Space Solar Power's antecedent Technical, Environmental, Economic and Energy Crunch

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President, Space Solar Power Institute
Space Solar Power Workshop, Ga Tech

www.solarsat.org
www.sspi.gatech.edu
Since a Space Solar Power Station would be 90 times farther away and it is about 90 times greater diameter it would subtend the same angle and would be about the same size and brightness as the ISS to an observer on Earth.
SSP would use no land since farming could be done under an elevated mesh rectenna. Prof. Durgin’s group is demonstrating research on the technology (Poster outside).
The chart above illustrates the world energy consumption from 1965 to 2013, with an emphasis on the increasing trend of energy consumption. The data is sourced from BP World Energy 2014, and the chart is created by Gail Tverberg, Director of Energy Economics, OurFiniteWorld.com.
Looking Back

"The world has made no progress over the past 20 years in reducing the carbon content of its energy supplies, despite over $2 trillion of investment into renewable-energy projects such as wind and solar power."

- "Scant Gains Made on CO2 Emissions, IEA Says, WSJ

Instead - Global CO₂ levels continue to increase more rapidly.
CO2 Emissions From Energy Use Continue To Rise

Emissions by region

Billion tonnes CO₂

IEA 450 Scenario

Energy Outlook 2035 © BP 2014
Latest $\text{CO}_2$ reading
December 13, 2015
402.41 ppm

“Effective control of rising CO2 is not financially feasible for even large electric power generation companies, using currently available technologies and RPS constraints. These companies and customers are not "capable ofshouldering heavy substantive and procedural burdens. (EPA wording)" as their visceral connection to global economies prohibits deploying grossly non-economic and reliability-reducing power generation technologies. Space Solar Power is required to effectively address rising global CO2.”

- Summary statement for Atlanta EPA Public Hearing
  November 19, 2015
Oil production has faltered, even as capex has soared.
Capex productivity has fallen by a factor of five since 2000.
Observed decline trend now approaching 5% per year.
High oil prices lead to RECESSION

Economist James Hamilton has shown that oil price spikes connected with 10 out of 11 recent US recessions! Our global and U.S. economy is dependent on stable and reasonable energy prices, especially oil, which directly affect commodities costs.
The inflation-adjusted net worth for the typical household was $87,992 in 2003. Ten years later, it was $56,335, a 36 percent decline. The average electric power bill increased 42% between 2003 to 2013.

### Table 1. Wealth of American households before and after the Great Recession (in 2013 dollars)

<table>
<thead>
<tr>
<th>Percentiles</th>
<th>2003</th>
<th>2007</th>
<th>2009</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>337,233</td>
<td>423,592</td>
<td>411,178</td>
<td>308,276</td>
</tr>
<tr>
<td>5th</td>
<td>-9,749</td>
<td>-13,482</td>
<td>-27,689</td>
<td>-27,416</td>
</tr>
<tr>
<td>25th</td>
<td>10,129</td>
<td>6,966</td>
<td>2,723</td>
<td>3,200</td>
</tr>
<tr>
<td>50th (median)</td>
<td>87,992</td>
<td>98,872</td>
<td>70,801</td>
<td>56,335</td>
</tr>
<tr>
<td>75th</td>
<td>302,221</td>
<td>367,959</td>
<td>302,412</td>
<td>260,405</td>
</tr>
<tr>
<td>90th</td>
<td>736,853</td>
<td>934,223</td>
<td>819,824</td>
<td>763,099</td>
</tr>
<tr>
<td>95th</td>
<td>1,192,639</td>
<td>1,629,133</td>
<td>1,420,304</td>
<td>1,364,834</td>
</tr>
</tbody>
</table>

*Source: Panel Study of Income Dynamics (based on 2013 early release data);*
Food Costs

ALL four monthly food plans which the USDA tracks increased by more than 50% from 2000 through 2015. (family of four data plotted)
The current wave of Arab wars began with the “Arab Spring”, whose #1 cause was the rising price of food. ISIL’s war is basically over control of Iraqi oil fields.
In Black & Veatch’s latest survey of the US Electric Power Industry, Reliability jumped to #1. Each category touches a potentially very costly issue. Since the Electric Power Industry is the most capital intensive business on the planet, these costs and issues will impact everyone and continue to point the way to why we need Space Solar Power!

