Online Journal of Space Communication

Volume 11
Issue 18 *International SunSat Design Competitions (Fall 2013 / Summer 2016)*

Article 8

October 2021

SunSat Design Competition 2015-2016 Second Place Winner – Team Pathway to Power : Wireless Power Transfer

Javier Tandazo

Ethan Wong

Curtis Waggoner

John Guggenheim

Alexander Carter

Recommended Citation

Tandazo, Javier; Wong, Ethan; Waggoner, Curtis; Guggenheim, John; and Carter, Alexander (2021) "SunSat Design Competition 2015-2016 Second Place Winner – Team Pathway to Power : Wireless Power Transfer," *Online Journal of Space Communication*: Vol. 11 : Iss. 18 , Article 8.
Available at: https://ohioopen.library.ohio.edu/spacejournal/vol11/iss18/8

Pathway to Power

Student Team:
Javier Tandazo, Ethan Wong, Curtis Waggoner, John Guggenheim, Alexander Carter

Faculty Advisor:
Peter Schubert, Director, Richard G. Lugar Center for Renewable Energy; Professor of Electrical and Computer Engineering, Indiana University-Purdue University, Indianapolis, Indiana

---

ABSTRACT

Solar Power Satellites (SPS) using Wireless Power Transfer (WPT) to beam renewable energy to consumers on earth face three grand challenges: moving parts, heat dissipation, and radio interference. Solutions to each of these “show stoppers” are presented here. Further, a progressively more-complex pathway is described which starts where we are now and leads step-wise to implementation of large-scale Space Solar Power (SSP).

The first two grand challenges are addressed by a novel SPS design based on a thin-walled cylinder configuration of solar panels. The remaining challenge is tackled through a newly-discovered antenna configuration which allows dramatic

reduction in radio/telecom interference from so-called “sidelobes.” The cost of this SPS (called the “tin can” for its resemblance to a soup tin with the “lid” antenna canted up at an angle) is made affordable through the use of raw materials already present in space. The techniques known as In-Situ Resource Utilization (ISRU, or “living off the land”) provide for the refinement of minerals (powdered rock or “regolith”) from the moon or from asteroids into the pure metals and semiconductors needed to build the tin can SPS. All these factors are brought together as the ultimate goal of a progression of value-added solutions leading to commercial feasibility of SSP.

TECHNICAL BRIEF

Why Space Solar Power?

As demand for energy increases worldwide, researchers are continually evaluating sources of renewable power. One promising technology is space solar power (SSP). There are multiple advantages to using SSP over conventional power sources such as fossil fuels, and even over conventional earth-based solar power. Like other renewables such as wind, hydropower, and terrestrial solar, SSP doesn’t produce atmospheric carbon emissions like the majority of our current energy sources do. The major drawbacks to terrestrial solar and wind is their unreliability. These intermittent power supplies have posed a significant drawback for the widespread adoption and the consumption of renewable energy. SSP offers a way to collect energy using solar power satellites (SPS) with a continuous (“baseload” or “always-on”) reliable supply of electricity with no CO2 emissions.

Space solar power is not a new idea; in fact, it has been discussed and researched since the 1970s. Although decades old, we have not seen any significant deployment of this concept since it was first conceived. The issue facing SSP is that it has a very high development cost, compared to more conventional sources of energy. Building a SPS will require that a large amount of hardware be launched into orbit. These high upfront costs, along with the relatively untested technologies required for such a project, have prevented the manufacturing of a solar power satellite up to this point in time.

There are several methods for reducing these costs and making this enabling technology a more economical energy source. By producing on a sufficiently large scale, costs per unit of energy delivered will go down. A 2015 study shows the potential for solar power satellites, whose infrastructure has been amortized over the first several units, to deliver wholesale electricity to a city at 36 USD/MWh2. This result depends on being able to harvest most of the materials needed for the manufacture of solar power satellites from the moon or from asteroids. Known as ISRU (in-situ resource utilization), the pulverized soil of the moon can be processed to extract oxygen, silicon, aluminum, and iron. By designing and producing advanced manufacturing stations in space and on the moon, powdered regolith can be used to produce pure oxygen plus silicon which can be processed into photovoltaic (PV) cells.3 The advantage of manufacturing on the moon – or other planetary surface - is that these locations require 24 times less energy to launch objects from the moon into orbit than from earth.

