Department of Mechanical and Aerospace Engineering

An Analysis on the Potential of Space Based Solar Power

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Sustainable Engineering: Renewable Energy Systems and the Environment

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Copyright Declaration

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Signed: Vithusan Ramanathan Date:25/08/2017

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Abstract

Space based solar power (SBSP) promises to be the solution to the current climate and energy issues, as well as a way to help meet the demands of future populations. Whilst it is technically possible, the currently technology to transmit energy wirelessly is not robust enough to warrant an investment of billions. Instead, it would be more appropriate to allow sectors such as wireless transmission and photovoltaics to improve in efficiency in their own fields before combining them in a project of great cost.

Introduction

Defining the Problem

The human population on Earth has been experiencing an exponential increase in numbers since the industrial revolution. The total population did not reach its first billion till the early 1800s C.E, whilst it only took another 130 years for this value to double (Roser, 2015). Within the next 90 years, the population had increased to over 7 billion and by 2050 it is estimated the population will reach 9.7 billion (DESA, 2015).

Additionally, the amount of resources each person has been consuming has been increasing due advances in numerous fields, such as medicine and science. These advances have led to not only higher life expectancies, but also an increase in the consumption of resources per capita across the world due to emerging technologies reducing the labour in the securement of resources. Specifically, there have been many changes in the sources of energy used since the industrial revolution.

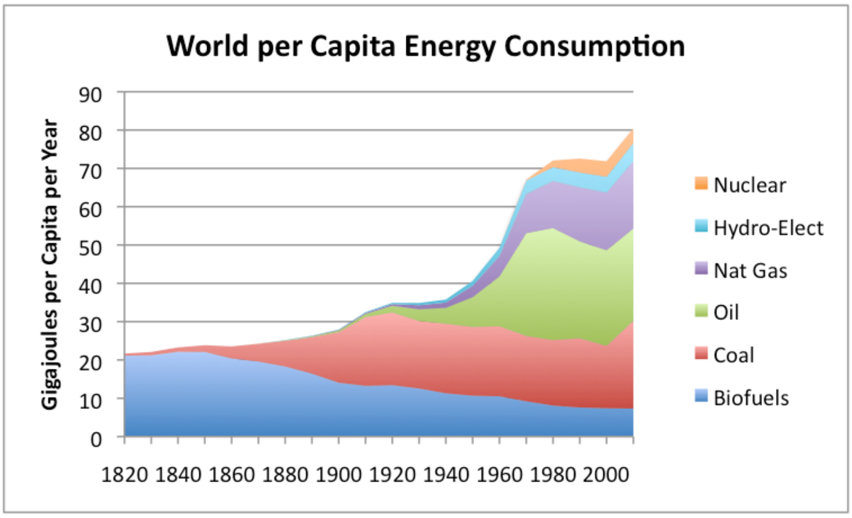

Figure 1- Graph showing the increase in energy consumption per capita over time

As can be seen in Figure 1, the diversity in the types of fuels used has increase since the industrial evolution which started the shift from using biofuels such as wood to using more energy dense materials such as coal and oil. With the human population growing at an exponential rate, and energy consumption of fossil fuels almost tripling in the last two centuries, it is clear an alternative source of energy needs to be established as the main source for energy before Earth is stripped of these finite resources. This has led to the development and increasing popularity of renewable sources of energy, such as solar, wind and hydro power in the past few decades.

Whilst this is a positive change as there are a plethora of environmental and health benefits to using renewable sources of energy over fossil fuels, it also has some drawbacks that do not affect fossil fuels. With current technologies, it is difficult to generate enough electricity to meet today's energy demands due to the rather low efficiency of these technologies. This problem will only get worse as populations and demand rises over time. The biggest issue however, is that power generation from renewable sources such as wind and solar are at the mercy of the climate. This does not always correlate with the demand, which can lead to an imbalance of the grid. To solve this, the grid often must pay to reduce energy generation during times of high supply and low demand as current energy storage technologies are insufficient to store large quantities of power for long periods of time. This is clearly not ideal and an issue that future technologies should strive to work around.

