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An Idea for Inexpensive Electricity: Concentrated Solar Power 12 Miles above the Earth

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This is a guest post by Keith Henson. Keith can be reached at hkeithhenson at gmail dot com.

A small number of volunteer engineers and scientists are working on what they think will be a low cost approach to solar energy.

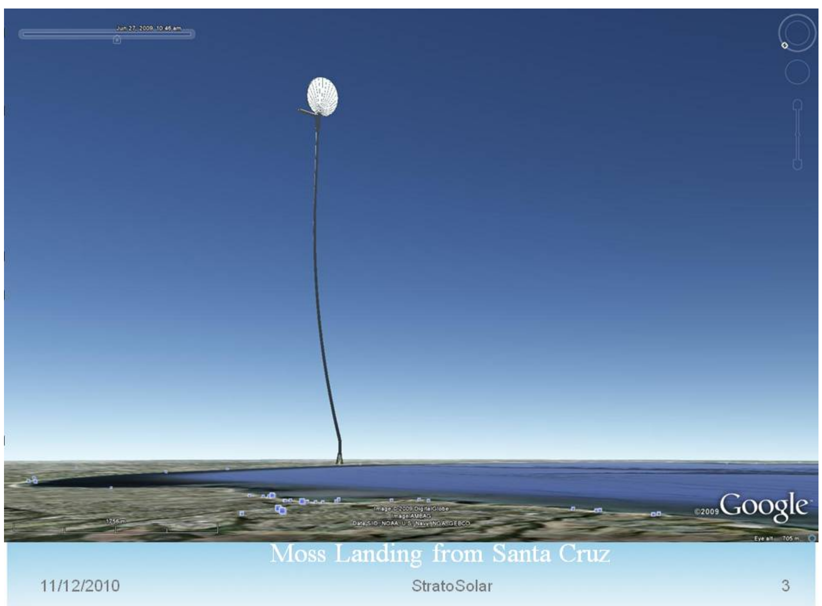

Figure 1. Artist's view of what tethered CSP might look like.

A few months ago, I wrote about Space Solar Power. The idea put forth in that post was to put solar power satellites into orbit around the earth, and beam the electricity back to the earth, using microwaves.

The concept in this article is closer to home. Sunlight for electricity production would be concentrated at 20,000 meters (12.4 miles), and come down to the surface in a hollow light pipe tethered to the ground. The light would be converted to heat at the ground, and used to drive combined cycle turbines to make electricity. They can be located almost anywhere, even places with lots of clouds. The volunteer research is being done at a company called StratoSolar.

While most of this post is about concentrated solar power (CSP) systems, the idea of using solar PV panels at 20 km is also being considered. A section at the end is devoted to the solar PV panel approach.

Why use a tethered approach, 12 miles up?

The stratosphere is a good place to collect solar energy. It is above 95% of the earth's atmosphere so there is much less of the atmosphere to absorb sunlight. There is no dust so the surfaces don't need cleaning. The winds are usually calm and there are no clouds, making the collection of solar power almost completely predictable.

The plants can be placed near loads, reducing transmission cost and losses. The solar flux models indicate this approach will work as far north as Stockholm, because of the greater solar intensity at that height. They occupy very little ground space compared to ordinary solar. The design calls for the collector surface to be pointed at the sun, so there is no cosine loss, a loss that affects ground-based solar power.

If collecting solar energy in the stratosphere works, it scales to human energy needs. It would take only 15,000 one-GW plants to replace all current sources of energy.

Based on a small multiple of the cost of common materials, electricity from the tethered CSP plants could be as low as 1.5 cents per kWh when mature.

On the down side, it will take an enormous amount of engineering and testing to determine if it will work. In addition, the power plants are a potential hazard for aircraft.

How Tethered Concentrated Solar Power Would Work

The tethered CSP design consists of a reflector made of many small (50-meter) elements arranged as an off-axis parabolic reflector. Look for one of those DISH TV antennas in your neighborhood and scale it up in your mind by a factor of 4000 in diameter, 16 million in area. Such a dish at 20 km would collect about 4 GW of sunlight from the time the sun comes up over the eastern horizon to when it goes down over the western horizon. The light curve is practically square.

The individual segments of reflective plastic would have computer-controlled rapid movement with a range of perhaps 2 degrees. The whole dish structure is kept pointed at the sun within a degree by a combination of aerodynamic vanes, fans on the scale of large wind turbines, and reaction (not torsion) on the light pipe.