Show Stoppers

Prior SPS designs have run into some hurdles that are difficult to design around. Our SPS design seeks to solve these "show stoppers" with its simplistic tin can design. A common problemfound in other SPS designs is the need for moving parts. If one portion of the satellite tracks the sun and another part has to face earth, these components need to rotate. This makes it very challenging to transfer power from the solar panels to the space antenna because complex mechanisms are needed to transfer huge amounts of power through rotating components. Previous SPS systems have also required structural support across kilometer-scale lengths. The tin can SPS design uses centrifugal force to hold the structure in its desired configuration. Furthermore, this innovative design can sway many degrees out of alignment, and the beam direction can be adjusted using diode-loaded transmission line infinitely-variable phase shifters to maintain transmission accurately to the ground-based rectenna (receiving antenna).

Thermal management is the second problem most frequently encountered by prior SPS designers. A total of 50 GW must be rejected radiatively. Approximately one third of the outer surface of the cylindrical cell is exposed to the sun. This heat transfers to the backside of the PV cells where it can radiate towards those solar cells presently in the dark. From there the heat is eventually radiated into space. Heat pipes and thermoelectric devices will also be utilized to aid heat flow from the sun-lit PV cells to the cold cells that are in the dark.

Lastly, beaming a multi-gigawatt power signal will tend to interfere with any other signals in the area. This interference is caused by side lobes that surround the main beam. A side lobe is like a echo of the primary power beam which until recently has been thought to be unavoidable. Our approach uses a newly-discovered configuration for broadside transmission of a phased array antenna that allows side lobe power levels to be arbitrarily reduced to insignificant levels. This new configuration will still produce high sidelobes when there is a significant fraction of failed or malfunctioning antenna elements. However, with proper design and maintenance a nearly-perfect "pencil beam" of power is delivered directly to the rectenna on earth, avoiding interference or "desense" of telecommunication and radio signals already in use around the globe.

Solar Power Satellite Design

Multiple considerations must be factored in and trade spaces explored when designing a solar power satellite. Figure 1 shows the "tin can" design first proposed by IUPUI Professor Peter J. Schubert in 201412. The basic design of this satellite is a hollow cylindrical shell composed of photovoltaic cells on the exterior surface. The shell is tethered to a central copper core or spire by using flexible polymer cables. At one end of the spire is a hexagonal transmitting antenna ("spacetenna"), where power electronics convert DC current from the solar panels into radio-frequency power signals delivered through a phased array of individual antenna elements, and thence to earth.

The entire assembly rotates slowly, completing one revolution every 24 hours. This permits the spacetenna to remain consistently pointing – at least substantially - at its dedicated rectenna. The angle at which the spacetenna is canted relative to the axis of the spire (which points to solar north) mirrors the latitude of the earth rectenna.

The simple cylindrical design solves many issues that have faced other designs. The most important improvement is that this approach doesn't require a high-power slip ring from the PV panels to the spacetenna because it is not necessary to separately rotate the sun-facing and earth facing sides of the satellite.2 The cylinder design, slowly rotating at the same rate as the earth, allows each and every panel to receive power for about one third of the time. This way the panels can be expected to last up to three times as long.

The number of solar panels needed is of course greater than those required on a flat or planar solar farm, but the significant benefit is that the hot solar cells facing the sun can reject their heat through the hollow center of the shell to the cool cells on the dark side. Because the shell rotates with the spacetenna, the need for a slip ring is eliminated. This will reduce energy losses caused by imperfect electrical connections and sharply reduce the risk of catastrophic electric failure from an unfortunately-located micrometeorite strike.

