Space Solar Power and the Environment

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Abstract

Large quantities of energy can make for substantial improvements in living standards: one can stay warm in the cold, and cool in the heat. One can travel great distances, desalinate water, convert materials into useful products and so forth. 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 (SSP) where 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

Consider SSP from a long term and strictly environmental point of view[1]. Any SSP system consists of satellites in orbit beaming power to antennas on Earth. From an environmental point of view, the costs are construction and launch of the satellites, interaction of the beams with the atmosphere, and the construction and operation of the antennas.

The ground antennas are simple metal structures with some electronics. The metal in the antennas can be easily remanufactured 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 antennas block essentially all of the beam's radiation but typical designs allow most of the sunlight to pass through, so the area under antennas can go wild or even be farmed. Thus, the antennas, while large (perhaps kilometers in diameter), will consume a great deal of land area but that same land can support a wild ecosystem or food production. Repair crews will need to enter this area 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 since any interaction involves loss of power to the ground and therefore 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

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[1] As we are concerned with costs long term (many decades or centuries), and the economic costs are dependent on many unpredictable factors on that time scale, we examine only environmental costs as they can be predicted from the physical characteristics of the system.

development proceeds very far.

Unlike the ground antennas and power beams, an SSP satellite segment (the powersats) large enough to deliver a substantial part of the 15-18 terawatts of power we use today[2] may have significant environmental impact if launched from the ground. Assuming a powersat mass of 5kg/kw, 40% end-to-end efficiency, and 500 tons/launch using the large Sea Dragon booster[3], to supply 10 TW[4] continuously would require 250,000 launches. This would dump a great deal of rocket exhaust into the atmosphere. While there are ways to minimize the impact, 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. In addition, if the space segment is launched from Earth, all the mining, processing, and construction must take place on Earth with the usual environmental costs. These costs can be eliminated entirely by taking the lunar option.

The Lunar Option

At 5 kg/kw we require 125 million tons of satellite to produce 10TW. Most of powersat mass will undoubtedly consist of metals for structure and mirrors and perhaps silicon for solar cells. Metals and silicon are abundant in all lunar regolith (soil) sampled to date[5]. Plans for mining and processing lunar regolith have been developed[6]. 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 antenna. As we have seen, these appear to be minor.

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[2] This figure includes all energy use, not just electricity. However, in most cases electricity can be substituted for other energy forms with sufficient R&D and infrastructure development, e.g., practical electrical cars. Also note that much of the world's population does not have access to significant energy resources and are unlikely to accept that condition forever. Thus, energy production needs to increase.

[3] The Sea Dragon is a large, robust, reusable, ocean-launched rocket design from the 1960s. See http://neverworld.net/truax/

[4] 10 TW continuously is somewhat more than half of today's energy use and will be used for our comparisons.

[5] R. Johnson and C. Holbrow, "Space Settlements: A Design Study," SP-413, NASA, 1975 http://www.nss.org/settlement/nasa/75SummerStudy/figure2.4.gif

[6] Mary Fae McKay, David S. McKay, and Michael B. Duke, "Space Resources: Materials," NASA SP-509
http://www.nss.org/settlement/nasa/spaceresvol3/toc.html

As the largest environmental impact of a non-fuel-based energy source is generally the construction and disposal of the plant, including mining and processing the materials, completely eliminating the terrestrial environmental impact of the most demanding portion of the system should give SSP built from lunar materials a substantial environmental cost edge over other systems. We now examine those tradeoffs.

Alternative Sources vs. SSP

Consider the environmental impact of other power production technologies: oil, coal, natural gas, fission, fusion, ground solar, biomass, wind, tides and waves[7]. All of these systems must be built on the ground and the materials for all systems must be mined, processed, and manufactured into the appropriate parts. None of these systems are typically mass constrained, as satellites are, so that 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 roughly the equivalent of two watts continuously per kg of panel[8]. This means 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 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 all require fuel. This is extracted from the Earth, processed, and then burned releasing CO_2 and other, often more noxious, materials into the atmosphere. The atmosphere, of course, is literally essential for our minute-to-minute survival. The environmental impact of these emissions is so great that entire forests have been put at risk by acid rain, millions of people have been sickened by urban air pollution, and there is substantial evidence that CO_2 emissions are noticeably warming the entire planet, especially the polar regions. SSP operations have no atmospheric emissions at all. The beam will slightly warm a column of air, but even this

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[7] We do not consider hydro and geothermal as they have a limited total energy production potential.