Currently, the instability in the generation of power via renewable sources means that it is impossible to use them to meet the base load demands and barely suitable as a source of power for peak load demands. However, as base load demand accounts for most of the electrical power consumption, it is important to focus on an alternative that can one day replace the fossil fuels that make up the current base load.

Space based solar power promises to be the future solution to all the aforementioned issues.

The Solution

Space based solar power (SBSP) is not a new concept. The term was first coined by Dr Peter Glaser, a Czechoslovakian scientist and aerospace scientist in the late 1960s and has since appeared in many forms of sci-fi media. However, this concept may one day become a reality as it promises to solve many issues related to renewable source of energy.

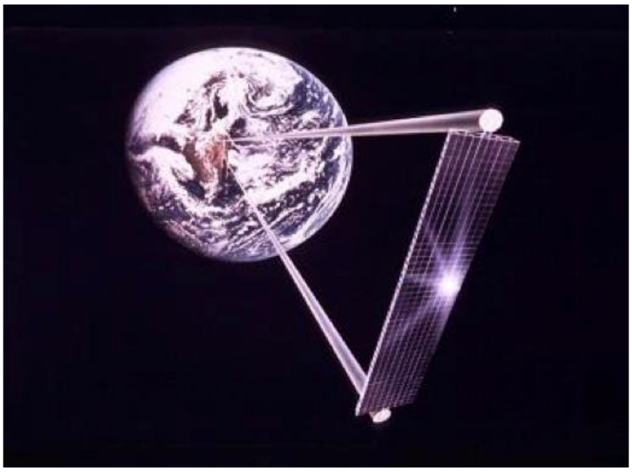

Figure 2 - Artist's rendition of the initial space based solar power concept (Space based Solar Power - American Security Project)

The concept of space based solar power generation is to send to space a large satellite equipped with a modular array of solar panels that would be able to generate a large amount of power. As satellites have been sent to space numerous times in the past and photovoltaics are a tried and tested technology, the biggest challenge that the proposition faces is a method of transporting the energy generated in space back down to Earth. The proposed method to transmit the power generated is to convert it into a signal be sent down to Earth via wireless transmission where it will be converted back to electricity.

There are two types of transmission technologies that have been considered for implementation: microwave power transmission and laser power transmission. Both technologies have pros and cons which would greatly impact the design of the satellite that the solar panels would be attached to. This piece will mainly focus on the proposed designs that utilise microwave power transmission due to the great deal of interest foreign space agencies have recently shown in that technology.

The Aims and Objectives of this Paper

This thesis aims to investigate the and analyse the promises of space based solar power and determine the feasibility of utilising said technology as means of meeting the inflating demand for energy of the future. This will include a brief look at an alternative design that uses a different method for power transmission whilst mainly focusing on microwave transmission. As the physics and aerospace engineering that comes with this topic is out with the scope of the course, it will only be touched on lightly. Instead, the technology will be compared to Earth based alternatives of a similar cost. The outcome of the thesis will be a conclusion on whether there should be more efforts and resources put into the development and eventual utilisation of space based solar power.

Literature Review

The Concept

Space based solar power was a term devised by Dr Peter Glaser in 1968 as an answer to overcome the limit that Earth based solar panels have, they produce no power during nightfall. As a result, the potential power generation is cut by half before even considering the efficiency of the solar polar and any further conversion efficiency (such as DC to AC).

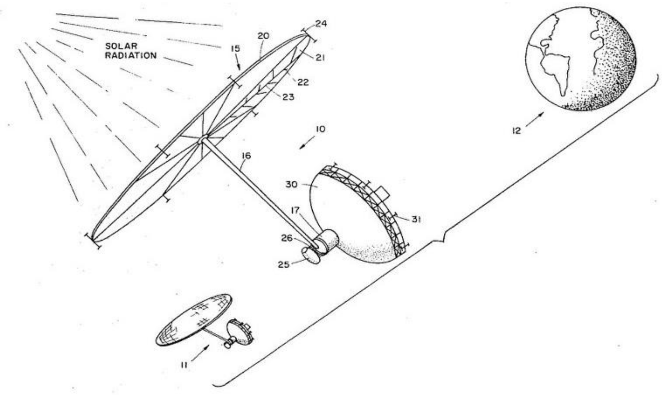

Figure 3- Drawing from U.S Patent visualising Dr Peter Glaser's SBSP system

Additionally, with the lack of atmosphere to partially block solar radiation, the available power per square meter is increased from roughly 1000W/m^2 on Earth to 1367W/m^2 (Lindsey, 2009). Thus, he had the idea to instead move the solar panel off Earth and into space in geosynchronous orbit around the Earth.