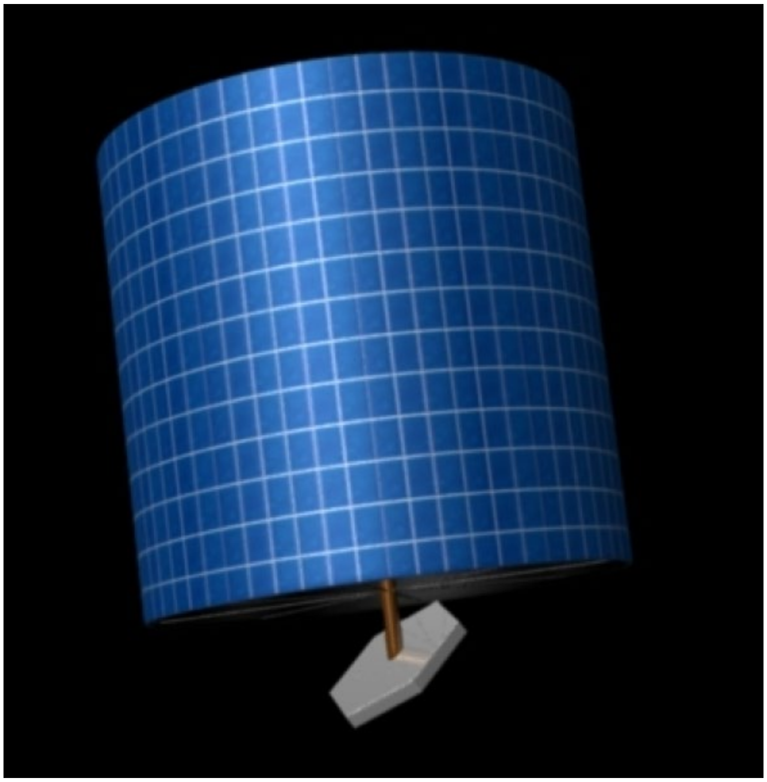

Figure 1: Solar power satellite 'tin can' design with hexagonal spacetenna.

Details of the tin can configuration underpin the economic assessment. Lunar-sourced PV cells (see Figure 2) are single crystal silicon with an assumed conversion efficiency of 22 percent. An anti-reflective layer of silicon dioxide, that has an refractive index of 1.46, provides a critical angle of +/- 75 degrees, such that sunlight incident beyond this range is completely reflected.2 The solar irradiation being equivalent to the solar constant of 1346 W/m2, and multiplying this by the cosine of the angle between the sun and PV panels and integrating within the critical angles yields an equivalent of 25% of the surface fully illuminated.2

While also considering the conversion efficiency between direct current (DC) to radio-frequency (RF) energy, which is assumed as 75 percent, the area required to produce 10 GW of electrical power is 29 million square meters.2 In order to meet this demand, the cylinder of the tin can will have a diameter of 6.4 km and will be 6.4 km tall. Each solar cell will be a square 0.167 meters per side. A bit more than 400 of these are combined into square frame solar panels with side lengths of 3.6 meters. There will be a total energy incident of 60 GW reaching the satellite surface, so 50 GW of thermal energy must be dissipated.

Hot surfaces reject heat via radiative thermal transfer. The hot solar cells facing the sun heat through their thickness and the hot backside radiates energy to the larger area of cold cells through the hollow interior of the tin can shell. These cooler cells heat through their own thickness, and the heat then pours out towards the cold of interstellar space. Calculations show steady state temperatures consistent with efficient operation of silicon solar cells.

A third improvement with this design is it doesn't require careful alignment of any parts because there are no moving parts. The cylindrical shell "tin can" design is simpler and has fewer design issues.

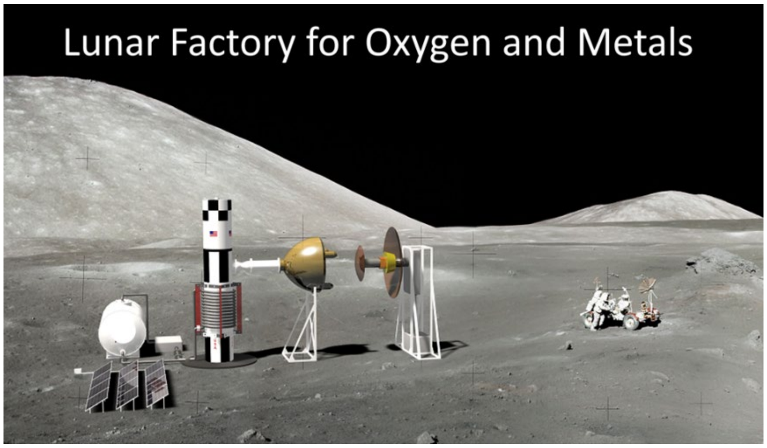

Figure 2: In Situ Resource Utilization concept – first installed unit.

