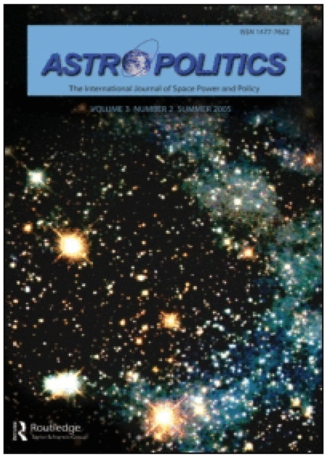

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SOLAR POWER BEAMED FROM SPACE

DONALD RAPP
Independent Contractor

Solar power satellites to beam electric power down to Earth from orbit, or the Moon, is a concept that can potentially provide the world with clean energy. However, the technical, environmental, political, and legal challenges are great. The size and scope of the solar arrays needed by SPS are orders of magnitude beyond the scope of any solar arrays ever used in space missions. Assembly on-orbit is another major challenge. The cost to transport mass to geostationary Earth orbit would have to be reduced by a large factor to make this technology competitive. Furthermore, the need to invest substantial capital for many decades before any payback will make financing of such ventures difficult. After an initial burst of enthusiasm in the late 1970s, further development of space power concepts has been sporadic. The concepts do not appear to be affordable or practical. The alternative of beaming power from the Moon has the potential advantage that the solar arrays could possibly be fabricated on the Moon from indigenous resources. Nevertheless, lunar solar power concepts suffer from many of the difficulties associated with solar power satellites in geostationary Earth orbit.

The burgeoning world population will demand more and more energy. Moreover, the goal of most of the people in less developed countries is to live a better life, which seems to require that they use up fossil fuels as fast as Americans do. Although world energy consumption has increased by a factor of about ten in the last hundred years, 70% of the world's population is still deprived of the benefits associated with adequate energy provision. For instance, about 33% of the world's population lives without electricity. United Nations (UN) figures suggest that the current world population of nearly six billion will approach ten billion by 2050—the bulk of the population living in developing and transitional economies. In this context, even the most constrained economic growth scenarios project an increase of 50% in the energy consumption by 2050 over the values in 1990. In a high growth scenario, this

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Address correspondence to Donald Rapp, Independent Contractor, 1445 Indiana Avenue, South Pasadena, CA 91030, USA. E-mail: drdrapp@earthlink.net

increase becomes three-fold.[1] There is little doubt that providing the world with energy, while preserving the environment, will prove to be one of the major challenges of the twenty-first century.

A wide variety of proposed solutions to future energy problems have been proposed, advocated, and even funded to a degree. Unfortunately, none of these are very satisfactory. Renewable energy concepts are likely to provide an increasing share of future energy consumption, but it remains uncertain how large that share can grow to. This background has provided the motivation for engineers to devise concepts for providing the world with its energy needs without pollution. That the need exists can hardly be denied. Whether such schemes can be made practical and affordable is uncertain.

Two imaginative possibilities for providing the world with a seemingly endless supply of energy include: (1) solar power satellites (SPS) to beam converted solar energy to Earth from space or the Moon; and (2) fusion reactors, possibly using lunar ^{3}He as a fuel.[2] Both of these concepts are characterized by potentially very high payoff, but the technical feasibility remains in doubt; the costs will be high, and the whole enterprise will take many decades of investment with no immediate return. At this stage, there is no benefit/cost ratio that can be realistically determined leading to a quandary as to the merits of further investments in such schemes.

In this article, the option of solar power from space is reviewed. Solar energy can be converted to electrical energy in space or on the Moon, and this energy can be beamed down to Earth in the form of microwaves or as laser beams. The original idea proposed by Peter Glaser in 1968 was subjected to a great deal of study in the late 1970s and has been further analyzed sporadically by a number of individuals and groups since then. It seems appropriate to take stock of the concept and summarize what has been done to date.

Solar Power Satellites in Geostationary Earth Orbit

The first concept reviewed herein entails a set of solar power satellites (SPS) operated in geostationary orbit (GEO) that convert solar energy to microwave energy, and beam this energy down to ground receivers where it is converted to electrical energy and distributed to the electrical power grid. Each SPS platform would beam enough power down to Earth to supply perhaps 1 gigawatt (GW) to 5 GW of electric power. It would require several thousand of these to provide the expected world demand for power by 2050. While many of the SPS studies were based on systems that provide all, or most, of the world's power needs, it is likely that such a technology might be phased in slowly to the energy supply mix.

GEO is located above the Earth's equator at an altitude of 35,786 km above mean sea level, where the period of the orbit is twenty-four hours. A spacecraft in such an orbit will remain above a single point on the equator. For a period of about a month centered on the equinoxes, GEO satellites enter their eclipse season, when they can spend some time near midnight of every day in shadow because the Earth lies in the path of the rays from the Sun. However, if there are a great number of SPS platforms in orbit surrounding the Earth, only those in the shadow of the Earth will be without power at any time. With an interconnected grid, this might not be an insuperable problem.