[8] Based on the specifications of Kyocera model KC200GT solar panel as advertised by Wholesale Solar.

effect can be minimized by the choice of the frequency used.

Fission also requires fuel, uranium in this case rather than carbon compounds. In addition to the environmental impact of these mining and processing operations, this fuel can be processed to provide material for nuclear weapons which, if used, will demolish whole cities. The waste from fission power production is extremely toxic and long lasting, requiring long term, expensive, and unpopular storage, at least with currently operational plants. A successful terrorist attack on a fission plant could easily make a substantial 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 there is no credible design for a commercial plant so the environmental effects are unknown.

Ground solar in large quantities uses a great deal of land. Covering roof tops with solar collectors avoids this problem, but if more power is needed then land use becomes a major environmental cost since the ecosystems beneath solar collectors become completely devoid of solar inputs. Assuming 80 kw continuous power per hectare[9], producing 10 TW of power would require over 12 million hectares of solar power plant, or a square 350 km on a side. The actual area removed from biological production would be less since rooftops already shade the ground completely. The total area needed for SSP antennas depends heavily on the power density which is a variable design parameter at present. Assuming a power beam with energy 50% of strong sunlight (800w/m^2 so the beam is 400w/m^2) and 80% conversion efficiency, 10 TW of SSP power would require roughly 31,250 km^2 or a square 175 km on a side. Thus, the area required is significantly less and the environmental impact per m^2 is less as well.

Biomass is really a fantastically inefficient 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. The net efficiency is usually far less than 1%. Solar cells, by contrast are generally 10-20% efficient or better. Of course, inedible biomass left over from food production need not be as concerned about overall efficiency as it is produced anyway, but there is not nearly enough of this to meet our energy needs. The production of energy from biomass, of course, has it’s own environmental costs.

A typical 1MW wind generator in a good location can produce the equivalent of

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[9] The 80 kw continuous equivalent per hectare figure uses data from the Wikipedia entry on solar power plants in the Mojave Desert; in particular, AV Solar Ranch One.

about 0.35 MW continuously[10]. Thus, to produce 10 TW would require roughly 28 million such windmills. Once built, assuming a 50 year life, these 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. The environmental cost of operations is not well understood, e.g., how disruptive will these technologies be to sea life? In addition, long lifetimes may be difficult to achieve due to the corrosive nature of seawater and interference by sea life[11]. In all, however, these technologies are not sufficiently well understood, at least by this author, for a sensible comparison at this time.

Ground solar, wind, tides and waves are all intermittent power producers and the power is not always produced when needed. Except for tides, all are somewhat unpredictable as well. In addition to producing the power, therefore, there must be some mechanism to store part of the energy or transmit it elsewhere where there is sufficient demand. Calculating even a very gross measure of the environmental cost of storage is very difficult, but it will certainly not be free. SSP has the opposite problem. SSP produces power almost 24/7 365 days a year[12]. Thus, if SSP provides all the energy for an area, there will be too much power at some times. This can be handled to a certain extent by directing powersat beams to other antennas, but otherwise the energy must be thrown away, stored, or used for non-time-critical tasks such as desalinating water.

In addition, 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 land lines should be substantially reduced.

Conclusion

When we examine the environmental costs of long term energy production, it is fairly clear that SSP built from lunar materials is far superior to coal, oil, gas, and nuclear energy. The comparison with ground solar, wind, waves and tides

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[10] Wikipedia http://en.wikipedia.org/wiki/Wind_power in the Capacity Factor section.

[11] This is a major problem for undersea cables today.

[12] At geosynchronous orbit there are a few hours of eclipse per year when a powersat will not produce power.

is much closer, and while SSP has certain advantages, these may well be competitive. Thus, the wisest energy policy from an environmental perspective may be to encourage wind and ground solar, particularly on roof tops where no land is consumed, in the near and medium term combined with a vigorous SSP development effort for the long term to enable the near elimination of the more environmentally costly technologies. A combination of distributed, intermittent energy production by wind, solar, waves and tides and the extremely large scale, predictable, 24/7 potential of SSP with the space segment built from lunar materials may provide the benefits of an ample energy supply with low environmental cost for the indefinite future.