Spacetenna

The spacetenna is the transmitting antenna attached to the copper spire at the center of the satellite shell. Large utility-scale inverters and transformers are needed for the electric power to be converted into a 2.45 GHz power signal and distributed as needed across the spacetenna. These power conversion devices are heavy and must be supplied from earth for the foreseeable future. Waste heat from conversion can be radiatively rejected up through the central axis of the tin can shell towards cold space in the direction of solar north (see Figure 3). Heat pipes can be used to spread the heat to additional radiators to maintain proper operating temperatures.

The 1978 Reference Design5 assumes a spacetenna of almost 1 km diameter with a tapered Gaussian distribution of power across its face. Through the Friis equation, this size of spacetenna can deliver power to a rectenna of approximately 10 km diameter. The beamed microwave power is rectified to DC and then fed into a public utility grid4.

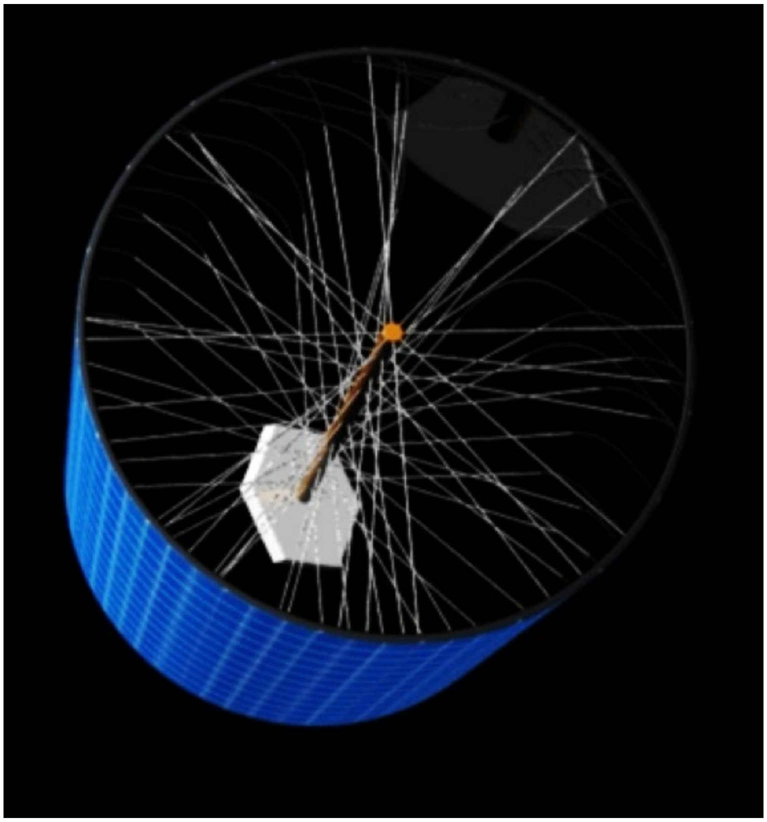

Figure 3: Interior of satellite showing the spacetenna and copper spire to which the outer shell is tethered.

The first segment is the Power Transmission and Management of the solar array. The function is to convert, regulate and transmit the electric power of solar array modules. A majority of the power is transmitted to the rotary joints. The remainder of the power is distributed to the service devices on the sub-arrays, including to the energy storage equipment needed to supply power during eclipse. The voltage of the output power of solar array modules is 500 V. The power is converted to 5000 V when transmitted to the rotary joints. So, for a solar sub-array, there are two output power buses and each bus is 5000 V, 4800 A.

