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SunSat Design Competition 2014-2015 Second Place Winner – Team SunFlower: Thermal Power Satellite

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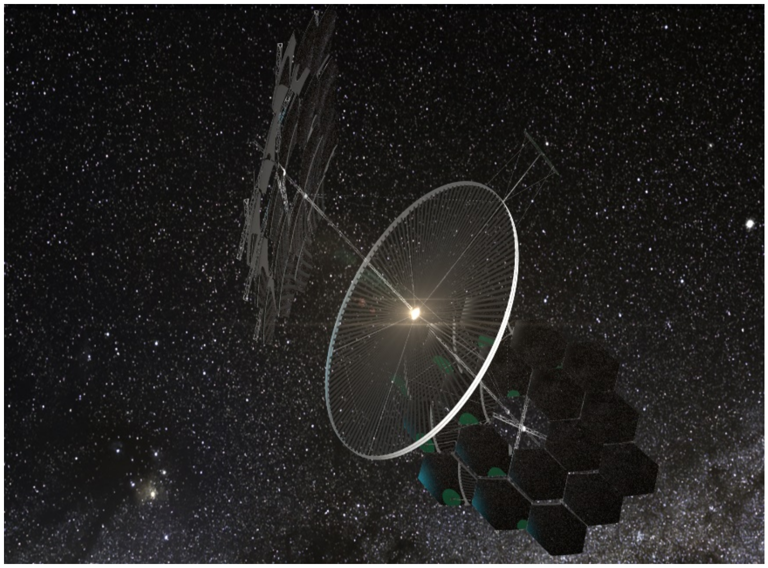

Thermal Power Satellites

A private collaboration between space scientists and media professionals

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ABSTRACT

Space-based Solar Power has failed to be competitive on cost in spite of decades of study. A new approach appears to resolve the cost issue, undercutting coal and opening huge markets for low cost solar power from space. There are two parts to the problem. First is the cost of lifting parts to Geosynchronous Earth Orbit (GEO; second is the mass of parts that make up a power satellite.

Our team is proposing a combination that makes use of Skylon to Low Earth Orbit (LEO), and a 15,000 ton payload ground powered electric propulsion from LEO to GEO. This strategy reduces the cost to under \$200/kg, a 100-to-one reduction from the current cost for lifting communication satellites to GEO. Reaching these numbers requires a Skylon flight rate in excess of 10,000 per year. Even at \$200/kg, the economics cannot tolerate more than 6.5 kg/kW for power satellites to undercut coal, e.g., 32,500 tons for a 5 GWe satellite.

Low (20%) efficient photovoltaic (PV) systems are very difficult to reduce below 10 kg/kW. A 60% efficient thermal design has one third of the light intercepting area of a 20% efficient PV power satellite. Carnot considerations require a high temperature ratio between boilers and radiators. The thermal cycles considered in our approach use concentrating mirrors to direct sunlight into high-temperature boilers.

The first working fluid proposed is potassium. After passing through a high temperature turbine, the condensing potassium heats a second working fluid (water or super critical CO2). Waste heat is channeled to low-temperature condensing radiators. Analysis found the radiators to be a relatively small part of the power satellite mass. Concentrators, boilers, turbines, generators, heat radiators and the transmitter massed close enough to 32,500 tons to merit further detailed investigation. The total, including rectenna, parts cost, labor and transportation, came to ~$2400/kW.

Levelized cost of electricity from $2400 capital expense came to 3 cents per kWh, comfortably undercutting coal at 4 cents. Displacing coal on financial merits bypasses debates about CO2 buildup and climatology. If designs and economics can be verified, and assuming rapid expansion beyond the first dozen power satellites, the human race could be off fossil fuels as early as the mid-2030s. To achieve this goal, power satellites must cost less than $2400/kW, installed. It all depends on keeping the power satellite reasonably low in mass and transportation costs extremely low.

Click here to see this team video: Team SunFlower - 2015 SunSat Design Competition

TECHNICAL BRIEF

INTRODUCTION

Note: for a more detailed analysis of the merits and limitations of the "Thermal Power Satellite", readers may click here to access the Keith Henson paper of that title. He also refers the reader to one of his earlier papers entitled "Solving Economics, Energy, Carbon and Climate in a Single Project" on which these technical and economic briefs and its visualization were based.

Transport of parts to GEO

The feasibility of power satellites depends on lowering the cost to orbit. The graph below, projecting cost to LEO for the Skylon, is included by courtesy of Reaction Engines, Ltd (UK).

