Online Journal of Space Communication

Volume 9
Issue 16 *Solar Power Satellites (Winter 2010)*

Article 23

Space Solar Power, Lunar Mining and the Environment

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Abstract

standards: one can stay warm in the cold, and cool in the heat. One can travel great distances, desalinate water and convert materials into useful products. However, power production involves substantial pollution. When making long-term energy investment decisions, it is worth considering which energy options can produce large quantities of power for long periods of time at the lowest possible environmental costs. Space Solar Power - when the space segment is built from lunar materials - may well be the best option for one simple reason: most of the work is done thousands of kilometers away from earth.

Introduction

Let's consider Space Solar Power (SSP) from an environmental point of view. Note that we are concerned with costs over many decades and centuries and financial costs are dependent on unpredictable factors on these time scales but environmental costs can be predicted from the physical characteristics of the system. Any SSP system will consist of satellites in orbit beaming power to antennas on earth. From an environmental point of view, the principal costs have to do with constructing and launching the satellites, the interaction of the beams with earth's atmosphere, and the construction and operation of the transmitting and receiving antennas.

The ground antennas are likely to be simple metal structures with some electronics. The metal in the antennas can be easily refabricated at end of life to make replacement antennas, so the mining and manufacture of the ground segment should have a relatively minor environmental impact. The receiving antennas block essentially all of the beam's radiation but typical designs allow most of the sunlight to pass through, so the land area under antennas can go wild or even be farmed. Thus, the antennas, while large (perhaps kilometers in diameter) and consuming a great deal of space, that same land can support natural ecosystems and food cultivation. Repair crews will need to enter such areas from time to time, but that can be accomplished with minimal disruption.

The power beam will be designed to interact with the atmosphere as little as possible. Interaction involves loss of power to the ground and therefore represents loss of revenue. While there is every reason to believe that the power beams will do little environmental damage, this has not been fully assessed and a rigorous environmental impact report will be needed before SSP development proceeds very far.

Unlike the ground antennas and power beams, an SSP satellite segment (the aggregated powersat infrastructure) large enough to deliver a substantial part of the 15 terawatts of power we use today may have significant environmental impact if launched from the ground. This 15TW figure includes all energy use, not just electricity, but with sufficient R&D and infrastructure development, electricity can in most cases be substituted for other energy forms, as with electrical cars. Also note that much of the world's population does not now have access to significant energy resources. These people are unlikely to accept that condition forever; thus, energy production will need to increase.

Ten (10) TW continuously supplied will provide somewhat more than half of today's energy use. This number will be used for our comparisons. Assuming a powersat mass of 5kg/kw, 40% end-to-end efficiency and 500 tons/launch using the large Sea Dragon booster (a large, robust, reusable, ocean-launched rocket design from the 1960s),[1] some 250,000 launches will be needed. Such an enormous number of launches from earth would dump a great deal of rocket exhaust into the atmosphere. In addition, when space structures are launched from earth, all the mining, processing and construction must take place on earth with the usual environmental costs. While there are ways to minimize the impact of lifting these satellites into space, for example using hydrogen/oxygen propellant which produces only water in the exhaust, from an environmental perspective it would be better to eliminate the launches altogether. These costs can be eliminated entirely by taking the lunar option.

The Lunar Option

At 5 kg/kw, some 125 million tons of satellite material will be required to produce 10TW of continuous power. Most of powersat mass will undoubtedly consist of metals for structure and mirrors and perhaps silicon for solar cells. As Figure 2-4[2] shows, metals and silicon are abundant in all lunar regolith (soil) sampled to date.