The second segment is Power Transmission and Management on the main structure. The function is to convert, regulate and transmit the electric power of solar sub-arrays. A majority of the power is supplied to the electric power interfaces of the antenna. A part of the available power is distributed to service devices (including electric thrusters) and the remainder of the power is used for energy storage to supply power for service devices during eclipse. The voltage of output power of solar sub-arrays is 5000 V. The power is converted to 20 kV and is transmitted to the antenna. So, for the antenna, there are two input power buses and each bus is 20 kV, 50 kA.

The third segment is Power Transmission and Management on the antenna. The function is to convert, regulate and transmit the electric power of the antenna. The voltage of input power of the antenna is 20 kV. A majority of the power is converted to 5 kV and is transmitted to the microwave generators to generate microwave. Some of this power is distributed to service devices (including electric thrusters) and the remainder of the power is used for energy storage to supply power for service devices during eclipse.

Spacetenna and Side Lobe Reduction

A discovery made in 2015, that is currently under peer review, appears to be a spacetenna configuration that had not previously been explored. Figure 4 shows this configuration, which features individual antenna elements on a hexagonal grid and having a hexagonal perimeter. The circular spacetenna depicted in many visualizations of SPS designs appears to generate significant sidelobes from poorly-matched array patterns at the periphery. A Dolph-Chebyshev distribution of power across the spacetenna (instead of the frequently-cited 10 dB Gaussian taper) can be designed for any arbitrarily low side lobe power level relative to the central power beam.

Figure 5 shows the profile of such a beam's far-field region taken through the horizontal axis of Fig. 4. Compared to prior designs limited to a -40 dB side lobe (0.01 percent of primary beam), Fig. 5 shows an amazing -240 dB reduction in side lobe power (10-24). At this level, side lobes will not cause appreciable interference with cell phones, emergency responder radios, aircraft send/receive, or amateur radio equipment.

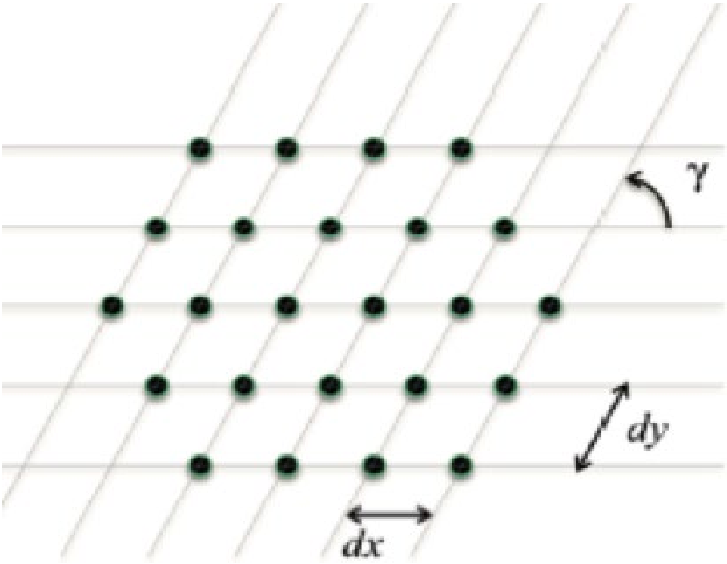

Figure 4: Triangular phased array configuration for spacetenna elements.