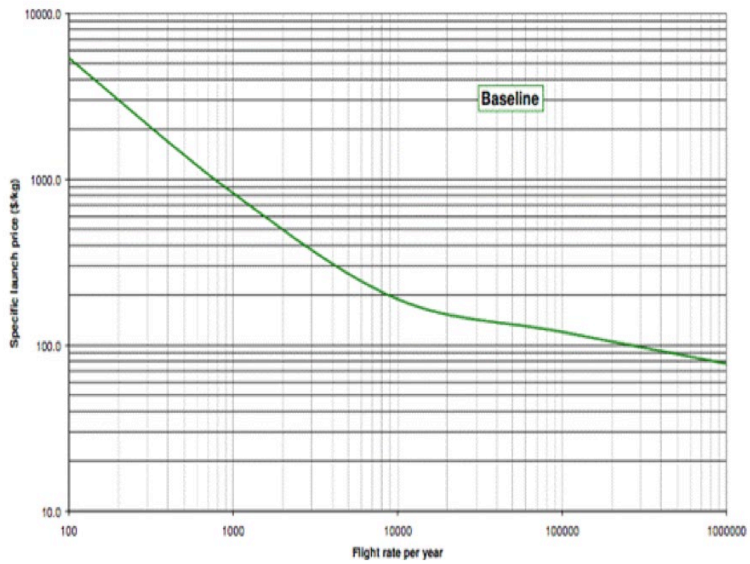


Figure courtesy Reaction Engines, Ltd.

To get the transport cost reduction required for power satellites to make economic sense, the flight rate for Skylon would have to be over 10,000 per year. A pilot (but profitable) project that built 4 or 5 power satellites per year would take that many flights. i.e., the flight rate to get the cost reduction required is not a problem.

Cargo to LEO is one thing, moving the cargo from LEO to GEO with *chemica*l propulsion is quite another. The problem is that the fuel needed to move from LEO to GEO has to be brought to LEO at a cost of (nominally) $120/kg. The cost multiplier between LEO and GEO (or the decrease in mass) is normally figured at 2.5 to one. That raises the lift cost per kg to $300, which makes power satellites uneconomical.

Operating in space in LEO makes electric propulsion an option, since much less reaction mass at the cost of huge amounts of energy (the kinetic energy applied to the reaction mass is proportional to mV2) is used. The energy needed for reasonable transit times (under a month) and a propellant mass of ~25% is quite large, about 4 GW, compared to a power satellite rating of 5 GW, suggesting a need to reverse the power satellite microwave power link and send energy up from the ground to power the LEO to GEO transfer.
This strategy applies a fundamental engineering principle, antenna reciprocity.

Reciprocity states that the power loss between two antennas will be the same regardless of which one is used for the transmitter and which is used for the receiver. This decision would require a rectenna in space the same size as a power satellite transmitter (1 km) and a ground transmitter the same size (10 km diameter) as a rectenna.

As part of this study, we modeled the cost on a per kg basis for a range of exhaust velocity. The model included a five-year write off cost for a ground station and orbital transfer vehicles plus reaction mass in LEO with energy fed into the ground transmitter.

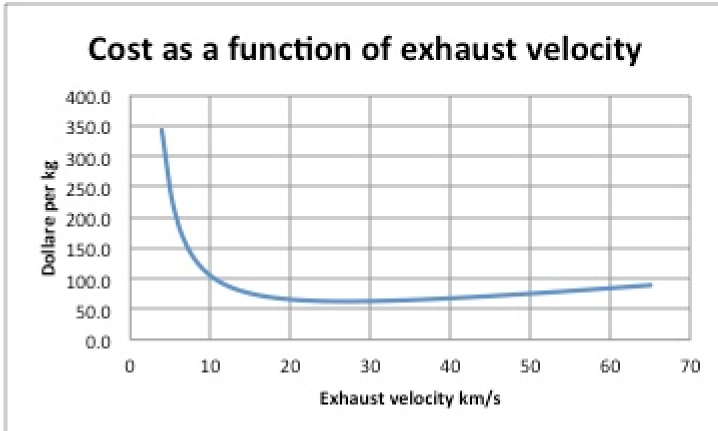


Figure from [IEEE.org]

For the assumptions made, the cost minimizes at 25 km/s, but is below $70/kg over 20-40 km/s. This brings the total cost to GEO to about $190/kg, a bit under the $200/kg limit established in the Economic Brief below.

Thermal Power Satellites

Power-satellite designs published over the past thirty years have all relied on the production of energy using photovoltaic (PV) solar cells. What is introduced in our design is an alternative approach that uses low exhaust-temperature turbines to produce energy.