Mass and Cost

It is widely agreed that costs for launch and delivering to GEO will constitute a major part of the total cost of any SPS. These transportation costs depend directly on the mass that must be transported to space. Hence, the mass of a SPS is a critical factor in estimating the installation cost, which in turn, affects the viability of SPS concepts. Several SPS concepts have been put forward, but most of the detailed analyses of SPS were done on early concepts in the late 1970s. Furthermore, it is difficult to project the mass of systems that lie so far in the future. A NASA study[3] estimated the mass of a five GW SPS Reference System to be in the range 34,000 to 51,000 metric tons (MT). This was based on a system with an overall efficiency of 7% (i.e., 7% of the solar energy impinging on the arrays of the SPS ends up as power fed to the grid on Earth).

This implies that to provide 5 GW of power on Earth, 70 GW of solar power must be intercepted by a large solar array. Using the solar intensity at one Astronomical Unit (AU), about 1367 W/m^2 (watts per meter squared), suggests that the size of such a solar array is about 50 km^2 (kilometer squared) or 7×7 km. Assuming that the solar array has an efficiency of $\sim 13\%$, this would imply that it generates about nine GW (0.13 × 70 GW) of electric power in space. Current solar arrays have specific power of 50 to 80 W/kg (watts per kilogram). Some studies assumed that in the future, this may be increased to say, 400 W/kg using thin film arrays. With this assumption, a 70-GW array with a conversion efficiency of say 13% would weigh approximately 9×10^9 (W)/400 (W/kg) or 22,500 MT. The mass of the associated microwave antenna has been estimated to be about 13,000 MT, so the mass of a SPS to deliver 5 GW at Earth would be estimated on this basis to be about 35,500 MT without contingency allowance. Using currently available solar arrays, it would be a good deal higher.

Current costs to deliver mass to GEO are around forty dollars per MT, so the cost to merely deliver such a SPS to GEO would be a prohibitive at 1400 billion dollars.[4] Most advocates of SPS assume that launch costs can be reduced by factors of up to 100 in the future. With this assumption, the cost to deliver such a SPS to GEO would be reduced to fifteen billion dollars. However, the basis for assuming such reductions in launch costs is a generic expectation that costs go down as activity increases.

Launch and Assembly on Orbit

A number of alternate SPS designs have evolved since the late 1970s. Regardless of the specific design details, the technical and economic challenges in developing a SPS are launch, assembly, and orbit-raising. It is generally conjectured that the modular elements of SPS would be brought up to low Earth orbit (LEO) via multiple launches with a heavy lift launch vehicle (HLV) and assembled into a working unit in LEO. Subsequently, either the entire assembled SPS, or a major module of the SPS, would be carried up to GEO by a reusable launch vehicle (RLV), possibly using some form of solar electric propulsion. However, one study concluded that assembly in LEO is not feasible due to problems caused by radiation exposure and space debris.[5]

Two problems stand out in regard to launching the material required for SPS. One is the cost and the other is scheduling the large number of launches that would be required. The number of launches required per SPS depends on the mass of one SPS and the assumed lift capability of the launch vehicle. The number of launches per year depends on the previous two quantities plus the assumed rate at which SPS systems are deployed. It has already been noted that an estimate for the mass of a 5 GW SPS is about 35,500 MT based on significant advances in solar cell technology. While some studies have assumed that a HLV capable of lifting 400 to 500 MT to LEO will be developed, the 125 MT-to-LEO HLV presently being developed by the National Aeronautics and Space Agency (NASA) for human lunar and Mars missions is more realistic. Delivery of one 5 GW SPS would require about 280 launches with this vehicle. It is not clear how frequently such heavy-lift launches can be implemented from ground facilities, but it seems likely that they might be limited to an upper limit of perhaps one launch per month per launch site. If there were say, three heavy-lift launch sites, each capable of sending up HLVs at the rate of one per month, the entire set of 280 launches for one SPS could be carried out in about eight years. To send up an entire family of 4000 such satellites would take 32,000 years at this rate. Even with the assumed super HLV capable of lifting 500 MT to LEO, it would still require 6000 years to establish the entire fleet of SPS, although one could establish the capability for say, sixty GW of power on Earth in one century.

Relatively little work has been done on assembly of the SPS in space. An URSI study briefly examined several scenarios in which assembly was carried out in GEO or in a lower orbit.[6] Another scenario involves rapid transport of thin-film cells to GEO to avoid cell degradation by radiation. In these scenarios, assembly at lower altitudes (assembly at 500 km) is undesirable due to debris impacts. The debris problem can be avoided by carrying out assembly at altitudes above 3000 km. However it was concluded that the SPS should not be assembled at any altitude between 3000 km and 11,000 km due to degradation of the cells in the radiation environment. Other papers on the SPS seem to imply assembly in LEO. This remains an issue that requires further study.

Orbit Raising

The requirement for orbit-raising from LEO to GEO is a change in velocity (Δv) of 3800 m/s (meters per second). Using, for example, chemical propulsion (LOX/LH2) with a specific impulse of 450 s, the ratio of initial mass in LEO to payload delivered (one-way) to

GEO is about 2.5:1. One of the virtues of using chemical propulsion is the quick transfer that takes place in a single day.