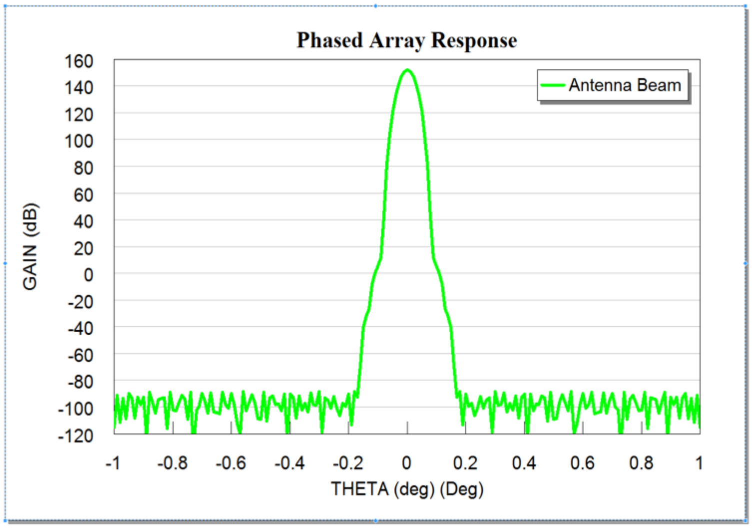

Figure 5: 240 dB Reduction > 0.2 degrees in 4000x4000 element.

The spacetenna is located at the end of the central spire of the tin can SPS. With the mass centroid so aligned wobbling of the entire structure is minimized. Gravity gradient considerations will likely require a counter-balancing mass at the opposite end of the spire to prevent torque on the structure by earth's gravity. All told, with this approach, we achieve excellent side lobe reduction and have "knocked-down" one of the shop-stoppers: radio interference.

Construction in orbit

One of the big challenges that Solar-Powered Satellites are facing is in the construction stage. Building a six kilometer diameter cylinder with a six kilometer length in space is extraordinary complex to contemplate. As with other SPS designs of large size, material transportation is a major consideration. A structure this big is going to need a lot of material for its construction. As launch cost are very high in energy and thus very expensive on a mass- or volume-basis, earth-based components must be minimized to keep costs reasonable.

The tin can SPS uses a combination of materials taken from earth and from the moon and/or asteroids. The central copper spire is assumed to be earth-sourced, although at sufficient scale this could be replaced by aluminum extracted from the moon and delivered to an orbital assembly yard. All of the materials for the cylindrical shell are assumed to be moon-derived, including the silicon solar panels, the iron frames into which they are grouped, and the aluminum wires to make connections within the frame and to deliver their power to the central spire3. Aluminum can also be used for the slotted waveguides of the antenna elements. Aluminum or iron can be cast into struts and trusses employed in the spacetenna.

Delivery of these materials to a construction orbit, say 500 km past geostationary earth orbit (above the "graveyard orbit" for end-of-life communications satellites) is done with electromagnetic catapaults sending iron-clad payloads to electromagnetic receivers on-station. Solar furnaces will smelt raw iron and aluminum, extruding simple shapes to build the frames that become the building blocks of the tin can SPS. At the large scales envisioned, a human astronaut work force is prohibitively expensive. Drones or waldoes will do most of the work, with automation increasing as learning progresses. Finished tin can SPSs can be moved into GEO slots, ready to deliver power to the earth, as depicted in Figure 6.

Figure 6: Multiple "Tin Can" solar power satellites in geosynchronous earth orbit beaming power to terrestrial markets.

Technological Development Strategy

Peer to Peer

As an emerging technology, wireless power transfer still has many issues and needs a significant amount of technological advancement before it will be feasible to provide solar power from space. To work towards the goal of ultimately providing significant amounts of power from space, we have planned out several smaller, attainable goals that will be stepping stones along the pathway to producing a solar power satellite.

The initial applications of this technology will start with stationary power transfer. This will be the simplest method of wireless power transfer (WPT), and it will help to provide additional credibility and increased interest in this technology and its many potential applications. One way this can be implemented is to construct a peer to peer stationary system for power transfer between nearby sites. As one non-limiting example, a building with solar panels can share power with a neighboring building with wind turbines so they can partly offset the intermittency of each others' renewable energy supply, thereby demanding less from the utility grid.

Car Charging

As more companies begin to see the potential of wireless power, an increase in research and investment will be seen. Innovations in the application of wireless power, for example, will find their way into the emerging electric vehicle (EV) industry, helping to boost over-all technological development of the sector. Batteries will become more efficient, with higher capacity.

As EVs become more common, a growing need will be to "charge" these vehicles. Unlike conventional vehicles, EVs can't "refuel" and continue driving the same way combustion engines can. When an EV battery needs recharging, it must be plugged into a power supply. Depending on the power source, it may take hours to recharge the battery, and even the fastest charging stations still take significantly longer than filling up with gasoline.