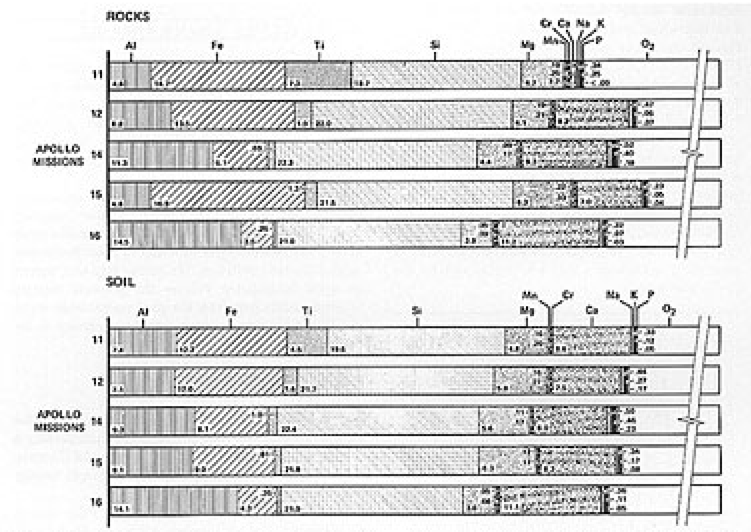

Figure 2-4. – *Average compositions of rocks and soil returned by Apollo missions, excluding oxygen (≈ 45%) and elements present in amounts less than 1000 ppm.*

(click image for larger view)

Plans for mining and processing lunar regolith have been developed.[3] Converting lunar regolith on the surface into powersats in orbit is an extremely demanding engineering problem, but that's the fun part. The pay off is eliminating the terrestrial environmental cost of the SSP space segment entirely, leaving only the cost of the power beam and the receiving antenna. These appear to have minor environmental impact relative to their contribution to developing a continuous non-polluting source of energy.

As the largest environmental impact of a non-fuel-based energy source is generally the construction and eventual disposal of terrestrial power plants, including mining and processing the materials, completely eliminating the environmental impact on earth of the most demanding portion of the system should give SSP built from lunar materials a substantial environmental cost edge over other systems. Those tradeoffs can also be calculated.

Alternative Sources vs. SSP

Consider the environmental impact of other power production technologies, such as oil, coal, natural gas, fission, fusion, ground solar, biomass, wind, tides and waves. Hydro and geothermal are taken out of this analysis as they have limited total energy production potential. All of these systems must be built on the ground and their materials mined, processed, and fabricated into their contributing parts. None of these systems are typically mass constrained, as satellites are, so producing 10 TW of power by any of them will require producing far more than 125 million tons of power plant. Furthermore, at end of life all this material must be either remanufactured or disposed of in the biosphere. It is safe to say that for any of these options, this environmental impact alone is as great or greater than SSP ground antennas. In some cases, such as disposing of irradiated components of nuclear power plants, it may be much greater.

Today's terrestrial solar cells appear to produce the equivalent of two watts continuously per kg of panel.[4] This means that five billion tons of solar cells would be required to generate 10TW of power. Furthermore, assuming a generous 50-year life, producing 10 TW of power requires that 100 million tons of solar cells annually must be manufactured and disposed of. Producing that same 10TW of power would require 10,000 one gigawatt (1GW) nuclear or fossil fuel power plants. Assuming a 50-year life, 200 new plants would have to be built and 200 decommissioned every year – almost one every day forever.

Oil, natural gas, and coal-powered plants all require a continuous supply of fuel, which must be extracted from the earth. These fuels must be processed and then burned releasing CO_2 and other, often more noxious, materials into the atmosphere. Maintaining a clean and healthy atmosphere, of course, is literally essential for our minute-to-minute survival. The environmental impact of these emissions is so great that entire forests and watersheds are put at risk by acid rain, millions of people are being sickened by urban air pollution, and there is substantial evidence that CO_2 emissions are noticeably warming the entire planet, especially the polar regions. Operation of solar power satellites produce no atmospheric emissions at all. Powersat beams will slightly warm a column of air, but even this effect can be minimized by the density of the beam and choice of the frequency used.

Fission also requires fuel, uranium in this case rather than carbon compounds. In addition to the environmental impact of uranium mining, processing and use, this fuel can be processed to provide material for nuclear weapons that can demolish whole cities and ecosystems, if used. The waste from fission power production is extremely toxic and long lasting, requiring long term, expensive and unpopular storage; at least in the case with currently operational plants. A successful terrorist attack on a fission plant could easily make its region unfit for human habitation for centuries, as has happened in areas near major nuclear accidents. Fusion power may reduce these problems, but after 60 years of research no credible design for a commercial plant exists, so the environmental effects are yet unknown.