In principle, a reusable solar electric propulsion (SEP) system could be used for orbit-raising and return. The spacecraft is spiraled out from the starting orbit to its destination. This approach minimizes the propellant required for the transfer, at the cost of increased transfer time. With its much higher specific impulse, the amount of propellant required would be greatly reduced. However, a number of issues would have to be dealt with:

- degradation of the solar cell performance when passing through the radiation belts;
- orbit-raising requires a very large solar array;
- developing and implementing high-performance ion thrusters;
- slow spiraling out of the SEP vehicle (several months required for transfer) creates time delays and operational scheduling difficulties;
- a fast "personnel taxi" powered by chemical propulsion would be needed to transport workers to GEO to avoid the radiation exposure with SEP; and
- the requirement for Xenon (Xe) propellant for SEP would far exceed world production levels.

While most SPS studies have assumed that reusable solar-electric orbit transfer vehicles would routinely drag huge masses from LEO to GEO, this approach is problematic. Orbit raising looms as a potential "show-stopper" for SPS as is launching to LEO.

Conversion to Microwaves and Microwave Transmission

A large phased array antenna with high efficiency must steer the power beam to a small rectenna target on the ground with a precision of 0.0005°. It is expected that the size will be of the order of a one or two km to transmit one to two GW at 2.45 GHz. It is typically assumed that the overall conversion efficiency, including all losses (e.g., in phase shifters, power circuits, and isolators) will be greater than 80%.

The rectenna located on the Earth receives the microwave power from the SPS and converts it to DC electrical power. An SPS rectenna sized to generate 5 GW of electricity at about 34°N latitude (corresponding to Los Angeles) would occupy an elliptical land area extending approximately 13 km north-to-south and 9 km east-to-west. The width of the rectenna area is essentially fixed, but the length, the north-south dimension will vary with latitude. Because the satellite will be in orbit directly above the equator, the circular microwave beam will project an ellipse on the Earth's surface anywhere except at the equator. The nominal dimension of a rectenna site including a buffer zone is estimated to be 17 × 13 km.

Environmental Impacts

There are many potential environmental impacts from SPS. These include: (1) effects of microwave radiation on the general public and SPS workers; (2) effects of ionizing radiation on space workers; (3) effects of SPS launch activities on atmosphere, weather, and climate; and (4) effects of SPS microwave power transmission on telecommunications. Environmental impacts have been assessed by NASA, involving work by various NASA Centers, universities, other government laboratories, and a few non-government organizations. While many good questions were raised, the assessments were apparently terminated prior to completion, and no answers seem to have been produced.[7]

Alternate Concepts

A number of alternative concepts have been proposed by Landis,[8] including use of non-tracking solar arrays for SPS in GEO, and locating SPS at the Sun-Earth point (L2). These offer some benefits but they do not appear to answer the fundamental questions regarding feasibility and affordability of SPS.

Beamed Energy from the Moon

There are many difficulties in the SPS concept, but the need to transport huge masses to GEO appears to be the most formidable impediment. Indeed, for a complete fleet of SPS to provide the entire world's energy, the required mass in GEO would exceed 100,000,000 MT, and perhaps several times that figure. Transporting that amount of mass to GEO is unimaginable in terms of implied launch facilities and the required frequency of heavy lift launches, not to mention the cost. But even a system to provide 5% of the world's energy, would weigh 5,000,000 MT.

To avoid the need to transport all that mass into space, Criswell has advocated locating the solar arrays on the Moon, fabricating solar arrays from indigenous resources on the Moon, and beaming power down to Earth from the surface of the Moon.[9] While that would greatly reduce the mass transported to space from Earth, it introduces a number of other challenges. In this concept, the Lunar Solar Power (LSP) System, uses ten to twenty pairs of bases, located on the east and west sides of the lunar hemisphere facing Earth with a similar number on the side facing away from Earth, to collect on the order of 1% of the solar power reaching the lunar surface. The collected sunlight is converted into many low-intensity beams of microwaves and directed to rectennas on Earth. Each rectenna converts the microwave power to electricity that is fed into the local electric grid. Criswell claims that the system could deliver the 20,000 GW or more of electric power required by 10 billion people.

Each lunar power base consists of tens of thousands of power plots distributed in an elliptical area to form a fully segmented, phased-array radar that is solar-powered. Each power plot consists of four major subsystems: (1) a solar array to generate electrical power; (2) buried electrical wires to carry the electric power to microwave generators; (3) microwave generators to convert electric power to microwaves of the correct phase and amplitude; and (4) screens that reflect microwave beams toward Earth. Because of the 2-week on/2-week off nature of lunar solar availability, such a base would operate on this 2-week cycle. To provide power during the 2-week dark periods, the array of bases on the side of the Moon facing Earth would be augmented by fields of solar converters located on the back side of the Moon, 500 to 1000 km beyond each visible edge and connected to the Earth-facing power bases by electric transmission lines. Alternate energy sources would be required on Earth for lunar eclipses.