This poses a problem for EVs because the driving range of these vehicles is limited. In order to travel longer distances, it would require stopping for some amount of time to recharge, which is inconvenient and impractical. By using wireless power transfer, we can charge EVs as they travel down the road. By strategically placing power transmitters on elevated locations such as billboards, street signs, and telephone poles, we can provide power to vehicles as they pass by. A receiving patch would be built into the car, and the power transmitters would track these patches and beam power to them as the vehicles drive past. These innovations could increase significantly the driving range of EVs. As the efficiency of power transfer from radio frequency converting back into electrical energy increases, battery charging will become a common feature of our transportation infrastructure.

Drones

Flying objects could be one of the next stops on the pathway to power. The same principle used for car charging applies for drones, but, in comparison to cars, these devices would be moving constantly. Imagine having an automated drone flying around the city doing deliveries and not having to worry about battery life. This application would increase productivity of drones and create a new market. Drones would have a receiving antenna that charges the battery while receiving power beamed from the antenna. This way, the drone can operate 24/7, making operations easier for such companies as Amazon and Dominos, using drones to expand market reach.

Aerostats

Now imagine using a blimp not only as a billboard, but also to generate power from the sun. An aerostat with solar panels can beam energy to receiving antennas on the ground. This concept is more complex than the previous ones. It requires power beams to travel further distances, and power transmission will need to have low side lobes to avoid interference with telecommunication systems. The solar incidence would be greater at higher elevation (e.g. 4000 meters, above most clouds) compared to solar panels at ground level, meaning that more power would be collected on the blimps. This stage is similar in many ways to our main objective, solar power satellites. In this stage we would be helping to satisfy energy demand by extending the availability of solar power, especially in regions with frequent cloud cover.

These real-life applications, involving wireless power transmission, help people visualize its feasibility.

ECONOMIC BRIEF

Introduction

In this section, we will cover the cost estimates, governmental effects, and economical factors of a solar satellite of large proportions. Frames of 3.6 meter side length are to be joined edge to edge around the circumference of a 6.4 km diameter cylindrical shell, extending 6.4 km from top to bottom. This equates to 19,857,968 frames, including the frame itself, internal support wires, clips for solar panels and aluminum wiring. These are connected via spokes of polymer cable (earth-sourced) to a central copper spire (also earth-sourced) delivering power to inverters and transformers, power amplifiers and rf distribution architectures to slotted waveguide anteanna elements13. All of the following calculations are based on this information.

1. Two large assumptions
    1. The cislunar infrastructure for transporting materials electromagnetically is pre-existing and the cost to operate is insignificant; and,
    2. that a large-scale lunar manufacturing facility is already in existence.
2. Project cost with above assumptions totaling 24.4 billion USD includes:
    1. Total launch mass of 4930 MT - $20.5 billion
    2. Component costs - $1.3 billion
    3. Ground System - $2.6 billion

3. Project production
    1. Solar panel frames having dimensions of 3.6 by 3.6 meters will combine to produce10 Gigawatts of energy, based on total area times 25% illumination factor (cited above) times solar constant of 1356 W/sq.meter. (Note that thermal losses have already been taken into consideration)
    2. Economic impact, of one satellite, will allow 2-6 cities being powered wirelessly (Indianapolis metropolitan area has 850,000 people with peak demand of 3.6 GW) – this is approximately $767 million dollars annually not spent on coal by consumers
    3. Economic impact is tremendous, especially in islands – which if Puerto Rico consumes 19*103 GWh8, and Hawaii consumes 3.94*103 GWh9, and Singapore consumes 46*103 GWh10– with sea-based rectennae, could begin exporting extra energy to neighboring islands
    4. This idea of exporting unused energy can range anywhere from 1.5-3 GW being exported attracting a steady stream of revenue.
4. Government regulations
    1. Government will need to implement no-fly zones around the beam receiving site, to avoid momentary disruption in communication of aircraft
    2. A minimum perimeter of the facility and certain distance from any nearby inhabitants could be considered proper precautions to ensure the safety of both the system and the people
    3. Orbital command will need to be initiated along with interactive code writers to command the assembly robots for either complex procedures or updated form of assembly
    4. Monitoring stations will need to be instituted in order to protect the satellite from possible debris
    5. Rights of way and permitting for power transmission and distribution.
5. Private Sector
    1. The private sector will benefit from such an investment. The economic effects of coal will subside, leading to more jobs and a higher interest in developing more solar powered satellites.

