ref. in notes)

SSP uses no water in operation.
Water Shortages Threaten Energy Output

By Eric Yep (WSJ), Nov. 7, 2013 - Water shortages are threatening energy output and increasing costs in some of the world's most prolific energy sectors including shale gas in the U.S., crude oil in the Middle East and coal in China, and the situation is set to worsen, Wood Mackenzie said Thursday.

The energy sector is already the world's largest consumer of water for industrial purposes, using over 15% of global supply, and this is rising, the consulting firm said in a report, noting huge quantities are needed to increase pressure at oil fields, in technologies like hydraulic fracturing and to upgrade coal quality.

Growing water needs will pit energy companies against other users and increase production costs significantly, it said.

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A New Alternative - Space Solar Power (SSP)

5. Reduce competition for other scarce resources besides water. (Steel, copper, “rare earths”, etc.,

SSP’s thin film PV uses much less high purity silicon and energy to fabricate – since it is 1% as thick compared to typical crystalline silicon ground PV. A PV panel at GEO would yield 9.6 times more energy per day compared to a same size panel at an average continental US (lower 48) site.
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5. (cont) Some planners forecast that SSP parts could eventually be delivered more cheaply from off-earth resource miners - telerobotics has advanced. Planetary Resources plans to mine Near Earth Objects using telerobotics:

“2,000 Apply for Jobs Building Asteroid-Mining Robots”
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6. Reduced land use.
   SSP uses almost no land since farming could be done under the elevated mesh rectenna.

Credit: MAFIC Studios
A New Alternative - Space Solar Power (SSP)

7. Environmentally safe - SSP ground receiver (rectenna) has benign power levels, within all regulatory limits.

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8. Reduce hazardous nuclear waste and nuclear weapons/materials proliferation to terrorists.

SSP keeps the nuclear material at a much safer distance – 93 million miles.

and in a broader sense . . . .
9. Minimize our environmental impact.

Existing energy production methods have wide environmental impacts. SSP appears to minimize that impact, since generation takes place at the sun.

SSP would permit virtually endless clean energy growth in energy consumption and eventually off-earth development, commercialization and civilization.
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10. Keep energy costs low.

The leading energy alternatives, such as wind, and ground solar are higher in cost. Japan’s SSP electricity is projected to cost customers eight yen (nine cents) per kilowatt-hour, six times cheaper than its current cost in Japan.[**]

A Japanese government panel has recently recommended adoption of a 52 cents/kwh 20 year feed-in tariff for solar.
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11. Not only lower cost generation but lower cost access. A transmission grid based on the central generating station model is simpler, more reliable, and lower cost than rebuilding to a distributed generation model. To meet California’s 33% RPS goal, ratepayer bills will rise drastically by 2020, not just from renewable energy’s higher cost, but also from CA-ISO’s required transmission upgrades:

![High-voltage Transmission Access Charge Chart]

- 2001: $0.00
- 2011: $4.00
- 2020 (Forecast): $18.00
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12. Simple to export and implement.

SSP could be easily exported anywhere in the world. Existing local, regional or national utilities are the natural delivery and contracting agency for SSP. Existing utilities provide the massive customer load SSP naturally delivers to with currently available technology. They would build and own the rectenna, which would be part of their transmission grid, in partnership with an international “Sunsat Corporation”. As the electric grid continues to be extended, it becomes even more easily extensible. SSP will both facilitate and benefit from this effect. Baseload, or high capacity factor plants have high T&D utilization, unlike distributed generation’s lower utilization and higher cost.
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13. Expand the economy.

SSP takes advantage of our historic investment in aerospace and other technical expertise to increase STEM jobs. SSP technology is near-term-available using a multitude of current technologies vitally relevant to building SSP, including:

- space transportation
- wireless power transfer
- environmental science
- materials science
- telerobotics
- photovoltaics
- control systems
- micro-electronics
- space environmental weather
- aerospace engineering
- space communications
- electromagnetic launch
Finally, our dream substitute should provide a high energy density fuel alternative for transportation. Oil supplies over 90% of the energy for world transportation.