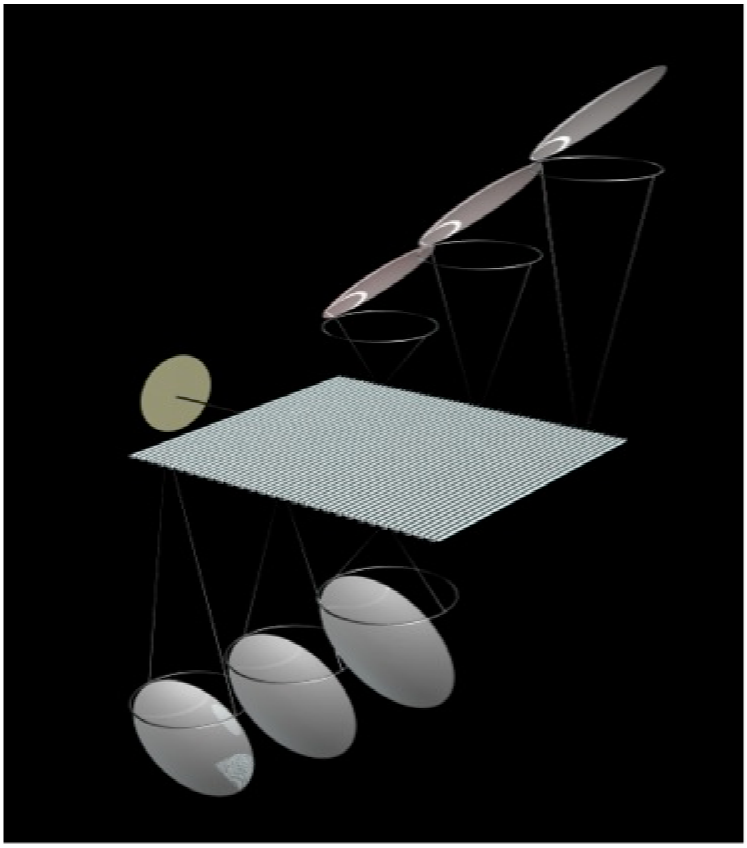


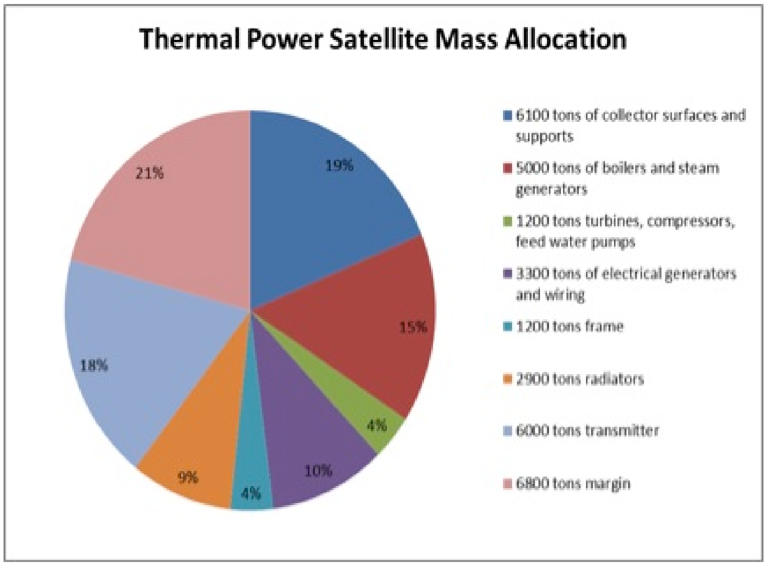
Figure 1. Thermal Power Satellite showing reflector-concentrators, support structures, radiators and transmitter. Not shown: boilers, frame structure, turbines and generators.

In this approach, about 12 square km of reflecting film concentrates 16.7 GW of sunlight into boilers. Tubular radiators with an area of about 17 square km cool the turbine exhaust by radiation. Thermal satellites have two advantages over PV. Turbines do not degrade over time from radiation(1) and thermal power satellites are three times as efficient as PV. This means a thermal power satellite would need only one third of the light interception area of a PV power satellite and needs 1/3rd of the station keeping against light pressure.

The scale of our design is 10 GW in space, with 5 GW delivered to the ground stations connected to the electrical grid(2). Our analysis assumes 2.45 GHz for the microwave link, the same as the original designs investigated in the 1970s.

On Earth, our rivers, oceans and atmosphere carry waste heat away from a thermal power plant. In space, the only choice is radiation into “deep space.”(3) Consequently, a thermal power satellite design must include radiators, and very large ones given the scale of the power plants. Efficiency is a concern; higher efficiency will reduce the size and mass of the sunlight interception area and the size and mass of the radiators. Unfortunately, higher efficiency requires larger and more massive radiators.