2. The private sector, seeing that the first installations have flaws that can be perfected and improved, will find new ways to use these emerging technologies.
3. Such technologies will not only develop in space, but also on earth. Peer-to-peer sharing centers can be placed all over the globe. As WPT technology progresses, its innovations could potentially eliminate power lines entirely.
4. The private sector will be presumed to have control of installation, creating new learning curves for future job opportunities.

CONCLUSION

The goal of our Pathway to Power project was not only to outline plans for the construction and implementation of Solar Power Satellites, but to inform, educate and promote the research and application of wireless power transfer to help tap the largely unused energy source that is the sun. Doing so will help alleviate the need for power provided by such conventional methods as coal, natural gas and petroleum. The scale of the project proposed is of an entirely new level. The costs, operations, and implementation requirements are unlike anything we have seen before. But, its impact could have an impact as great as the launch of the first satellite.

For the first time, we will have power generated from beyond our atmosphere. In our proposal, we have identified the grand challenges that must be overcome and we have outlined a solution for each. Hopefully, we have also provided a clear roadmap for the maturation of wireless power transfer, a world changing technology. Clearly, the first step we have to take is to educate the public about the need for clean and renewable energy sources and the vast potential that is present in solar power. There have been monumental leaps in electronic advances that have happened since the launch of the first satellite. What if space solar power and wireless transmission became the next step in that journey to the future?

REFERENCES

1. National Space Society, http://www.nss.org/settlement/ssp/, accessed April 12, 2016

2. Schubert, P., Pinto, S., Pires, B., Nascimento, M., Barks, E., Nderitu, J., Goncalves, G., Tokmo, F., “Analysis of a Novel SPS Configuration Enabled by Lunar ISRU” American Institute of Aeronautics and Astronautics, SPACE 2015, 31 Aug. to 2 Sept. 2016, Pasadena, CA.

3. Schubert, P., “Solar Panels from Lunar Regolith,” International Space Development Conference. Chicago, IL 28-31 May 2010.

4. Love, A. W., “Basics of SPS Power Transmission from Space” IEEE Antennas and Propagation Society Newsletter, Dec. 1980

5. Department of Energy and NASA, “Satellite Power System Concept Development and Evaluation Program, Reference System Report,” Oct. 1978

6. Goncalves, G, “Sidelobe Reduction for SPS Configuration,” internal publication IUPUI August 2015.

7. "Puerto Rico Electricity - Consumption." - Energy. Index Mundi, 30 June 2015. Web. 17 Apr. 2016.

8. Index Mundi, https://www.ema.gov.sg/cmsmedia/Publications_and_Statistics/Publications/ses/2015/energy-consumption/index.html, accessed 15 June 2016.

9. Hawaii State Energy Office (2015, November). Hawaii Energy Facts & Figures. Retrieved April 18, 2016, from http://energy.hawaii.gov/wp-content/uploads/2011/10/HSEO_FF_Nov2015.pdf

10. Energy Market Authority, Singapore Government, https://www.ema.gov.sg/cmsmedia/Publications_and_Statistics/Publications/ses/2015/energy-consumption/index.html accessed 15 June 2016.

11. U.S. Department of Commerce, (2016, April). 2016 Top Markets Report Renewable Energy. Retrieved from: http://trade.gov/topmarkets/pdf/Renewable_Energy_ Top_Markets_Report.pdf

12. Schubert, P., "Energy Resources Beyond Earth – SSP from ISRU," Gateway-to-Space 2014, St. Louis, MO, Nov 7-9, 2014.

13. Mailloux, R.J., Phased Array Antenna Handbook, Artech House, 2nd Ed. ISBN 1580536891, 2005.