As the satellite is in geosynchronous orbit, the satellite will be orbiting around the Earth in synchronisation with the Earth's spin, causing the satellite to remain above a certain point on the Earth's surface. For this to be possible, the satellite would have to be over 35,000km above the surface of the earth.

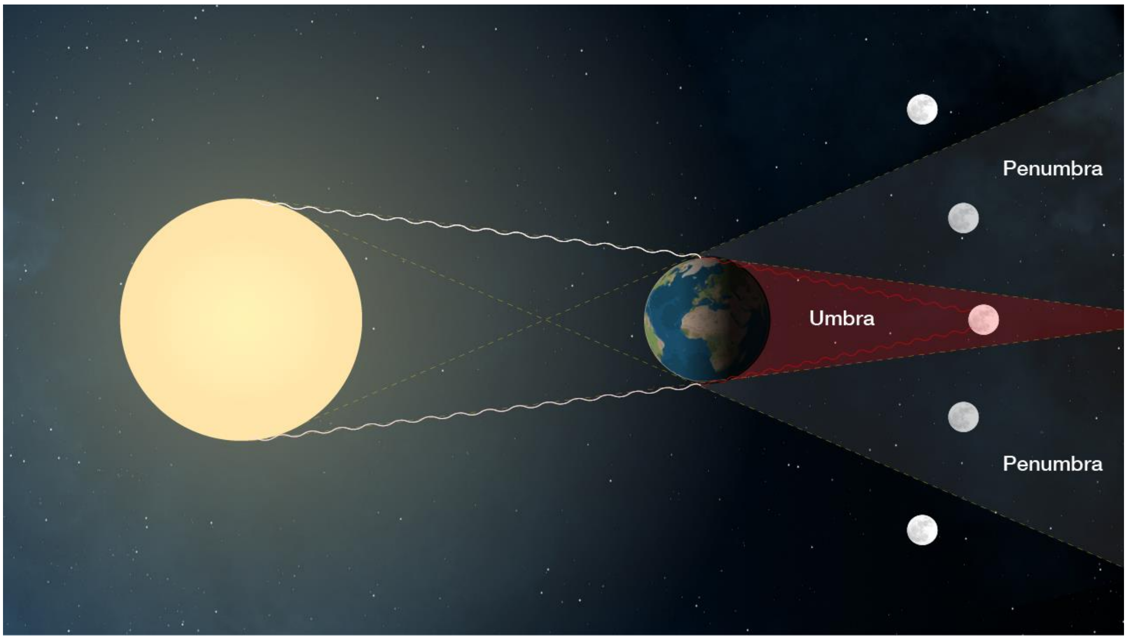

Figure 4- Illustration showing the shadow casted by the Sun being blocked by the Earth. This region is mostly avoided due to geosynchronous orbit of the satellite. (Macrobert, no date)

As the Earth's rotational axis is tilted by around 23°, the satellite would escape the Earth's umbra (which is the shadow casted by the Earth rotating around the Sun. This means that the satellite would almost never be in total darkness, essentially doubling the potential power output that could be obtained from Earth with the same area of solar panels.

Precedence of Technology

Figure 5- A view from the ISS of one of its solar panel array "wings" (Loff, 2015)

Whilst there has never been a large-scale satellite launched with the purpose of generating and transmitting energy for consumption on Earth, many satellites launched into space that are expected to be used for decades are equipped with an array of solar panels to power on-board instruments. The most iconic being the International Space Station.

Launched in 1998, the International Space Station was launched to be a modular space laboratory which has had multiple modules attached onto it since then. As of 2017, the ISS has the capability of generating around 120kW of power. The station itself uses around 40% of this power generated to operate the all the instruments and technologies within the satellite and the rest is used to charge on-board batteries that come online when the station in the umbra of Earth. Since the addition of modules up to 2017, the cost of the whole satellite has been estimated to be around $100 billion, which was shared between all participating countries over 30 years (ESA, 2013).