Rectennas located on Earth between 60°N and 60°S can receive power directly from the Moon approximately 8 hours a day. However, power could be received anywhere on Earth via a fleet of relay satellites in high-inclination, eccentric orbits around

Earth. This enables each rectenna to receive power 24 hours a day. Although Criswell claims that the area of the relay stations would be less than 1% of the area of a GEO system,[10] Kulcinski provided an independent assessment of Criswell's concept and challenges this assertion.[11] Kulcinski pointed out that due to diffraction, the required product of transmitting and receiving antenna diameters for a lunar SPS is ten times that of a GEO SPS. His estimate of overall efficiency is 0.27%. For a 0.27% overall efficiency, it would require covering 15.3% of the lunar surface with sites to produce 20,000 GW on Earth. Such an enterprise appears more than daunting. Of course, it might take centuries to install such a system.

Solar Cell Technology

Several references discuss approaches for in-situ production of solar cells, as well as other products (e.g., aluminum, glass, iron, etc...) from lunar regolith. Landis discussed a number of difficulties involved in preparing solar cells on the Moon.[12] A conductor metal will be needed on top of the contact metal. For lunar produced cells, Landis indicates that the best choice will be aluminum. Yet, that entails producing aluminum in a useable form on the Moon.

For an amorphous silicon (Si) cell, a front transparent conductor is typically used rather than connecting directly to the silicon. Typical choices are not abundant on the Moon. Landis then goes on to point out that even radiation-tolerant a-Si cells will require at least a thin protection layer, or cover glass for radiation protection. There is also need for an adhesive between the cover glass and the cell, and adhesive technologies typically require organic materials not easily available from lunar sources. Alternatively, Landis suggests the front surface radiation protection can be same as the superstrate, if the cell is produced by a technology that deposits the silicon directly on glass in an inverted configuration. Landis suggests use of aluminum for interconnects and wiring, which also requires aluminum production and fabrication facilities on the Moon. Landis described his concept for extraction of Si and production of solar cells on the Moon using a fluorine process. However, the process requires many steps and involves toxic materials. The practicality of this approach is uncertain.

Land Use on Earth

Land use is discussed at length by Kotin.[13] As previously discussed, the dimension of a rectenna site is estimated to be seventeen by 13 km for 5 GW of electricity at 34°N latitude. The land area occupied by the entire installation would be about 200 km^2. Kotin hypothesizes an ensemble of sixty of these installations across the United States (U.S.) providing a total of 300 GW of electric power capability. Such a 300 GW system provides about 25% of future U.S. power needs. Based on 300 GW, the required total area for these sixty sites of five GW installations is roughly $60 \times 1{,}700 \sim 10^5\,\mathrm{km}^2$ or an area $300\,\mathrm{km} \times 300\,\mathrm{km}$. References [12] and [13] estimate an area of about 10% of this estimate due to use of smaller buffer zones.

Stated in the simplest possible terms, the objective of any land use/siting study is to answer the question, where can we put rectenna sites, and are there sixty sites in the continental U.S. where rectennas can be located? Several studies were carried out in the 1970s regarding these questions. Not all land areas are appropriate for siting rectennas because of topography, terrain, intense weather, drainage, flooding, location relative to population centers, seismic activity, communications interference, airline corridors, recreational needs, national forests, parks, bird flyways, and so on. Kotin discussed offshore rectennas.[14] They will, however, have a very high capital cost and a significant impact on shipping lanes. A Japanese proposal for a planned city under a suspended rectenna may be difficult due to fears of radiation. Thus, the siting of rectennas remains a significant open question.

Cost Estimates

It is well known that it is difficult to estimate the cost of a small space mission on the order of 1 billion dollars. As the years go by, it has found that all cost estimates are typically low and all projects overrun. To compensate, NASA requires that after preparing detailed cost estimates, mission proposals must tack on additional cost reserves to account for unforeseen factors that will inevitably drive up the mission cost. Such small space missions typically utilize mainly proven technology. We can then imagine how difficult it must be to estimate the cost of a futuristic enterprise, much greater in scope than a small space mission, which utilizes many new, unprecedented technologies and systems.

Two critical aspects of the SPS cost are: (1) future launch and orbit-raising costs per MT; and (2) mass of future solar arrays per kW generated in GEO. If one utilizes current data for these factors, the cost of an SPS is clearly unaffordable. However, a number of investigators have made various projections of significant future reductions in these quantities—and even then, the projected cost of an SPS is very high; although some have argued that under those assumed conditions it can become cost-effective.

GEO Cost Estimate Using Current Capabilities

Robert Zubrin has argued against the cost effectiveness of the SPS using current technology capabilities.[15] Based on a 50% transmission coefficient from solar-generated electric power in space to power at the buss bar we can estimate that the power generated by the solar array for a 2-GW SPS must be 4 GW. Current solar array technology can produce about 50 W/kg; therefore, the mass of the solar array using current technology is estimated to be 8×10^4 MT. If the remainder of the system is neglected, and only the solar array is included, the cost of delivering the solar array to GEO becomes the determining factor in the SPS cost. Zubrin estimated the current cost to deliver one MT of payload to GEO at 40 million dollars. Thus, the cost to deliver the entire array to GEO is $8 \times 10^4\,\mathrm{MT} \times \$40 \times 10^6/\mathrm{MT}$ or 3.2 trillion dollars. Zubrin suggested that the total cost of the entire SPS system, when all the other subsystems are included, might be about double this value or roughly 6 trillion dollars. He then went on to show that the cost of the SPS is several thousand times the cost of conventional power plants, and the annual interest alone on a 3 trillion dollar investment would be unaffordable. The fact that terrestrial power plants require fuel would not affect the conclusion substantially. The bottom-line cost of electric power to the consumer would be over a thousand times the cost from conventional sources.