We analyzed the various parts that go into a power satellite to see whether the mass could be kept under 32,500 tons (6.5 kg/kW). The pie chart below provides a preliminary mass allocation for the major parts of a power satellite.



Radiator Tubes

Kris Holland and Anna Nesterova animated the transportation and construction details of a radial thermal power satellite for the SunSat 2015 contest. 120 radial tubes. As shown in the image below, the design consists of a central boiler and turbines exhausting into 120 radial tubes. The radial radiator tubes are single ended, about 1800 meters long, with the outer end 29 meters in diameter. There are concentric 10-meter internal tubes that carry the turbine exhaust steam out to the end of the radiator tubes. There the steam returns to the hub in the annular space while condensing.

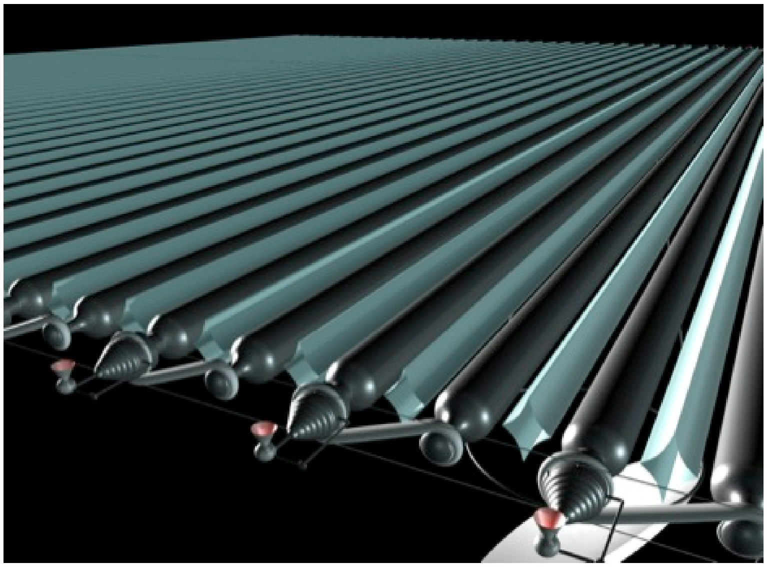


Figure 2. Showing boilers, turbines, radiator tubes, reflectors and steam compressors.

This design has a modest penalty (about 14%) over a design with parallel tubes and reflectors. This is due to the radiator tubes partly blocking the view of the sky for each other. In compensation, a radial design may need less structural mass for the frame.

The rest of the design, potassium boilers, steam generators, turbines, generators and transmitter are closely similar in mass. The mirrors passively focus sunlight on a circular ring boiler around the center of the “flower.” It is a lot less complicated to keep the sunlight focused into the ring as it rotates under the mirrors than it is to switch among the many boilers in previously analyzed design. Determining the relative merits of this designs as well as a comparison with PV designs is a work in process.

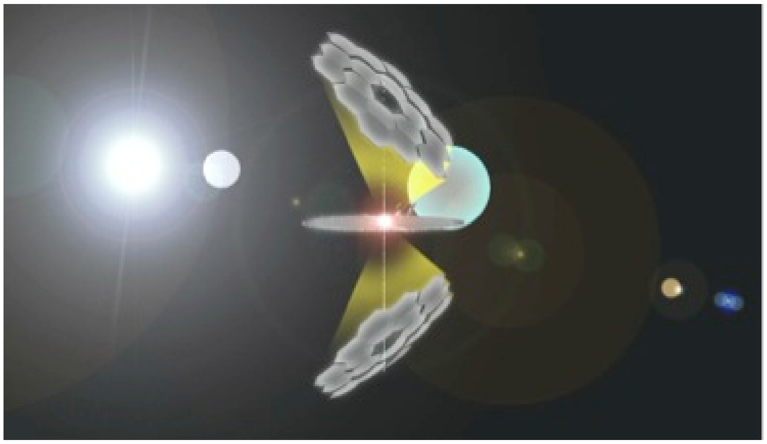


Figure 3. Artistic design of the SunFlower satellite from space perspective.

ECONOMIC BRIEF

There are two parts to our economic brief: 1) the cost of producing power satellites on an ongoing basis and 2) the cost to set up the transport and production infrastructure. The former determines whether power satellites can undercut coal and attain a substantial (perhaps near total) market share as humanity's primary energy source. A model of the second determines the capital investment needed to build the transport infrastructure and get started.