Wireless Transmission of Energy

Since the discovery of electromagnetic waves, such as radio waves by Heinrich Hertz in the late 19th century, it had been theorised that it may be possible to use it as a medium to transfer energy from one point to another (Shinohara, 2014). Tesla was one of the first to theorise that power could be transmitted wirelessly which gave birth to the concept of the World Wireless System. The proposed World Wireless System would allow power to be transmitted without the use of wires but instead using an focused beam of ultra violet radiation, by utilising the ionosphere and Earth as conductors, whilst using the lower dense atmosphere as the inductor (Benson, 1920). This idea fell through, however, due to lack of funding and the limitations of ultraviolet spotlights in their ability to produce enough ionised pathways.

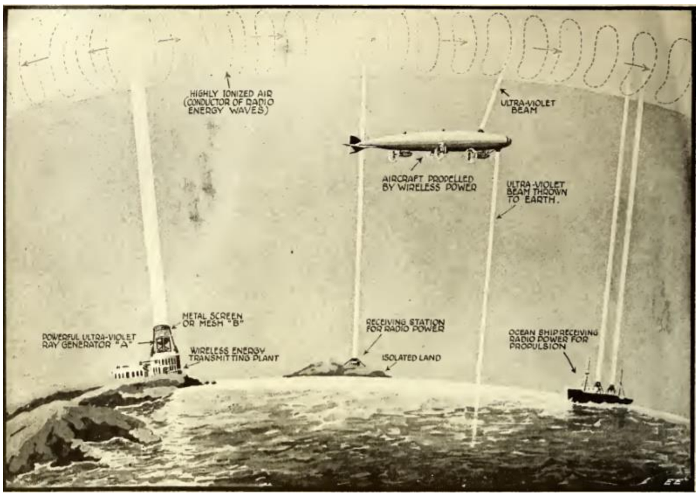

Figure 6 - An illustration showing the World Wireless System, which Tesla hoped would be used to transmit power from one point to another, even flying aircraft (Benson, 1920)

Whilst Tesla's experiment failed, the concept of wireless power transmission was revived post World War II, with the development of high power and efficient microwave tubes necessary for the advancement of radar technology during the war. This opened the opportunity to take a different approach to wireless power transmission that involved the use of microwaves as a medium to transfer energy in a focused beam directly to a rectifying antenna, which would go on to covert this microwave beam to electrical energy at the receiving end. Whilst at that time, it was researched as a potential method for transmitting power to troops in remote locations, it has become an integral part of space based solar power.

Technical and Economic Evaluation

Solar Power Satellite Design

Whilst there have been many different designs propositioned for solar power satellites (SPS) all designs have three parts in common: solar panels to convert solar energy to electrical energy an array of mirrors to reflect solar energy onto the photovoltaic array, and a microwave transmitter that uses the converted electrical energy to send a focused microwave beam down perpendicular to the Earth's surface. Here are a few of the designs that were prepositioned:

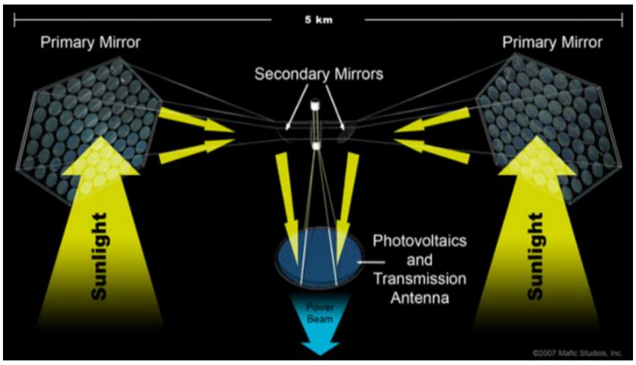

Figure 7- Diagram showing the most common design for SPS systems (National Space Society, 2016)

This is the most popular type of Solar Power Satellite, where two large arrays mirrors reflect solar energy to a set of smaller mirrors before being reflected onto a photovoltaic array. Most designs that have been considered are some derivative of this design. The Japanese Aerospace Exploration Agency (JAXA) launched a project to develop a twenty-year plan to utilise space based solar power as a move to become less dependent on nuclear energy (which took a large hit in reputation since Fukushima in Japan).

