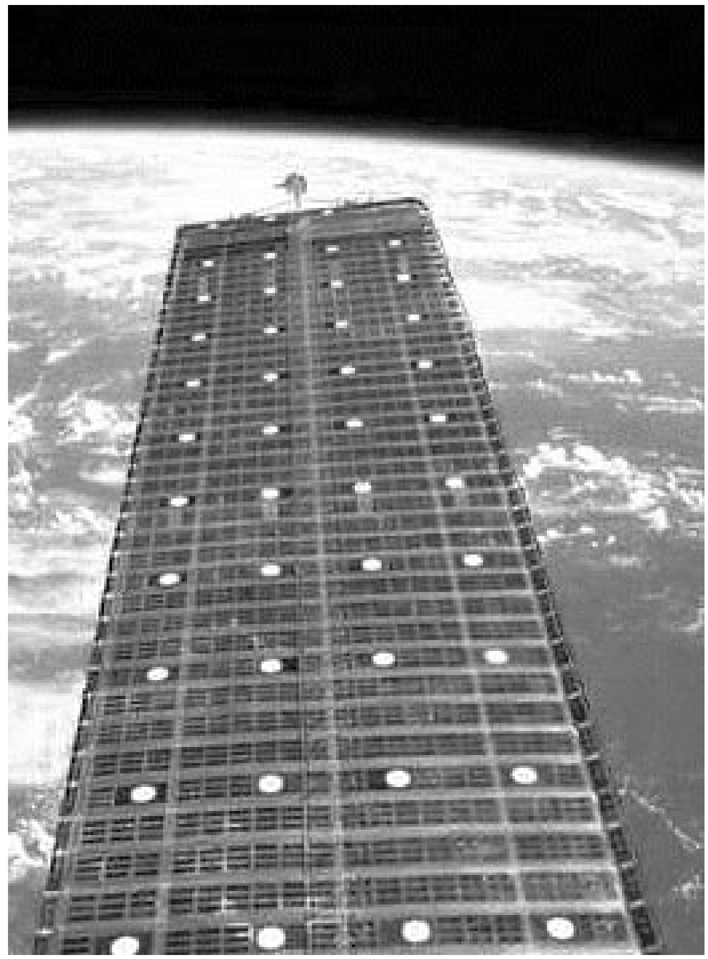
Space-Based Solar Energy

A Brief Review and Analysis

Introduction



Energy is one of the most fundamental components of nature. Energy demonstrates its importance in human society from calorie-filled food at dinner to wars over oil in the Middle-East. The beauty of energy is embodied in the simple glow of a flame or a gentle ripple from a leaf falling upon water. Its ugly face is seen in the pollution caused by utilizing fossil fuels, processing nuclear fuel, and manufacturing solar cells.

Philosophy and beauty aside, energy is indispensible to human life. Society has become dependent upon fossil fuels which are increasingly scarce and expensive to extract. Yet, continuing to burn fossil fuels could worsen the proposed greenhouse effect and perpetuate urban smog.

Nuclear fuel produces worries about dangerous radiation. Earth-based solar energy is popular for use in remote locations and for mobile applications, but is still economically uncompetitive for most consumer, industrial and transportation requirements. It is no wonder there is a renewed interest in space power satellites (SPS) which would cleanly collect and transmit solar energy from space to the Earth for conversion into electric power. This report briefly explores solar power technology as well as SPS concepts and a few selected proposals. For additional information, see "References", p. 8 for information about obtaining a copy of our indepth report.