One watt of grid electricity is as good as any other watt, which makes electricity a commodity. The tried-and-true way to gain market share with commodities is lower prices. Base load electrical energy from coal costs about 4 cents per kWh.

Electricity at 3 cents per kWh from a reliable source would undercut coal by 25%, leading to rapid displacement of coal-sourced electricity.

To reach that level of cost and reliability with other "renewable" sources such as ground solar or wind plus storage does not seem possible, but with this approach to power from space, required capital investment is close to $2400/kW ($12B for a 5 GW power satellite including the rectenna).

Breaking down the cost, the rectenna is around $200/kW ($1B for 5 GW). The parts for the power satellite are about $900/kW. That leaves $1300/kW to lift the parts to GEO (labor in space is assumed to be comparatively small). This means that the product of kg/kW and lift cost to GEO in $/kg cannot exceed $1300. In the Technical Brief, the lift cost is slightly less than $200/kg and the specific mass is determined to be about 6.5 kg/kW, meeting the requirement.

"Solving Economics, Energy, Carbon and Climate in a Single Project" is the first of two Henson papers reviewed for this brief. That paper combines the Reaction Engines Skylon at upwards of 10,000 flights per year with an old idea explored by IEEE Fellow William Brown to get the cost to GEO under $200/kg. The expected cost breakdown is $120/kg based on economic studies using the Reaction Engines vehicle. A cost of less than $70/kg for the lift from LEO to GEO via a spiral orbit was the final piece of the puzzle to make power satellites economical.

The specific proposal to get the GEO-transit cost that low is to power high exhaust velocity electric thrusters with energy beamed up from a transmitter on Earth. The ground transmitter is as large as the rectenna for a power satellite.

A large antenna can beam perfectly well to a small antenna because of the principle of Antenna Reciprocity. The principle states that the end-to-end loss will be the same if we swap the transmitting and receiving antennas. Based on many studies of power satellites and microwave power transmission, we can confidently expect that 8 GW input to a 10 km diameter transmitter on the ground will get 4 GW out of a 1 km diameter rectenna in space at GEO. That represents the worst case. That 50% transmission loss is reduced to less than half when the rectenna is closer to the transmitter.

The other paper "Thermal Power Satellites," is an analysis of the mass of parts such as mirrors, supports, boilers, turbines, generators, radiators and the transmitter to get the energy from GEO to the surface of Earth. From this analysis, it looks like a 5 GW power satellite will mass close to 32,500 tons (6.5kg/kW). Combining all the parts, with transportation cost from LEO to GEO of under $200/kg and the specific mass of a power satellite of 6.5 kg/kW or less, gives energy from space for a capital cost of $2400, cheaper than the cost of electrical energy from coal.

The expectation is that cheap power will rapidly displace relatively expensive power. This is what happened 200 years ago when coal replaced wood and later when oil and natural gas partly replaced coal. The replacement might go much faster since it only replaces the generation of power and not the many uses of it.

Energy from power satellites is not cost effective to shut down (sunlight is free). It is also less expensive than peaking plants, meaning that the number of plants will expand well beyond base load. When this happens, grid management will need to migrate from control by generation to control by load.

The obvious way to soak up the available power between full capacity and current load is electrolyzing water to make hydrogen. We can then feed the hydrogen to Fischer-Tropsch Synthesis along with CO2 from air to make inexpensive, carbon neutral, hydrocarbon fuels. How inexpensive? It depends on the power costs. One, two and three cents per kWh makes $30, $50 and $70 per bbl. synthetic oil, respectively.

Getting Started

There is another economic aspect to this project: How much does it take to get the project to a stage in which it is self-supporting? The numbers are only preliminary, but the infrastructure build-out brackets between $40B and $70B. See Figure 7: Cumulative P&L graph in the first Henson paper. For comparison, the worldwide non-governmental spending on "renewable energy" over the last decade exceeds $2.4 Trillion. Normal "renewable energy" projects are so expensive that this huge expense has barely made a dent in the energy problems.

The power satellite project being proposed here is large and full of unusual risks, such as a lower cost source of energy possibly emerging after a lot of investment. The scale and risk probably relegate it to being a government-funded project. That may be fine, since governments are desperate for an approach to cutting CO2 emissions that does not destroy their economies. It also appears that power satellites will be much less expensive than conventional "renewable energy," in terms of both capital cost and the resulting electricity rates. It even appears to undercut coal.

Here we have a concept that offers a solution to energy, carbon and climate change, with the prospect of ushering in a long period of health, economic growth and overall prosperity based on clean, reliable, low cost energy.

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