The most recent design for a potential SPS released by NASA is SPS-ALPHA which was modelled in 2012 (Mankins, 2012). The design allows for a greater concentration of solar energy, captured via a greater surface area.

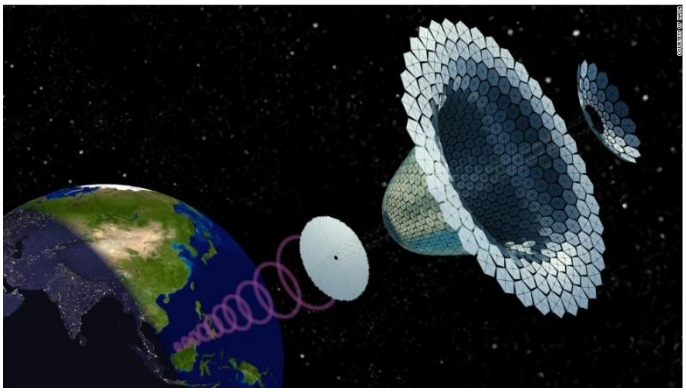

Figure 8 - A rendering of NASA's SPS-ALPHA 2012 (Mankins, 2012)

Since the technical implications of the different designs is outwith the scope of the course, this will not be covered in this thesis.

Sizing Rectenna

As the purpose of this thesis is to analyse the potential in space based solar power, it is important to size the system for it to be compared with what could be achieved using a terrestrial energy system.

It was assumed that the whole system would be able to achieve an output power of 1GW after reductions in power delivery from inefficiencies of all parts of the system.

The efficiency of the rectenna is completely untested at the scale of what would be required for a space based solar power system. The highest ever recorded efficiency of a microwave rectenna was 90.6% which was found when the input was 8W (Brown, 1977). The following table shows some of the results from the NASA's tests on the loss of rectenna elements based on computer simulation and measured data:

Table 1- Table showing test results from NASA rectenna power loss experiments (Brown, 1977)

Incident Microwave Power (W)	Absorbed Power in Element (W)	DC Output as % of Absorbed Power
0.1	0.085	56.5
0.4	0.375	74.30
0.6	0.573	77.80
2	1.997	86.12
4	3.998	88.45
5	4.992	89.06
8	7.958	90.54

These results produced the following trend:

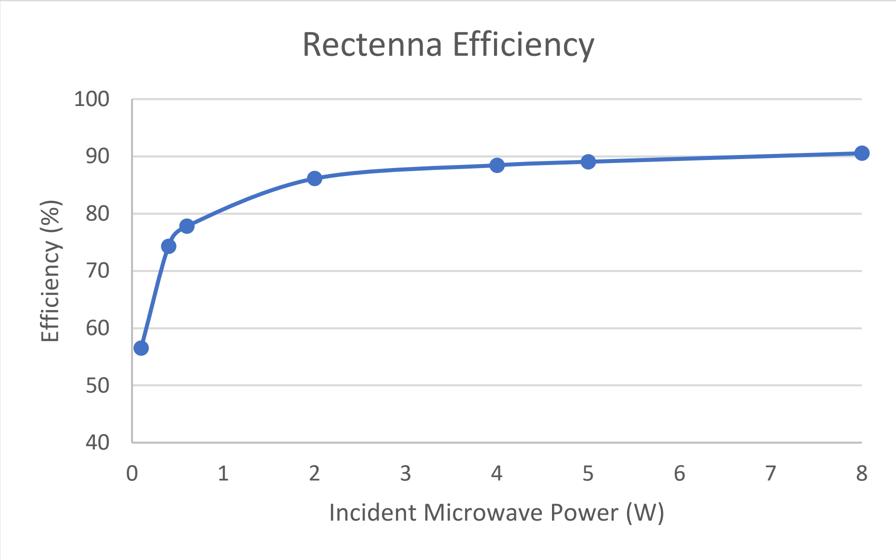

Figure 9 - Graph showing the trend in efficiency of rectennae with low input power

The results show that increasing power seems to increase the efficiency of the rectenna. However, the distance travelled by the incident microwave signal also has a large effect on the power harvested by a rectenna.