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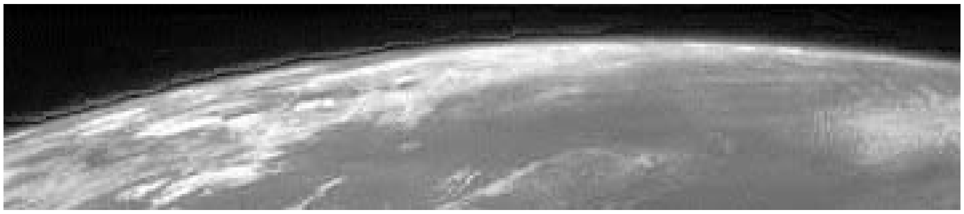
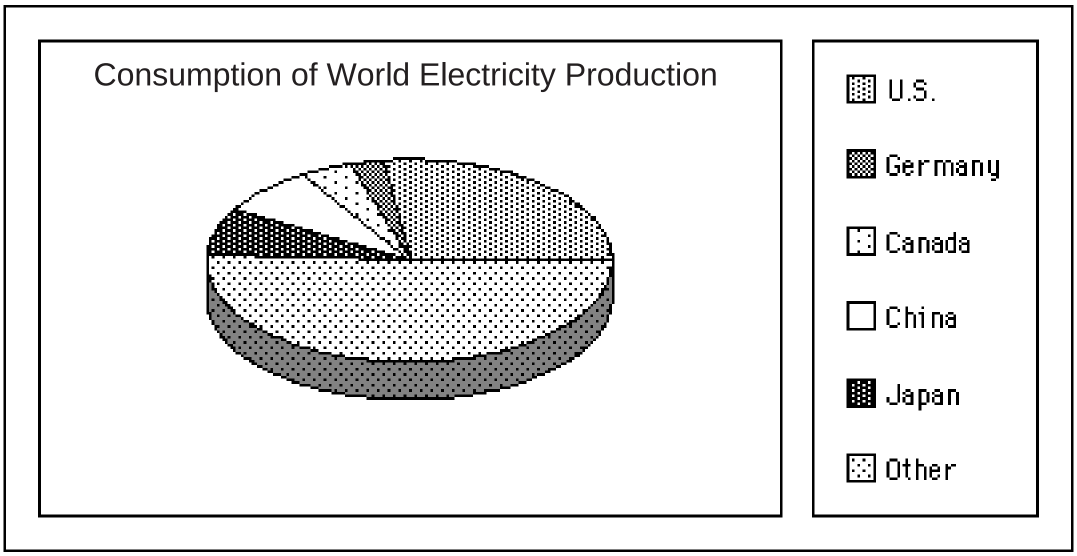


World Energy Consumption

The United States consumes over 27% of the world's electricity production as seen in the pie chart of world electricity consumption below.



Energy consumption figures are shown in the following chart along with population figures for top consumers as well as a sample of other countries.

World Energy Situation (Jul 1995 Est.) Source: En. Inf. Adm.

Country:	Pop.	% of World	Coal	% of World	Elec.	% of World	Petrol.	% of World
	Millions 1997 Est.		M Sh Tons		B kW hrs		K Bar/Day	
U.S.	268	5%	941	18%	3163	27%	17725	25%
Russia	148	3%	303	6%	760	6%	2976	4%
China	1222	21%	1490	29%	881	7%	3331	5%
Japan	126	2%	140	3%	864	7%	5711	8%
Germany	84	1%	298	6%	473	4%	2875	4%
Canada	30	1%	59	1%	462	4%	1755	3%
U.K	59	1%	79	2%	301	3%	1845	3%
France	58	1%	26	1%	365	3%	1896	3%
Brazil	166	3%	19	0%	288	2%	1491	2%
India	967	17%	312	6%	367	3%	1575	2%
Egypt	65	1%	1	0%	43	0%	460	1%
World Total:	5800		5120		11767		69926	

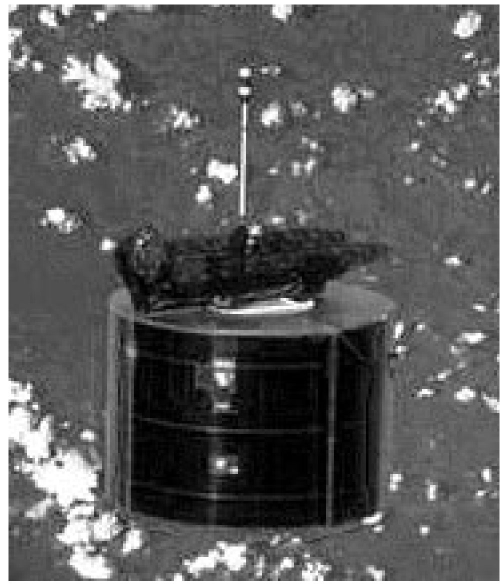
Earth-Based PV Technology

Photovoltaic cells convert light into electric energy. Originally intended for satellites, such cells are also used on Earth for powering consumer electronics (calculators), mobile devices (portable highway signs), remote applications (medical facilities in rural areas of developing countries), as well as self-sufficient locations (mountain cabins). The efficiency of a cell usually refers to the percentage of energy from light falling onto the cell that is converted into electric energy.