<table>
<thead>
<tr>
<th>Position</th>
<th>Issue</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>Reliability</td>
<td>4.64</td>
</tr>
<tr>
<td>2.00</td>
<td>Environmental Regulation</td>
<td>4.50</td>
</tr>
<tr>
<td>3.00</td>
<td>Economic Regulation</td>
<td>4.31</td>
</tr>
<tr>
<td>4.00</td>
<td>Cybersecurity</td>
<td>4.27</td>
</tr>
<tr>
<td>5.00</td>
<td>Natural Gas Prices</td>
<td>4.20</td>
</tr>
<tr>
<td>6.00</td>
<td>Long Term Investment</td>
<td>4.17</td>
</tr>
<tr>
<td>7.00</td>
<td>Aging Infrastructure</td>
<td>4.16</td>
</tr>
<tr>
<td>8.00</td>
<td>Physical Security</td>
<td>4.09</td>
</tr>
<tr>
<td>9.00</td>
<td>Natural Gas Fuel Supply Reliability</td>
<td>4.06</td>
</tr>
</tbody>
</table>

Top 10 Industry Issues - Respondents rated from 1 to 5 the importance of electric industry issues. 1 indicates Very Unimportant and 5 indicates Very Important. This chart shows the mean rating of each issue by utility respondents.
#1 Reliability

Energy Return On Investment (EROI) = how many BTU’s of energy are brought to market per BTU invested.

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.
Natural Gas Prices

Henry Hub Natural Gas Spot Price

Source: U.S. Energy Information Administration
Natural Gas Prices

Between 1999 and 2004, the US electric power industry built **200,000 MW** (about “4 Californias” worth of generation capacity or almost 10% of all US generation) of natural gas fired generation. Natural gas was **cheap** - $2 to $3 per Million BTU. By Dec 2005 the price soared above $14 per Million BTU and US electric power consumers were burned. The DOE then retracted their estimation that Mexican natural gas would remain cheap.

Natural gas has now, once again, entered that “cheap” range.
The average electric power bill increased 42% between 2003 to 2013. But natural gas prices declined by the same amount during that period, which ought to have reduced prices!

When will natural gas prices rise $400% again, as they did ten years ago?
No company(s), countries or agency(s), are yet 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.

No Utilities can order a Sunsat yet.
How to proceed?
Comsat Corp, a public/private corporation chartered in 1962, opened space for communication satellites - when we knew nothing about space, rockets or space communications. Communication satellites are now a $300+/year Billion industry. The “Sunsat Act” would accomplish the same task, creating a space solar power corporation and industry of far greater size.

The first US aerospace company, Northrup Grumman has now thrown their hat in the SSP ring, signaling that the checkered flag has just dropped for the US Sunsat competition!!
WHY SPACE SOLAR POWER (SSP)?

1. LOW CO2 INTENSITY
2. ZERO FUEL COST
3. USES NO WATER
4. CLEAN, NO WASTE
5. SOLAR @ GEO COLLECTS 9.6 TIMES MORE ENERGY THAN ROOF TOP SOLAR
6. RELIABLE: 24 / 7, WEATHER INDEPENDENT
7. REDUCED LAND USE
8. UNLIMITED ENERGY
A New Alternative - Space Solar Power (SSP)

1. Low CO$_2$ emission intensity:
Climate Change - nutritional (1)

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 CO₂.

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 CO₂.
• 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. www.plantsciences.ucdavis.edu/Faculty/bloom/bloom.htm
**Topic #5: Biosphere and Climate**

**Learning Objectives**

Upon successfully completing this topic's activities, you will be able to:

- Explain how elevated CO$_2$ levels influence plants.
- Describe the effects of elevated CO$_2$ on food quality.
- Understand the potential effects climate change will have on a many species and why.
- Discuss the effects of increased temperatures on a wildlife, pathogens, and humans.
- Consequences of elevated CO$_2$ on water availability and acidification of water.

**Videos**

- **Carbon Dioxide Sensing.** This video describes how organism sensing of carbon dioxide affects organism life cycle and geographic distribution.
- **Organisms.** This video gives more examples of species responses to temperature change, including wine grapes, disease vectors, and humans.
- **Precipitation/Salt.** This video discusses how anticipated changes in precipitation and salinity will influence many organisms.
- **pH.** How the acidification of the seas from rising CO$_2$ levels influence marine life.

**Textbook Readings**

- Chapter 5: Biological Impacts of Higher Carbon Dioxide Concentrations.
- Chapter 6: Climate Change and the Biosphere.

**Supplementary**

- **Food Quality by Bloom.** A magazine article about the instructor’s research.
- **Encyclopedia of Earth: Biosphere, Ecosystem Disturbance, Species Shifts.** An encyclopedia entry that covers some basic issues with anticipated effects of climate change on species.

- **Prof. Arnold Bloom, Univ. California, Davis**
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6. Should be dispatchable, or “baseload” - reliable.