A study by the Polytechnic University of Bucharest showed the relation between distance and power harvested from the rectenna (Tudose and Voinescu, 2013). The incident microwave signal had a power level of 100µW, of which the rectenna could output 67µW at 20cm. Beyond this distance, the power output rapidly declined. This is as expected however, as at low power, a larger portion of the microwave signal is reflected and more likely to scatter off than to be absorbed by the rectenna (Mankins, 2012).

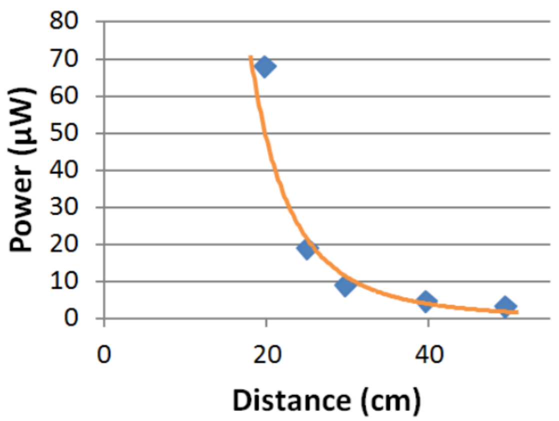

Figure 10 - Graph showing the trend in power output against the distance between the incident and rectenna (Tudose and Voinescu, 2013)

There is a severe lack of data for high power transfers. Whilst there have been ground breaking tests run by JAXA and Mitsubishi recently, there has not been any data released on the efficiency reached during the tests. The closest to the required data available is that of an test carried out by JAXA, where they stated they expected to be able to harvest about 350W from 1.6kW microwave beam at 50m (Sasaki, 2014). This would make the efficiency of the microwave beam to DC current conversion to be around 22%, which is quite far from what would be required to make SBSP feasible. It should be noted however that the test executed so far have been more a proof of concept than a focus improving the efficiency of the technology.

Despite this, JAXA and NASA are aiming to reach a rectennae efficiency of at least 85% (Mankins, 2011) before the launch of SBSP. For the purpose of this thesis, it is assumed that the rectenna efficiency will be at 85%.

The diameter of the rectenna (D_{ground}) can be calculated using the relationship (Mankins, 2011) (Zhang and Huang, 2012) between it, the size of the incident antenna (D_{space}), wavelength (λ) and distance between both antennae ($\kappa_{seperation}$) as can be seen below:

$$D_{ground} = D_{space} + \frac{\lambda \times \kappa_{seperation}}{D_{space}}$$

The wavelength of the microwave signal can be varied to an extent, but it was calculated to be 0.122m, using a frequency of 2.45GHz. The separation, as previously mentioned was assumed to be 35786km, which is the distance required to be from the Earth for geosynchronous orbit. The diameter of the antenna in space however was to be estimated. Considering the largest commercial antenna in space is around 22m (Amos, 2010), it was assumed that the microwave emitting satellite would be around 40m in diameter.

$$D_{ground} = 40m + \frac{0.122m \times 35786000m}{40m}$$

$$D_{ground} = 87630m$$

This resulted in the diameter of the rectennae would have to be 87.63km (an area of $6.031 \times 10^9 m^2$). This is clearly unrealistic; the current largest antenna in the world is only 500m wide (Wall, 2016), about one hundred and seventy five times smaller. This is due to the large effect wavelength and the distance between the antennae have in the relationship.

For example, when decreasing the wavelength of the microwave beam to 3mm (to have a frequency of 100GHz), the diameter of the rectenna drops to 2.2km (and an area of $3.8 \times 10^6 m^2$) which is far more feasible. Changing the wavelength of the beam however, has further complications when it comes to the transmission of the microwave beam.

Transmission of Power

Though electromagnetic waves have no problem travelling through a vacuum such as space, it is important to consider the effect the Earth's moist atmosphere has on a focused microwave beam.