SSP’s electric power, water and air could make fuels such as anhydrous ammonia, and isobutanol or other fuels using carbon based blends. Ammonia is 111 octane, with the same energy as methanol. It fueled the X-15 rocket plane. We have been making liquid ammonia for 50 years for farming and moving it in pipelines. - Source, Ammonia Fuel Association: http://www.nh3fuelassociation.org

Bio-fuels could not keep pace with our expanding transportation energy requirements.
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Boeing’s Subsonic Ultra Green Aircraft Research (SUGAR Volt) Hybrid Electric Aircraft concept (~2030) would:

- reduce fuel burned by 70% compared to current aircraft.
- have a shorter takeoff and better wings
- turbojets that could be battery powered during most of the flight.
Space Solar Power Characteristics

15. Eventually a Sunsat Corp could provide much of its own “rocket fuel” through ion-drives and electromagnetic launch:

Electromagnetic Aircraft Launch System (EMALS), a launch system designed for Aircraft Carrier Class CVN-21 now under construction:
http://www.defenseindustrydaily.com/emals-electromagnetic-launch-for-carriers-05220/
How to proceed?

A public/private Congressionally chartered corporation has all the requisite advantages.

Comsat Corp., chartered in 1962, opened space for communication satellites - when we knew little about space, rockets or space communications. Communication satellites are now a $250+ Billion industry per year.

The “Sunsat Act” would accomplish the same task, creating a space solar power corporation and industry of much greater size.
This legislation would provide a launch “subsidy” to new private or public/private businesses, such as SunSat Corp, which are contracting for space transportation. This subsidy would be in the form of stock transfers and loan guarantees.

Sunsat Corp. would require thousands of flights per year. Launch prices would be pushed below current prices once subsidies established a high market volume:
US could start SSP construction just as Japan has done

No US company(s) or agency(s), is now prepared to assume the immense financial risk of initiating SSP construction.

There are simply too many engineering, financial, regulatory and managerial risks for any group we have been able to identify to undertake SSP today.

You can’t order your Sunsat yet.
Ground solar (or wind) to SSP conversion ratio

A PV panel at GSO will collect about 9.6 times as much power per square meter per year as an average location in the continental US and require less maintenance. To store the sun or wind, to make it 24/7 like the grid, how long do we need to store it?

To store power to compensate for just one day, suppose we have a 1 MW ground PV or wind power unit that over some days stores 24 MWH into our CAES. When it has been thus loaded, we can then get about 6.48 MWH generated by the CAES when we want it, since the best existing CAES is about 27% efficient operationally.
<table>
<thead>
<tr>
<th>Storage Type (See footnotes)</th>
<th>$/kW</th>
<th>$/kWh</th>
<th>Hours</th>
<th>Total Capital, $/kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressed Air Energy Storage</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large (100-300 MW Underground storage)</td>
<td>590-730</td>
<td>1-2</td>
<td>10</td>
<td>600-750</td>
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<tr>
<td>Small (10 - 20 MW Above ground storage)</td>
<td>700-800</td>
<td>200-250</td>
<td>3</td>
<td>1300-1550</td>
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<tr>
<td><strong>Pumped Hydro</strong></td>
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<tr>
<td>Conventional (1000 MW)</td>
<td>1300</td>
<td>80</td>
<td>10</td>
<td>2100</td>
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<tr>
<td><strong>Battery (10 MW)</strong></td>
<td></td>
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<td></td>
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<tr>
<td>Lead Acid, commercial</td>
<td>420-660</td>
<td>330-480</td>
<td>4</td>
<td>1740-2580</td>
</tr>
<tr>
<td>Sodium Sulfur (projected)</td>
<td>450-550</td>
<td>350-400</td>
<td>4</td>
<td>1850-2150</td>
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<tr>
<td>Flow Battery (projected)</td>
<td>425-1300</td>
<td>280-450</td>
<td>4</td>
<td>1545-3100</td>
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<tr>
<td>Lithium ion (small cell)</td>
<td>700 - 1250</td>
<td>450 - 650</td>
<td>4</td>
<td>2300 - 3650</td>
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<tr>
<td>Lithium ion (large cell, projected)</td>
<td>350 - 500</td>
<td>400 - 600</td>
<td>4</td>
<td>1950 - 2900</td>
</tr>
<tr>
<td><strong>Flywheel (10 MW)</strong></td>
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<tr>
<td>Superconducting Magnetic Storage</td>
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</tr>
<tr>
<td>commercial</td>
<td>3360-3920</td>
<td>1340-1570</td>
<td>0.25</td>
<td>3695-4313</td>
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<tr>
<td><strong>Supercapacitors</strong> (Projected)</td>
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<td></td>
<td>250 - 350</td>
<td>20,000 - 30,000</td>
<td>10 sec</td>
<td>300 - 450</td>
</tr>
</tbody>
</table>

1. In this table, Total Capital Cost = $/kW + (Number of Hours x $/kWh)
2. All figures are rough order-of-magnitude estimates and are subject to changes.
3. Total capital costs include power conditioning system and all equipment necessary to supply power to the grid. Not included are battery replacement costs, site permitting, interest during construction and substation costs.
4. These costs are for the hours shown ±25%.
5. Cost may vary depending on the price of commodity materials and location of project.
33% RPS by 2020 ?