Type	Description	Advantages	Disadvantages
Single--crystal Silicon	A doped wafer formed from a slice of single silicon crystal	• Good Efficiency: 15% to 20% • Durability for outdoor uses	• Need for high-grade silicon crystals makes this material expensive to produce; costs $4.00 per peak Watt
Poly-crystalline Silicon	A thin ribbon of polycrystalline silicon cut into pieces then doped	• Moderate efficiency: 10% to 14% • Less expensive to produce than single-crystal silicon material	• Requirement for high-grade (though not single-crystal) silicon makes this material moderately expensive to produce; costs $3.90 per peak Watt
Amorphous/ Thin Film	Thin films of semiconductors deposited on glass or other transparent substrate	• Inexpensive for use in small, low-power cells; popular for small consumer elctronic devices • Can be deposited on inexpensive substrates, such as glass	• Low current output • Low efficiency: 5% to 9% • Degrades after only a few months in sunlight which results in a 10% to 15% output loss
Gallium Arsenide (GaAs)	A compound semiconductor made of gallium (Ga) and arsenic (As)	• Highest conversion efficiency of any PV cell: 25% to 30%	• The difficulty of producing suitable crystals of GaAs makes this the most expensive type of material
Spherical	Small silicon spheres upon aluminum substrate	• Inexpensive - can be produced without high-grade silicon.	• This material is still under development
Dynamic	Solar concentrator upon a mechanical heat engine (not photovoltaic; cited for comparison)	• Good economies of scale. • High conversion efficiencies (one system has a 30% efficiency)	• Expensive minimum costs • Higher maintenance required • Often not suitable for small applications

Analysis of Contemporary Space Power Systems

Solar power has already been used extensively by satellites and space stations, from systems involving a few Watts to nearly 100 Kilowatts.



Satellites

Most satellites are powered by sunlight falling upon photovoltaic (PV) cells which directly convert light into electricity. Power levels range from a few Watts to a few Kilowatts. Most satellites are used for communications and Earth observation.

Skylab

The first U.S. space-station, Skylab was built with two large and four small panels of PV cells. One large panel was damaged during Skylab's deployment due to mechanical factors, but the other panels functioned properly, providing about 20 Kilowatts.

Mir

A multi-module Russian space-station (to be replaced by ISS) powered by photvoltaic panels at about 25 Kilowatts. ISS solar cell technology is being tested on Mir.

International Space Station (ISS)

Several scenarios have been proposed for powering the ISS, including: (1) 75 Kilowatt pure photovoltaic; (2) 93 Kilowatt pure photovoltaic; and (3) 75 Kilowatt, partly PV and partly dynamic (with reflectors). The present scenario is for ISS to have a 105 Kilowatt power system comprised of about a dozen PV arrays when completed.

Non-Photovoltaic

A tether (Italy) suspended in Earth orbit from the space shuttle produced an electric current (due to E&M fields from Earth), but was mechanically difficult to handle. While of use for spacecraft, it is probably not useful for SPS due to drag it could create.

Reducing the Cost of Space Power Systems

At present, all space power systems are fabricated on Earth and launched into space. Launch costs exceeding US $2000 per pound add greatly to the cost of space power systems. However, for very large systems such as those proposed for SPS, it may be economically advantageous to produce parts of these systems from materials mined from asteroids and the Moon, which could significantly reduce transport costs.

SPS Demonstration Projects

Some progress has been made towards demonstrating the technical feasibility of SPS components as well as further developing SPS-related technology.

Achieved

Solar energy collection and conversion

• **Dynamic Reflector System.** Similar to terrestrial solar dynamic systems (such as Barstow), a solar collector heats a mechanical engine which generates electricity. NASA tested a 2 kW system in a large thermal/vacuum facility with a simulated sun at Lewis Research Center. This system was originally intended for possible use on the International Space Station but has been considered for SPS proposals as well.
• **Advanced Phtovoltaic Technology.** NASA tested advanced solar panels on the Mir space station.