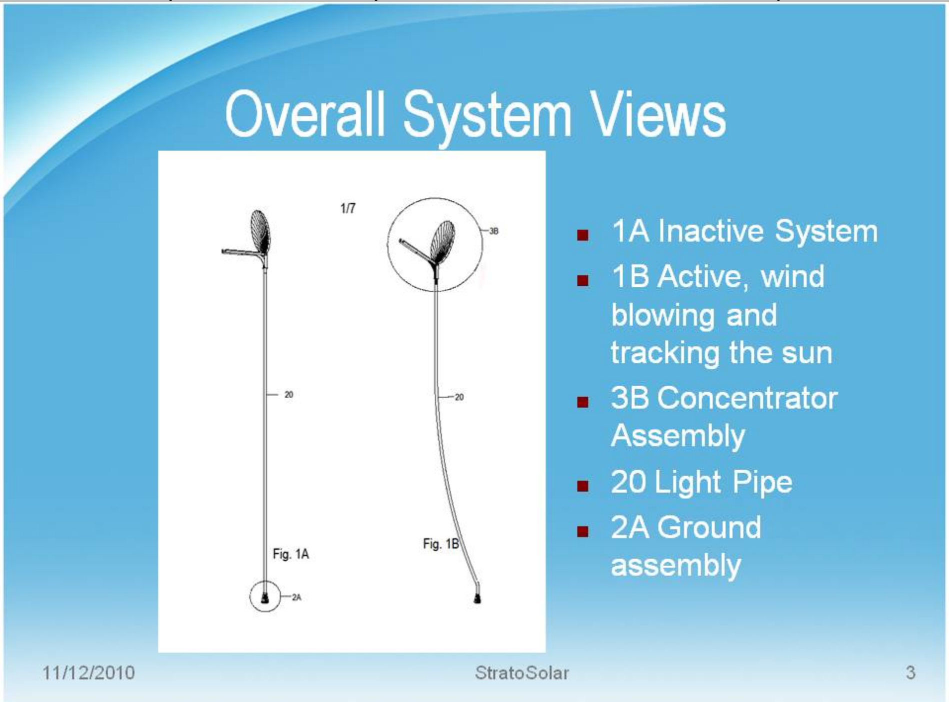

Figure 2. Systems view from Stratosolar

The concentrated light from the primary collector bounces off a secondary mirror and into a hollow light pipe that conducts it to the ground (see Figure 2). The calculated attenuation is around 7% for a 20-km by 50-meter light pipe lined with highly reflective plastic film similar to 3M™ 2301 Optical Lighting Film. 3M thinks they can make the film to 99.5% reflectance and, with considerable research, to 99.7% or better. The angular divergence of radiation from the sun is about 0.28 deg. This increases by approximately the square root of the concentration factor and means the light will reflect about once every 20 diameters (with no bending).

At the ground, concentrated sunlight (~6 MW per square meter) heats air to 1400 deg C at 20 bar, half of which runs an ordinary 60% efficient combined cycle power plant. The other half is directed into a buried 70,000-cubic-meter chamber half filled with firebrick (or other heat storage media). At night heated air is drawn from the heat store and used to power the turbines until dawn.

The firebrick heat store is known as a "Cowper stove." They have been used to preheat air going into blast furnaces for the past 150 years and are well understood. A cheap firebrick at 1400 K has about the same energy stored in it as an expensive lithium ion battery of the same size. For a GW scale base load, it costs around 1/10th of a cent per kWh to store heat for 24-hour power production.

As noted in the introduction, the buoyancy needed to keep the collector at 20,000 meters would be provided by metalized plastic bags filled with hydrogen inside the structure.

So the three elements in the system consist of a concentrator held up by buoyancy with optics to focus sunlight into a 20-km light pipe and a relatively conventional combined-cycle power plant on the ground.

Problems

There are serious engineering problems in designing such a power plant. The buoyancy gas must be hydrogen in metalized plastic bags. There just isn't enough helium available and it is far too expensive. We think separating the hydrogen from air by a meter of nitrogen will cope with the problem of hydrogen fires. Even a rocket fired through the structure should not ignite the hydrogen.

The light pipe is exposed to the worst of weather and wind. Lightning and electrical discharge is a concern but with more than a square foot of steel cable to conduct it to ground, it should not be a serious one. Ozone and UV at high elevations will be problems that require careful materials selection. Hail has not been a problem on the large number of plastic stadium roofs that have been in service for the last 40 years, so may not be a serious problem in this application.

Icing is a concern, mostly because of thick buildups falling off the light pipe. (The concentrator is above where icing occurs.) In addition, there is the man-made hazard of aircraft flying into them. A large aircraft flying into a light pipe would be a disaster for both the aircraft and the power plant.

Wind: the biggest engineering problem

The optimization that led to a ~1 GW size is partly due to the volume of the buoyant support structures. The volume (and lift) goes up by the cube of the linear size while the area (and therefore wind resistance) goes up as the square of the size. Additionally, the light pipe losses go up as the reflectance raised to a power proportional to the length over the diameter.