Ground solar in large quantities uses a great deal of land. Covering roof-tops with solar collectors avoids this problem but is limited in the total power produced. Centralized solar plants carry a larger environmental cost since the ecosystems beneath solar collectors become completely devoid of solar inputs. Assuming 80 kw continuous power per hectare, producing 10 TW of energy would require over 12 million hectares of solar power plant, or a square 350 km on a side. Of course, the actual area removed from biological production would be less since rooftops already shade the ground completely. By way of contrast, the total area needed for solar power satellite antennas depends heavily on the desired power density, which is a variable design parameter at present. Assuming a power beam transmitting energy 50% of strong sunlight (400w/m^2) and 80% conversion efficiency, 10 TW of power on the downlink would require roughly 31,250 km^2

or a square 175 km on a side for safe reception on earth. Thus, the area required is significantly less and the environmental impact per m^2 is less as well.

Biomass is extremely inefficient as a way to harness solar energy. All the energy from biomass is derived from the sunlight falling on plants. The efficiency of plants converting sunlight into energy is typically a few percent (sugarcane is higher). There are also inefficiencies when converting biomass into usable energy so net efficiency is usually less than 1%. Solar cells, by contrast, are generally 10-20% efficient, or better. Of course, inedible biomass left over from food production and waste from timber production need not be as concerned about overall efficiency as it is produced anyway, but there is not nearly enough of this by-product to meet our energy needs. The production of energy from biomass has it's own environmental costs.

A typical 1MW wind generator in a good location can produce the equivalent of about 0.35 MW continuously. Thus, to produce 10 TW of energy would require roughly 28 million such windmills. Once built, assuming a 50-year life, these installations must be replaced at a rate of about 571 thousand per year. Like SSP antennas, most of the mass of a wind turbine is metal and can be fairly easily recycled into new turbines. The necessity of moving parts, however, means that lifetimes will be shorter.

Waves and tides are a promising source of energy, but the technology is currently underdeveloped and the environmental cost of operations is not well understood. For example, how disruptive will these applications be to sea life? Long lifetimes may be difficult to achieve for these types of technologies due to the corrosive nature of seawater and interference by sea life, a major problem for undersea cables today. In brief, sensible comparisons cannot be made at this time.

Ground solar, wind, tides and waves are all intermittent power producers and the energy they produce is not always available when and where needed. Since these sources are somewhat unpredictable, with the exception of tides, there must be mechanisms for storing some portion of the energy generated, and there must be ways to transmit it to off-site locations where demand exists. Calculating even a very gross measure of the environmental cost of storage is difficult, but storage will certainly not be free.

Space solar power generation has the opposite problem. SSP produces power almost 24/7 365 days a year. At geosynchronous orbit, there are only few hours of eclipse per year when a solar power satellite will not produce power. Thus, when solar power satellites are dedicated to providing all the energy needed for a given area on earth, there will at times be too much power. To a certain extent, this can be handled by directing powersat beams to other antennas. Otherwise, the energy must be thrown away, stored, or used for non-time-critical tasks such as desalinating water.

All of the terrestrial options require power to be distributed by wire from the place produced to the point of use. Each power source can only insert power into the grid at a single point. SSP, however, can redirect the power of satellites to different antennas as demand fluctuates. As long as the antennas are placed fairly near the point of use, the total need to deliver power over landlines should be substantially reduced.

Conclusion

When we examine the environmental costs of long term energy production, it is fairly clear that SSP infrastructures built from lunar materials will be far superior to coal, oil, gas, and nuclear. While space has certain advantages, ground solar, wind, waves may well be the most competitive in the short term. The wisest energy policy from an environmental perspective may be to encourage wind and ground solar, particularly on rooftops where no land is consumed, combined with a vigorous SSP development effort. In the long term, a combination of distributed, intermittent energy production by wind, solar, waves and tides and the large scale and constant 24/7 potential of SSP could prove best. When the space segment can be substantially built from lunar materials, the benefits of an ample energy supply with low environmental cost will be possible for the indefinite future.

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