Wireless Power Transmission

SPS systems require a way to move power from space to the Earth. Unlike from the local coal-burning electric plant, you can't have a wire running from space to your house! Most SPS scenarios utilize microwave beaming. Several successful beaming demonstrations have been undertaken.
• **Goldstone**. In 1975, 30 Kilowatts were beamed over a distance of 1 mile with a rectenna efficiency of 82%.
• **MINIX**. In 1983 MINIX (Japan) sent a beam of power through the atmosphere.
• **ISYMETS**. In 1993 ISYMETS (Japan) beamed 832 Watts of power between two spacecraft.

Planned / Proposed

Power Relay Satellites (PRS)

Suggested demonstration is for a PRS that would transmit 4 GW from Venezuela to Spain to be built 15 years from now. A PRS network could provide access to large-scale renewable energy sources worldwide as well as possibly creating a global electric power "grid" (resulting in a global market for electric power).

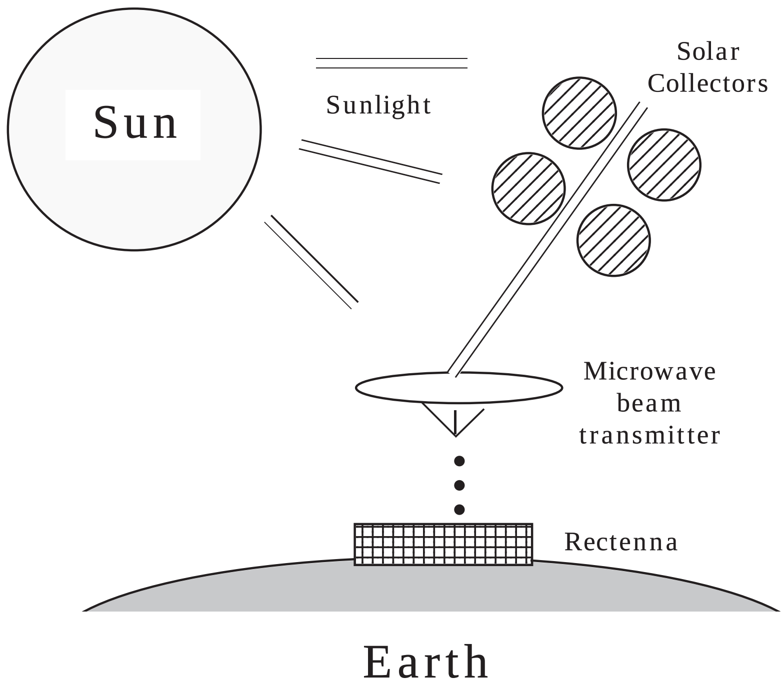
Solar Aquaculture Demonstration Project

Aquaculture is unlikely to generate electric power in sufficient quantities for SPS but may provide a key part of regenerative life support for SPS personnel in space. NSPRI has been working on a demonstration model of a sunlight-driven aquaculture chamber which could provide oxygen production / CO_2 absorption as well as food for astronauts someday.

Introduction to Large SPS

Since 1967, Solar Power Satellites (SPS) have proposed to collect solar energy in space and beam it down to the Earth. With the energy crisis of the early 1970's, SPS was seriously considered as an alternative to producing electric power from fossil fuels (during the 1970s, petroleum was used to produce a significant fraction of the U.S. electric power supply). With worldwide demand for electric power increasing as well as concern growing over urban smog and the greenhouse effect, SPS is again attracting mainstream interest.

There are sevaral advantages to SPS. Solar radiation can be more efficiently collected in space, where it is roughly three times stonger than on the surface of the Earth and it can be collected 24 hours per day (since there are no clouds or night in high Earth orbit). SPS does not use up valuable surface area on the Earth and can be beamed to areas with the highest demand at any particular time.



Functional diagram of SPS system (not to scale!)