Depending on the reflectance, the hollow light pipe optimizes at 30-50 meters. That size, and the resultant maximum wind drag for a cylinder, is just too high to be practical. A rotating aerodynamic shroud around the light pipe was required to reduce the wind drag into a manageable range (the shroud cuts wind drag by a factor of 10).

The shrouds turned out to be heavy, but large enough in volume that it was practical to offset their own weight and the weight of the light pipe and hold down cables with buoyancy cells. This prevents the exponential growth in cable size seen in space elevator designs when supported only from the top.

Even with aerodynamic shrouds, the models involve huge forces, 30-50 million Newtons of wind force, and four times that much excess buoyancy to keep the light pipe from bending over more than 15 degrees in a high wind. Made from inexpensive steel wire, the hold-down cables have a cross-section area similar to that of a medium-sized suspension bridge (upwards of 16 inches in diameter).

Every couple of years there is a high-wind event in the stratosphere that reaches 50 m/s (180 km/hr) for as much as a week. The 2-km diameter collector at the top simply can't take the stress of that high a wind, so provisions have to be made to fold it into an aerodynamic shape, and the power plant needs to burn gas or oil for that time if it is to be as reliable as a conventional power plant.

Cost

A quick and dirty metric for base-load power is to take the income for ten years (~80,000 hours) times the revenue per kWh to be the allowable capital investment per kW of capacity. One cent per kWh would allow $800/kW and two cents would allow $1600/kW or $1.6 billion per GW.

The estimated cost of the CSP based system based on design plans come in at about $1.2 B per GW based on a moderate multiple of materials cost (the rough breakdown is $400 M for the power plant, $50 M for the heat store, $500 M for the light pipe and $250 M for the collector. The materials in the proposed design—aluminum, steel and plastic—are produced in huge volumes. There is considerable uncertainty in construction and lifetime issues, but if these are tractable, $1.2 B/GW capital cost would set the minimum price (no profit) for electric power at about 1.5 cents per kWh.

Ongoing maintenance costs are not yet known with any degree of certainty. An initial estimate might be 0.1 cents per kWh. The power generated would be base load, so there would perhaps be fewer maintenance problems than combined cycle. It is not clear yet how the maintenance of the concentrator and upper light pipe would be handled. If it is done by robots, the cost of the robots would be one of the maintenance costs. If it is done by humans, they would need to wear space suits.

Why should this kind of solar power come in at something like 1/6th of the lowest-estimated cost for other forms of solar energy? The 60% efficiency of combined cycle thermal plants accounts for a factor of four compared to 15% efficient solar cells, assuming similar cost per square meter. The rest of the lower cost comes from the increased solar energy due to being above over 90% of the atmosphere, being above the clouds, and not having the cosine effect of ground solar power. Moreover, 24-hour power is simple using low cost high-temperature thermal storage.

Energy Payback Time

Hydrogen is expensive in terms of energy, about 50 MWh per ton. A tethered CSP plant would take a lot of hydrogen for buoyancy, around 5,000 tons. It also leaks hydrogen, around 1-3 percent per year. To fill one up would take 250,000 MWh or 250 GWh.

That's about 10.5 days for a one GW plant. The total energy investment for plastic, aluminum and steel wire, and a combined-cycle power plant is around 5 times as much as the hydrogen so the energy payback is about two months, about a tenth of the energy payback time for PV cells in a desert.

After a year and a half of trying to find showstoppers, we feel confident that there are solutions to many of the problems identified. There is a lot of detailed engineering to do and there are problems we have identified but not solved—particularly how to construct the light pipe and the huge rotating aerodynamic shrouds. If anyone has ideas about how to construct objects of this size without wind destroying a partially completed section, please post your thoughts.

Photovoltaic variation

There is very little (almost no) experience with large tethered stratosphere structures. It is not surprising that people are reluctant to venture into this area for objects on the scale and cost of GW power plants, as required by CSP.

Can we start smaller? Not with the thermal type because the light pipe can't be made any smaller than a few tens of meters. If the pipe is a few meters, all the light is lost in the reflections.

Understanding that it isn't optimal, is it possible to put PV into the stratosphere? The power could come down at 20-30 kV in aluminum conductors inside the tethers.

There are enough advantages to consider this approach, particularly in Northern Europe and Japan. If the cost per square meter for cells supported in the stratosphere is close to the cost of a ground solar there is some, but not a not a lot of advantage, for putting PV solar collectors the in the stratosphere instead of a desert.It's a different story in places where there is persistent heavy cloud cover such as Germany and Japan. There the advantage over PV on the ground is a substantial multiple because of the high and predictable light levels.

The minimum size would be a lot smaller, in the few tens of MW.

More detail regarding these proposals is available from the StratoSolar website.

Note: The author has no financial interest in StratoSolar. His involvement with the company has been in the role of a volunteer engineer.