Future Transport and Solar Array Costs

Advocates of the SPS concept have projected significant reductions in future launch and orbit-raising costs. Reference [16] states that published SPS cost estimates are based on a launch cost of \$150/kg. However, these estimates remain controversial. For example, present-day launch and space assembly costs are greater than two orders of magnitude higher than the desired \$150/kg. While NASA expects launch costs to decrease by a factor of 100 by 2025 and by a factor of 1000 by 2040, ESA [European Space Agency] is less optimistic. In a corresponding report, ESA assumed transportation costs of \$1500/kg. However, in the same report it was suggested that transportation costs may be reduced to \$200/kg in the future. Fetter argued that launch costs must be less than \$200 to \$460 per kg to enable SPS as compared to the current cost to low-Earth orbit of about \$10,000 per kg.[17] Thus, it is claimed that launch costs must fall by a factor of 20 to 50 simply to allow SPS to break even with terrestrial solar power. However, Criswell suggests that launch costs would have to be reduced by a factor of 10,000 to make SPS competitive.[18] Reference [7] emphasized that many of these goals for launch costs and for system mass and cost must be significantly lower if the system is to produce competitive terrestrial power. Reference [5] echoed this by saying that launch costs are the single most important parameter in assessing the economic viability of solar power satellites.

NASA studies have assumed that future launch costs will diminish sharply with increasing activity. Reference [19] said that no concept-unique Earth-to-orbit transportation system is required, beyond that necessary to achieve extremely low launch costs (on the order of \$200 to \$400 per kg). Non-NASA papers have also made similar assumptions. Hoffert suggested that orbit-capable scramjet/rocket hybrids may be feasible at launch costs of \$200 to \$400/kg.[20] Reference [21] treated the launch cost as a parameter. With current launch costs of 10,000–20,000 EUR/kg pay load at current transport mass capacities of 100 MT per year, they assumed that learning curves would effect cost reduction for payload transportation of 20% with each doubling of mass capacity. In their analyses, a European study considered launch costs as low as 323 EUR/kg.[22]

Hoffert[23] suggests that reductions occur in many technology classes from learning-by-doing and research, and that innovation can change the game entirely akin to what is assumed with Moore's Law.[24] He emphasized the danger that overly conservative approaches based on extrapolated economics, as opposed to inventions and system based on physics, may miss potential solutions. He said that a potentially fatal failure for any high-tech civilization faced with existential threats is "failure of imagination." Hoffert also presented a figure prepared by Ivan Bekey showing launch costs dropping from \$20,000/kg to \$2/kg from 2010 to 2030 based optimistically on Moore's law and assumed learning curves.

The point of controversy here is that some would argue that as the business of frequent heavy-lift launching expands, there will be a "learning curve" and through mass production, unit costs will diminish with time. Some of this is undoubtedly true. It must also be remembered that much of the cost savings in microelectronics resulted from placing more features per unit area on a chip, rather than by reducing the innate cost of producing a chip. No such parallel exists for launching and orbit-raising. While it is likely to be overly pessimistic to use current launch costs in projections for a mega-program like SPS some half a century hence, estimates of a few hundred dollars per kg to LEO range seem to be unlikely.

Cost Reductions

The simple estimate of solar array mass and cost to deliver unit mass to GEO, based on current technology, that was given previously suggests that the product of these two factors must be reduced by a factor of over 1000 to bring down the cost of the SPS so that it can provide electric power at rates competitive with conventional schemes. Zubrin supports this viewpoint.[25] However, a number of analyses have been carried out by various investigators that claim that the required reduction in launch cost is less extreme. A complete economic analysis of a hypothetical SPS, and its comparison with conventional power plants, is a complex topic requiring a great deal of effort. This discussion is relegated to transportation costs. There are also significant development and operations costs. Typically, the bottom line figure is the cost per kW of electric power, which presently for conventional power plants is of the order of \$0.05 per kW.

Reference [11] quotes several ESA studies. One ESA study claims that the power generation cost would be \$0.20/kw if the "transportation cost" was reduced to \$1500/kg and the specific power of the array was 200 w/kg.[26] This would suggest that a factor of 4 reduction in array mass, and a factor of 7 reduction in launch cost would bring SPS electric power costs down to about 4 times that of conventional power—thus implying that an overall reduction factor of $4 \times 7 \times 4 = 56$ would make the SPS competitive. Fetter compares the SPS to terrestrial solar power—[27] that is not necessarily a concern here, since the issue is to compare the SPS with conventional electric power, but some insights are provided by the analysis. This reference concludes that the cost of transporting one kW of solar array from the Earth to LEO must be less than $1000 to match the $1000 cost per kw of a terrestrial system. Of course, when the remainder of the system (other than the solar array) is taken into account, this would likely drop to perhaps $500. Thus, the transportation cost from Earth to GEO would have to drop from $40,000 to $100 to $200 per kg to make the SPS competitive according to this method. Based on fuel costs, Fetter[28] concludes that the minimum conceivable future cost for delivery to 1000 km orbit is $250/kg, while Zubrin[29] concludes that the minimal conceivable future cost to deliver payload to GEO is of the order of $300 to $400 per kg. But, these estimates are rather speculative. Criswell[30] says: “To achieve this margin, launch and fabrication costs would have to be lowered by a factor of 10,000.”