Below is data from NASA showing how different wavelengths (and thus different types of electromagnetic waves) are affected by the Earth's atmosphere (Graham, 1999).

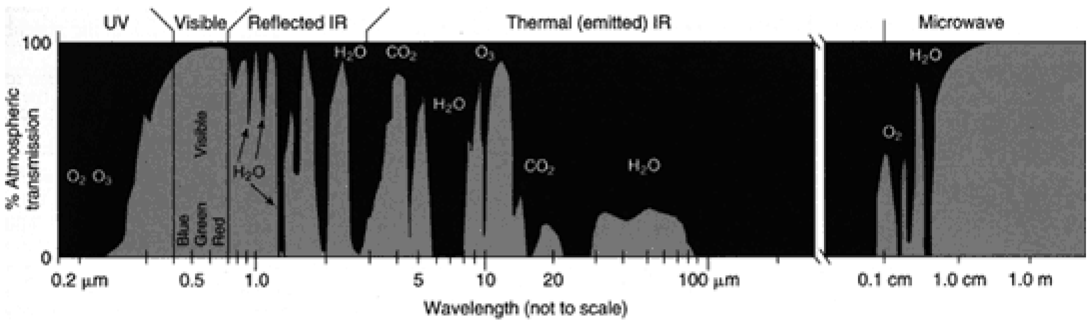

Figure 11- Graph showing different EM waves atmospheric transmission rates (Graham, 1999)

As can be seen above, microwaves and visible light are the most suitable mediums for power transmission as they seem to be able to go through Earth's atmosphere with the least amount of interference at their respective wavelength bands. In particular, the longer the wavelength, the lower the loss of transmission with microwaves. This is important to note as it creates a direct conflict with the prior mentioned calculations to do with the radius of the rectenna, where a shorter wavelength reduced the amount at which the microwave beam would diffract and thus reduce the area required for the rectenna.

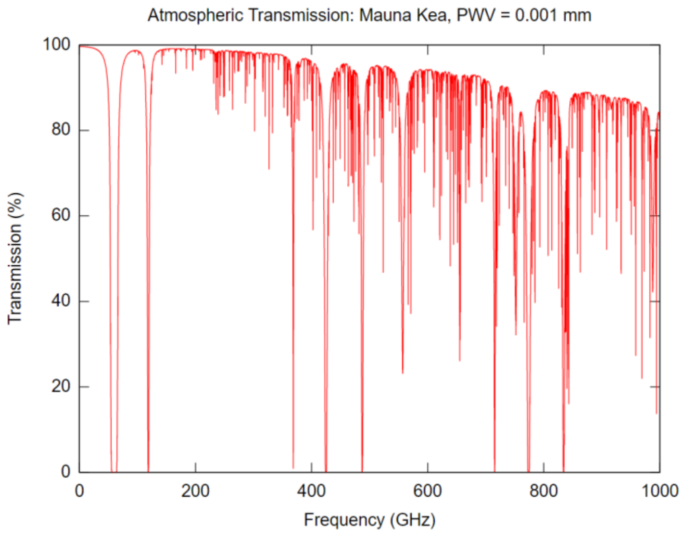

Figure 12 - Graph showing the relationship between frequency and transmission rate of microwave radiation (*Atmospheric Microwave Transmittance at Mauna Kea (simulated)*, 2012)

The graph on the left is from a simulation of microwave transmission from the sun to Mauna Kea (a Hawaiian dormant volcano). It shows that a low frequency, such as 2.45GHz, would result in an almost 100% transmission of the microwave beam to the rectenna. Thankfully, at 100GHz, which is still relatively low, the transmission seems to be in the upper nineties which means that the effects of the atmosphere on the microwave beam would be almost negligible. The points at which transmission dip to zero are when the microwave's wavelength is being blocked by water and oxygen molecules, which causes friction which in turn releases the beam's energy as heat.

The microwave transmitter that will be constantly pointing at the rectenna on the Earth's surface have not really been a topic of discussion it is a technology that has been developed in conjunction with the development of other technologies, such as radar and would most likely use a parabolic reflector model (typical satellite dish) as it would allow the transmission of microwaves in one direction. The goal is for this technology to be at least 90% efficient before launch (Mankins, 2011).