<table>
<thead>
<tr>
<th>1 MW CAES Plant</th>
<th>1 MW Fossil Plant</th>
</tr>
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<tbody>
<tr>
<td>8,200,000 BTU</td>
<td>10,000,000 BTU</td>
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<tr>
<td>(2403 kWh) plus</td>
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</tr>
<tr>
<td>4,600,000 BTU</td>
<td></td>
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<tr>
<td>(natural gas)</td>
<td></td>
</tr>
<tr>
<td><strong>12,800,000 BTU</strong></td>
<td><strong>10,000,000 BTU</strong></td>
</tr>
<tr>
<td>27% Efficient</td>
<td>34% Efficient</td>
</tr>
</tbody>
</table>
Can ground solar (or wind) run our grid?(cont.)

It may take 4 days of sun to get 24 MWH. We need 14.8 of avg. sunny days to store our 24 MWh to cover a sunless 24 hour day. That is for just one 24 hour day.

(Note - CAES uses natural gas to make most efficient use of the cold compressed air to generate the power, but PV or wind cannot provide gas so it still depends on a fossil fuel.)

Approximately 50% of space solar’s PV output will get to the grid, so that 9.6 factor is reduced to 4.8 ;

Attempting to make terrestrial PV or wind “dispatchable“ using the best available storage technology, we have shown by comparison that SSP provides 71 times (= 14.8 x 4.8) more dispatchable baseload energy.

(This assumes that we can perfectly predict the weather and the cost of CAES storage equipment is zero, since we don’t know how long storage may be required.)
Prices drop as flight rate increases
Red dots are Elon Musk, SpaceX, $1300/lb and Roger Angel’s $20/lb (Sandia electromagnetic launch)

More Flights, Lower Cost

Cheap Rides? Falcon9, Dnepr, Kistler, ISRO Avatar, ?
Commercial Space Transportation Forecasts show a flat launch market. SSP must incentivize the orbital launch market it needs to lower launch costs to close the SSP business case.

SSP is the only market large enough to do this. It won’t happen with business as usual - we need the Sunsat Act.
Continuing - since space transportation is expensive we want to find high performance photovoltaic cells.

PV efficiency alone is not the right goal we want to increase the power output for the same weight carried to orbit.

Space qualified thin-film solar cells in the fabline today can provide 16,800 Watts/Kg. These are adequate specifications to begin SSP design and/or construction now.
Photo courtesy NASA, and ManTech-SRS Technologies
ASTRO Captures NextSat

On July 23, 2007, for the first time ever, a satellite autonomously rendezvoused with and captured another orbiting satellite, pioneering future robotic work in space. ASTRO (Autonomous Space Transport Robotic Operations), part of Boeing’s Orbital Express system, successfully demonstrated advanced on-orbit satellite refueling and reconfiguration capabilities with NextSat. ASTRO, the robotic, on-orbit spacecraft mechanic, successfully captured NextSat. Orbital Express is a DARPA program which has validated on-orbit satellite servicing technologies.
SkyWorker
an autonomous robot to build multi-kilometer size space structures

Credit – Red Whitaker, CMU Robotics,
http://www.frc.ri.cmu.edu/projects/skyworker/temp/skyworker2.mpg
Space assets must be defended from junk!

- A dead Russian satellite collided with an Iridium satellite on Feb 10 shocked world satellite community. The crash was not predicted by the U.S. military or private trackers, underscoring the vulnerability of U.S. satellites.
- The Air Force tracks more than 20,000 objects in space, but the actual number of objects is much greater.
- "Our goal is to do conjunction assessment for all 1,300 active satellites ... by the end of the year and provide that information to users," Gen. Chilton told reporters. About 500 of those satellites are not maneuverable.
- We must have an active defense against meteorites and other Near Earth Objects!

- Washington, Nov 3, 2009, by Andrea Shalal-Esa; editing by Alan Elsner and Chris Wilson © Thomson Reuters 2009. All rights reserved.
www.reuters.com/article/rbssTechMediaTelecomNews/idUSN0351968920091103