Cost Estimates for SPS

Reference [31] emphasized that current overall cost estimates for the SPS and its major components are highly uncertain. The assessments of up-front costs range from $40 billion to $100 billion. The NASA reference design calls for a 22-year investment of $102.4 billion (1977 dollars), including transportation and factory investment costs to produce the first 5 GW satellites, with each additional satellite costing $11.3 billion. Based on past experience, it is expected that such estimates will be low—possibly very low. Reference [12] goes on to say that opponents believe these cost estimates are unrealistically low, and the cost of SPS would significantly increase as SPS is developed—as in other aerospace projects and the Alaskan pipeline. Most opponents also do not believe that SPS will be cost competitive and argue that the amount of energy produced by SPS would not justify its large investment cost.

Landis “reinvented” the SPS as a system at Lagrange point L2 because of technical and economic difficulties with the GEO SPS concepts.[32] He argued that “even with extremely optimistic assumptions of system cost, solar cell efficiency, and launch cost, each design [of the 'Fresh Look' study[33]] ... results in a cost which is either immediately too expensive, or else yields a cost marginally competitive with terrestrial power technologies, with an internal rate of return too low for investment to make money. Only if an "externality surcharge" is added to non-space power sources to account for the economic impact of fossil-fuels did space solar power options make economic sense.

Cost of a Lunar Solar Power System

In order to produce one GW at Earth, a lunar site is required with area of 300 km^2, of which about 20% is covered by solar cells. To supply the ultimate 20,000 GW of power envisaged by Criswell[34], these figures can be multiplied by 20,000. The cost of such a system (together with associated relay satellites and ground systems on Earth) is difficult to predict. One important cost will likely be the cost to transport equipment to the Moon. Zubrin[35] estimates that the cost to transport materiel to the Moon is about 5 times the cost to transport materiel to LEO; hence he suggests a current cost of $50,000 per kg for delivery to the Moon. How much that can be reduced in the future is uncertain.

Kulcinski[36] quoting a 1996 paper by Criswell, provided mass and cost estimates based on a ten-year ramp-up to a 20,000 GW system. The estimated cost, in 1995 U.S. dollars, was $5,000 billion for space systems, and $17,000 billion for Earth installations, for a total cost of $22,000 billion. At current rates of $50 per MT to deliver material to the Moon, the cost of annual deliveries of 1.7×10^5 MT would be $9,000 billion. In terms of invested capital per unit power, the figure is $1100 per kW capacity ($\$22 \times 10^{12} \times 20 \times 10^9$ kW), which is not attractive. In addition, the reliability of these mass and cost estimates are unclear.

In general, the advantage of locating the solar conversion systems on the Moon is that the solar arrays, representing up to 67% of the total mass delivered to GEO in a GEO SPS, can be manufactured on the Moon, thus saving a factor of 2 or 3 compared to positioning the arrays in GEO. Even though the arrays on the Moon need to be much larger—because the lunar solar collectors average out to 32% solar availability whereas the GEO solar collectors have almost 100% solar availability—this may not be a detriment if they are manufactured on the Moon. In addition, the transmitting antennas on the Moon need to be larger because of diffraction effects over the greater distance. Since the transmitting antenna in a GEO SPS represent more than 1/3 of the mass on orbit, it is likely that it would also have to be manufactured on the Moon to provide a cost advantage to the lunar solar power system. Criswell was not clear on this point.

Financing

Hickman provides an extensive discussion of capitalization of very large futuristic space projects.[37] This reference points out that popular science writers typically describe the benefits to be derived from their favorite very large space development project in detail, but their treatment of the crucial initial capitalization of such projects is typically sparse or implausible. The crucial problem for these projects is capitalization because the total capital investment required is very large and the investment takes a very long time before producing economic returns. Such investments are unattractive to most private investors and lenders. He argues that very large space development projects are best understood as massive public works projects, and despite the libertarian sentiments in much of the popular science writing on very large space development projects, government would likely have to play a large role in capitalizing such projects.

Hickman goes on to ask why investors would risk the enormous sums necessary to realize these dreams? He says that space development enthusiasts typically respond to this question indirectly by itemizing the likely economic benefits derived from space *after* the capital investments necessary to open the frontier have been made. He points out that the technology and personnel for very large space projects are less in doubt than is the necessary capital investment. Hickman concluded that "very large space development projects are probably too unattractive as investments for private investors and lenders."