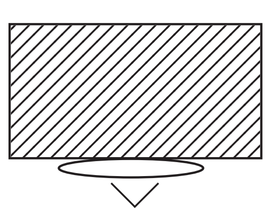
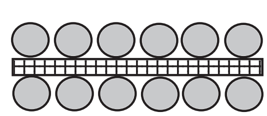
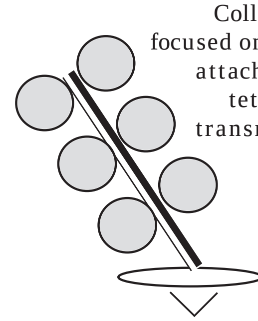
Most of these systems would utilize photovoltaic (PV) cells similar to those on Earth-based systems (such as those used by home power systems and highway sign panels). Others would utilize reflectors and mechanical collectors similar to those used in special large-scale solar facilities in France and the California desert (Barstow). Some PV systems would also use reflective concentrators.

Most of these systems collect solar energy in space and transmit it via a microwave energy beam to an Earth-based rectenna which converts the beam into electricity for use on Earth. Microwave beams have a fairly low wavelength (lower than visable light) and do not appear to pose any danger to the Earth's atmosphere. In fact, telephone companies have been beaming microwaves through the atmosphere for over thirty years without any known problems.

High launch costs, which can run roughly between $1,000 to $10,000 per pound, are the greatest barrier to the development of SPS. Most SPS proposals require launch costs of about $200 per pound to compete with your local utility company. However, growing demand for electric power could outstrip traditional production capability, driving prices up to the point where SPS would be competitive. If limits on producing electricity by burning coal (in order to reduce pollution) are enacted, SPS could become competitive even earlier.

Matrix of SPS Proposals

There are many SPS proposals. Three of these are discussed in the following matrix.

Proposals	Reference System	Empower-ment	Sun Tower
Features Brief Description	Classic SPS proposal (1979) utilizing a giant array of PV cells as-sembled by hundreds of astronauts in low-Earth orbit (LEO) and trans-ported to Geosynchonous Orbit (GEO).	12 dynamic reflectors from an early Interna-tional Space Station (ISS) design (see demo.s on p.5) on a truss (1992).	Pairs of reflectors with advanced PV focus (non-dynamic) attached to a tether backbone with reflector facing the Earth.
Proposer	Derived from P. Glaser's con-ceptual work by DOE et al.	Mark Reiff	John Mankins, NASA
Type	Photovoltaic (PV): giant arrays of PV cells	Dynamic: Brayton Cycle Solar Dynamic Power Generator Modules	Photovoltaic (PV): concentrators focusing upon advanced PV material
Specs Output Orbit Cost Lifetime	• 5,000 MW • Assemble in LEO; operate in GEO • $250 billion to 1st pow-er for a single satellite • Perhaps 20 years	• 0.3 MW • Assemble in LEO; operate in GEO • At least $2 billion • Perhaps 10 to 20 years	• 50 - 400 MW (depends on how many pairs of collectors) • LEO / MEO (6000 km) • $10 billion to 1st power • Perhaps 10 to 20 years
Pros/Cons Pros (incl.core adv.) Cons Brief Evaluation	• Less than 200 re-quired for entire U.S. power requirements • Good economies of scale • Not modular • High start-up costs • Highly sensitive to launch costs Large scale could make it useful as Keynsian-type economic stimulator.	• Technology exists • Relatively low start-up cost • Launch costs possibly higher due to mass of dynamic components Empowerment is a fairly inexpensive and low risk proposal for a first SPS facility.	•"Organic" design mimics nature • Lightweight components • Demonstrations of tethers in space have had technical difficulties in terms of deployment and control Use of innovative technolo-gies such as inflatible concentrators and tethers may reduce sensitivity to launch costs.
Rough Diagram of Concept	Large PV array attached to transmitter 	Collectors focused upon dynamic engine attached by truss to transmitter 	Collectors focused on PVs, attached by tether to transmitter 

Conclusions

Due to high launch costs, SPS is still more expensive than Earth-based solar power and other energy sources. Yet, even now, a small SPS system could be economically justified to provide otherwise unavailable emergency power for natural disaster situations, urban blackouts and satellite power failures.

References

References for this report can be found in our background report which can be obtained from our web site (www.nspri.com) or in hard copy form on a cost-basis (write to our address found at the bottom of page 1 for details).