SSP would be available 24/7. In full sun - 99.3% capacity factor at GeoSynchronous Orbit (GEO). They are not pseudo-random intermittent like wind or ground solar, so this provides a much greater increase in both total energy delivery and energy security or reliability. Light rain does not reduce energy delivery, but very heavy rain can reduce it by about 3 - 8%.
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Ground solar (or wind) to SSP conversion ratio

If we compare a Sunsat collecting about 9.6 times as much power per square meter per year as an average rooftop PV installation in the continental US and want 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>
</tr>
<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>
</tr>
<tr>
<td>Pumped Hydro</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional (1000 MW)</td>
<td>1300</td>
<td>80</td>
<td>10</td>
<td>2100</td>
</tr>
<tr>
<td>Battery (10 MW)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<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>
</tr>
<tr>
<td>Flow Battery (projected)</td>
<td>425-1300</td>
<td>280-450</td>
<td>4</td>
<td>1545-3100</td>
</tr>
<tr>
<td>Lithium ion (small cell)</td>
<td>700 - 1250</td>
<td>450 - 650</td>
<td>4</td>
<td>2300 - 3650</td>
</tr>
<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>Flywheel (10 MW)</td>
<td>3360-3920</td>
<td>1340-1570</td>
<td>0.25</td>
<td>3695-4313</td>
</tr>
<tr>
<td>Superconducting Magnetic Storage commercial</td>
<td>200-250</td>
<td>650,000-860,000</td>
<td>1 sec</td>
<td>380-489</td>
</tr>
<tr>
<td>Supercapacitors (Projected)</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?

How? CAES (Compressed Air Energy Storage), the lowest cost energy storage is actually a natural gas plant “in disguise”, burning natural gas with the decompressed air stream.

<table>
<thead>
<tr>
<th>1 MW CAES Plant</th>
<th>1 MW Fossil Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>8,200,000 BTU</td>
<td>10,000,000 BTU</td>
</tr>
<tr>
<td>(2403 kWh) plus</td>
<td></td>
</tr>
<tr>
<td>4,600,000 BTU</td>
<td></td>
</tr>
<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.)

On average, it takes about 4 days of full sun to get 24 MWH. We need 14.8 of those days to store 24 MWh in order to power 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 be provided to the grid, so the factor of 9.6 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.)
We need to cut launch to orbit prices down to about $150 per lb. Elon Musk’s SpaceX is leading the market charge to do this with reusable commercial launch vehicles (RLV):

The United Launch Alliance, the Pentagon’s old primary launch supplier, is developing a new Vulcan rocket powered by a reusable engine designed by Blue Origin. Japan’s government has instructed Mitsubishi to cut the cost of Japanese rocket in half, and China is planning a new family of kerosene-fueled Long March rockets and “Stimulated by SpaceX’s work on reusable rockets,” reports SpaceNews, Airbus is developing a reusable first stage for Europe’s Ariane. – WSJ, June 12, 2015, http://www.wsj.com/articles/spacex-and-the-russian-rocket-mess-1434149145
Rockets for Space Solar Power (SSP)

"The payload penalty for full and fast reusability versus an expendable version is roughly 40 percent," Musk says. "[But] propellant cost is less than 0.4 percent of the total flight cost. Taking into account the payload reduction for reusability, the improvement is therefore theoretically over a hundred times." This would drop the cost per kg for his Falcon Heavy rocket to just $10. That, however, requires a very high flight rate, just like aircraft," Musk says. - “Elon Musk on SpaceX’s Reusable Rocket”, Feb. 7, 2012, http://www.popularmechanics.com/science/space/rockets/elon-musk-on-spacexs-reusable-rocket-plans-6653023
A New Alternative - Space Solar Power (SSP)

10. Space Solar Power is estimated to have an EROI of 300 or higher, using thin-film photovoltaics and reusable commercial launch vehicles (RLV). Achieving that EROI depends on cutting launch to orbit prices down to about $150 per lb. to orbit. Elon Musk’s SpaceX, is leading this race:

"The payload penalty for full and fast reusability versus an expendable version is roughly 40 percent," Musk says. "[But] propellant cost is less than 0.4 percent of the total flight cost. Taking into account the payload reduction for reusability, the improvement is therefore theoretically over a hundred times."

A New Alternative - Space Solar Power (SSP)

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 Activities in China

Li Ming, Hou Xinbin, Wang Li
China Academy of Space Technology (CAST)

International Space Development Congress 2015
CANADA Toronto (May 21, 2015)
Recent Advances and Development Trends of Space Solar Power Station

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Abstract—The concept of Space Solar Power Station (SSPS) has been invented for almost five decades. As a promising way for providing primary power supply to the earth, there have been great attention and numerous researches. Particularly, several concept schemes have been proposed and remarkable technological achievements made. This paper reviews the progress of SSPS briefly, with some typical schemes presented. Moreover, a novel scheme named SSPS via Orb-shape Membrane Energy Gathering Array (SSPS-OMEGA) is presented. The paper also concludes some development trends, which will lead to SSPS economically and technologically viable.

Keywords—Space solar power ; Space solar power station ; Photovoltaic ; System configuration ; WPT ; Coupled problem
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www.solarsat.org
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IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE)
Dec 14-16, University of Central Florida, Orlando, FL

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Government and industry panels
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