A Congressional Office of Technology Assessment (OTA) Report[38] discussed difficulties with private involvement. An initial investment of $40 billion to $100 billion over 22 years—with additional much larger investments to build a complete system—would be unprecedented for private-sector financing of a single project. Especially in the first years, borrowed funds would be available, if at all, only at prohibitively high interest rates. Stocks and bonds would be unlikely to attract large investors when profitability lies some 30 years in the future. Both institutional investors and large corporations allocate only a small proportion of their funds for high-risk long-term projects; in some cases, such as pension funds, there are legal limitations on high-risk investments. A SPS system will require a great deal of political support both locally, nationally, and internationally: land-use conflicts, monopoly considerations, environmental standards, tax incentives, and radio frequency allocations are a few of the political issues that SPS will need to confront. The OTA report also discusses difficulties with federal involvement in such a large long-term project, suggesting that financial and management problems are likely to ensue. These include: (1) lacking a profit motive and the discipline of responsibility to owners and stockholders, there is less incentive to reduce costs; (2) civil service regulations can interfere with hiring and firing and limit salary ranges, decreasing flexibility, and making it difficult to retain personnel; and (3) annual government funding produces uncertainties and leaves programs vulnerable to political pressures and "earmarked" compromises.

Political Issues and Space Law

Some of the fundamental political and legal questions include: who owns space; who regulates what is placed in GEO; and who owns the Moon?[39] SPS will be a world project having vast international and national legal ramifications. Success of a SPS program will depend on the skill with which a legal framework is established for construction and operation. It is necessary to examine SPS in light of current international political and legal matters, including specifically international space law and national space legislation. However, such a study is rendered somewhat futile because: (1) SPS will absolutely require new laws and treaties; and (2) dealing only with space law is inadequate since SPS will engage all aspects of law.

In 1959, the UN General Assembly established as a permanent body the Committee on the Peaceful Uses of Outer Space (COPUOS), which today has sixty-four member states. COPUOS drafted the five major international space law instruments—the *Outer Space Treaty, Rescue Agreement, Liability Convention, Registration*

Convention, and the *Moon Agreement*—that govern space activities. In addition to COPUOS, important decisions on frequency allocations and orbital positioning are made by the International Telecommunications Union (ITU). Furthermore, a private international institution with a scientific focus on space is the Committee on Space Research (COSPAR) of the International Council of Scientific Unions (ICSU). International space law bears directly on the uses of space or the Moon by SPS.

- Treaty on the Principles Governing the Activities of States in the Exploration and Use of Outer Space including the Moon and Other Celestial Bodies (or Outer Space Treaty), which entered into force in 1967. This treaty establishes a framework for international space law; provides that space shall not be subject to national appropriation, that exploration and use of space shall be for the benefit of all countries ("province of all mankind"), limits military uses of space, and provides that space shall be used for "peaceful purposes."
- Convention on International Liability for Damage Caused by Space Objects (or Liability Convention), which entered into force in 1972. This treaty provides that the launching State is liable for damage caused by its space objects on the Earth's surface or to aircraft in flight and also to space objects of another State or persons or property onboard such objects.
- Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, 1979 (or Moon Agreement) elaborates on the Outer Space Treaty, provides that the Moon and its natural resources are "the common heritage of mankind," and that an international regime should be established to govern the exploitation of such resources when such exploitation is about to become feasible.

The U.S. is a party to the 1967 and 1972 agreements. As a chief proponent of these two major international legal instruments, the U.S. has sought to assure the full and free use of the space environment for all peaceful purposes. Thus, the space environment is open for the use of all who are able to use it. It cannot become an area subject to the sovereignty of a nation-state. The Liability Convention is intended to prevent against misuse of the space environment. It provides that monetary damages will compensate for misuse. Neither the U.S. nor any spacefaring nation has become a party to the *Moon Agreement.* Most space legal experts believe it should be either amended or abolished. The *Moon Agreement* applies as well to "other celestial bodies within the solar system."

Since all spacefaring states have freely used solar energy in space by equipping solar panels onto satellites or on the International Space Station (ISS) without any objection from other states, the utilization of space solar energy is internationally and customarily legal, even under the *Moon Agreement.* The outstanding international legal issues that might affect SPS development include: (1) jurisdiction over the placement of satellites in GEO; (2) provisions against environmental disturbances; and (3) military uses of space, as well as other aspects. In recent years a number of states located on the Equator have claimed jurisdiction over the geosynchronous orbit on the grounds that it is not part of "outer space" but is determined by the Earth's gravitation, and is a limited natural resource requiring national control. The equatorial states' claims have been rejected by the majority of other nations including the Soviet Union/Russia and the U.S. as legally and scientifically untenable.

Control over the orbit by a few states would prevent free and equitable access to a crucial position by space-capable countries. Nevertheless, there still remain problems of allocating positions and of deciding competing claims to scarce orbital slots. The question here is part technical and part legal: how much space is there, and what constitutes infringement? This is dependent on the state of technology, since "infringement" is not so much a problem of two or more objects trying to occupy the same place as of electromagnetic interference between nearby satellites. Since the acceptable limits vary with the size and type of SPS used, the size and type of future communications satellites, and advances in transmission technology, it is impossible to say at this time how many SPS could be built without unacceptable interference. Allocation of frequencies and positions has to date been the province of the ITU.