Harvesting Solar Energy

The photovoltaics on the satellite would be slightly dissimilar to those fitted on the International Space Station, as at over 35000km away, the SPS would be located outside the ionosphere. This means that it would be subject to solar flares and radiation exposure that it would otherwise be protected from had it been located within Earth's ionosphere. Furthermore, it can also be subject to micrometeoroids and small particles of space debris (ESA, 2006), much of this man made.

For the purpose of this thesis, it is assumed that the photovoltaics will be composed of multi junction cells which would make the efficiency of the solar panel array around 39% (Kurtz, 2006).

Using all the aforementioned efficiencies and with the knowledge that with the lack of atmosphere to partially block solar radiation (1367W/m^2), it is now possible to calculate the area of photovoltaics required to provide 1GW of power:

$$A_{panels} = \frac{P_{required}}{P_{available} \times \eta_{panel} \times (1 - \kappa_{atmosphere}) \times \eta_{rectenna}}$$

$$A_{panels} = \frac{1 \times 10^9 W}{1367 \frac{W}{m^2} \times 0.388 \times (1 - 0.0004) \times 0.85}$$

$$A_{panels} = 2.218 \times 10^6\ m^2$$

Furthermore, the power required and the overall efficiency of the system can also be calculated:

$$P_{generated} = P_{available} \times \eta_{panel} \times A_{panels}$$

$$P_{generated} = 1367 \frac{W}{m^2} \times 0.388 \times 2.218 \times 10^6\ m^2$$

$$P_{generated} = 1.176 \times 10^9 W$$

$$\eta_{overall} = \frac{P_{required}}{P_{generated}}$$

$$\eta_{overall} = \frac{1 \times 10^9 W}{1.176 \times 10^9 W}$$

$$\eta_{overall} = 0.85$$

Whilst a system that is 85% may seem like it would be well worth investing into, one should keep in mind that many of the assumptions made were in the best-case scenario for the technology. For example, the efficiency of a rectenna is yet to hit over 50%, so to assume that it would be 85% is not the more likely scenario. However, if the efficiencies of the technologies involved reach the goals that have been placed, it would seem that it may be worth the investment.

Economics of Space Based Solar Power

As there has yet to be an SPS sent into geosynchronous orbit, the costing of such a grand project is very rough. The estimated cost of SPS by experts is far beyond $100 billion, but proponents claim it to be able to provide energy at $0.10 to $0.50 per kWh, which is undoubtedly hopeful as although the price may settle to be within said range after initial investment; it is more likely for the price to be well above $1 per kWh during the first decade. This is not only because of the cost of materials, but parts of the satellite would be far too large and cumbersome to launch with at once. For example, the mirrors are each over 1km across. It would be near impossible to launch with something so large and delicate.

Instead, this would require multiple launches and for it to be built in space. This in turn would then require for a base to be built in space and prehards even the use of robotics to build the satellite. All of these things only increase the already expensive concept. There have been advancements in reusable rockets by SpaceX, which will dramatically decrease the cost of launching payloads into space but this is still far from being achievable within the next decade.

Figure 13- The Falcon heavy is a reusable rocket capable of launching with payloads as heavy as 26,700kg to geosynchronous orbit (Henry, 2017)

Furthermore, there is still very little understanding of the effects overexposure to microwave radiation on the health of nearby humans/animals. As the risks have yet to be quantified, it is difficult to support a project of this scale. Even the use of this in remote locations is without risk as there is still little understanding on the effects the shooting of a intense microwave beam could have on the ionosphere, the shield that protects Earth from radioactive bombardment (including microwaves).

Conclusion

In conclusion, whilst the technology may be technically achievable, there are too many short comings in the current technologies that would make SBSP feasible. As of right now, it is not even clear whether the efficiency of transmitting energy through microwaves will reach a high enough value for it to be technically viable. Furthermore, the cost of actually launching the materials into space to be built would be astronomically increase the cost of the project. All of this on top of the health risks, makes space based solar power a financial and health risk to invest into in its current form.

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