In 1979, at the ITU's World Administrative Radio Conference, the U.S. raised the question of allocating a frequency position for future SPS testing; the proposal was referred to a specialized study group for evaluation and future decision. Allocation decisions by the ITU have been characterized by debate over the "first-come first-serve" tradition, whereby first users have priority in the use of frequencies and orbital slots. Newly space-capable states as well as least developed countries (LDCs), and others who intend to develop such capabilities in the future, have urged since 1971 that all states have "equal rights" to frequencies and positions, and the ITU has called both the radio spectrum and the geostationary orbit "limited natural resources" that "should be most effectively and economically used." A number of LDCs have proposed that space be reserved for their future use. Since there is no legal basis for permanent utilization or ownership of positions, the possibility of future reallocation clearly has considerable support among LDCs. Established users such as the U.S. remain opposed to a priori assignment of slots and frequencies. Again, the ITU debate is part of LDC attempts to gain leverage. SPS development could be affected by attempts of disaffected states to block development by denying frequency allocations, or by making consent contingent on concessions by states with the most interest in SPS.

International law has not established international microwave exposure standards. Nonetheless, the *Liability Convention* has established international tort law rules. If microwave transmissions of energy from geostationary levels were to cause harm to plants, animals, and tangible items, the Convention would cover the subject. It is difficult to summarize the legal and political aspects of beamed solar power. Clearly, there are serious issues involved in allocating space in GEO or on the Moon to specific projects and countries, but perhaps more vexing problems would be caused by filling up atmosphere with microwave or laser beams with as-yet unclear impacts on biota. The ramifications if there is a system failure or an act of terrorism are difficult to imagine. It is perhaps not an exaggeration to suppose that the political and legal aspects may be as challenging as technical and economic aspects.

Conclusions

A multitude of issues hang over the SPS concept. These are summarized briefly below.

- It is not clear how many SPS can be safely placed into GEO.
- The greatest technical and economic challenge of the SPS concept is the problem of transporting huge amounts of mass to GEO. Two problems stand out in regard to launching the materiel for SPS. One is the cost and the other is scheduling the large number of launches that would be required.

- Orbit-raising from LEO to GEO is another major challenge for SPS. Use of reusable SEP vehicles has been proposed for this purpose, but this approach has significant problems. The viability of the SEP tug concept depends critically on use of hypothetical high-efficiency lightweight solar arrays that are likely to be difficult to develop, and lightweight propulsion components. Radiation would gradually diminish the efficiency of the solar arrays with each passage through the radiation belts.
- The size and scope of the solar arrays needed by SPS are orders of magnitude beyond the scope of any solar arrays ever used in space missions.
- Assembly on-orbit is another major challenge. On-orbit construction requires a massive construction facility in involving hundreds of astronauts working continuously over several decades. While most concept papers assume assembly in LEO and transport of the assembled SPS to GEO via SEP, Reference [4] claims that assembly in lower orbits is not viable due to space debris and radiation.
- Degradation of the solar cells and their optical coverings due to the space environment.
- Research planned by the U.S. Department of Energy (DOE) in 1979 on environmental effects does not seem to have been carried out to completion, leaving many uncertainties.
- In order for SPS to have any hope of becoming economically competitive, large reductions must be made in current launch and orbit-raising costs and the mass of solar arrays per kW generated must also be reduced significantly. It is not clear how feasible this will be.
- Of equal importance is the fact that no revenues are generated until the entire system is complete and operational. The very large cost-to-first power characteristic will be unattractive to investors.
- The outstanding international legal issues that might affect SPS development include: (1) jurisdiction over the placement of satellites in GEO; (2) provisions against environmental disturbances; and (3) military uses of space.

The problem with evaluating the prospects for SPS is that the benefit/cost ratio cannot be determined. While a number of authors have made specific cost estimates for SPS, these estimates require great future transportation cost reductions, and lack depth and detail. While some analysts have warned us against being overly conservative in predicting future cost reductions, and indeed that is a danger, the tendency seems to be greater in the opposite direction. A system that could potentially provide the world with almost unlimited power is too important to be treated with brief, simplistic evaluations that lack depth and substance.

On the other hand, the problems associated with the SPS concept for deployment in GEO appear to be so great as to cast great doubt on the whole enterprise. Chief among these are the requirements to lift huge masses to GEO, as well as the problems in scheduling heavy-lift launches. There are other problems as well across environmental, political, technical and economic factors. The need for making unprecedented large investments for many years with no return on investment looms as a potential show-stopper. Based on what is known at this point, the SPS in GEO concept does not appear to be affordable or practical. That does not necessarily mean that further study is not useful, but it does cast a shadow of doubt on the concept.

Beaming power from the Moon has the potential advantage that the solar arrays could possibly be fabricated on the Moon from indigenous resources. Nevertheless, lunar solar power concepts suffer from many of the difficulties associated with SPS in GEO. Furthermore, lunar solar power has not received the attention, analysis, and evaluation given to SPS in GEO. The fact is that lunar solar power requires a great deal more study. The elimination of the need to lift solar arrays from Earth appears to be an important tipping point in favor of the lunar approach, and based on the very incomplete analyses available today, it appears likely that the only form of beamed power that has even a small chance of becoming practical half a century from now is lunar solar power.

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