Energy Generation Systems in Space

James Wan
College of Engineering
Swansea University
Swansea UK
958177@swansea.ac.uk

***Abstract* – There have been numerous space solar power station designs presented over the previous half century with the aim of producing large amounts of energy by converting solar energy to electric power in orbit where the suns energy can be converted at higher efficiencies than on earth. This paper will present a new design for a space solar power station focusing on being simple but effective with the aim of being feasibly constructable within the next decade.**

Keywords – Space solar power station (SSPS), Geostationary Orbit (GEO), Concentrated Solar Power (CSP), Reaction Wheels

I. INTRODUCTION

In the UK the bulk of energy produced comes from non-renewable sources with most being from coal and gas at 35.3% and 26.7% respectively in 2013 according to the Office for National Statistics [1]. In comparison, from the same data the percentage for all the renewables combined is 14.6%, which is nowhere near the level that would be required for achieving net zero emissions by 2050 as the UK government are now legally bound to achieve [2]. Where many other countries have climates more suitable for generating large quantities of solar power, the UK's latitude means that its annual average solar irradiance is very low which would render large scale solar power plants ineffective [3]. However, where higher annual irradiance found solar power plants have been shown to be an effective source of energy such as the plants found in Spain and in the USA [4]. In the paper by V.K Jebasingh et al.[5] a table has been quoted showing 28 Solar power plants, some operational and some under construction, showing India and Spain having the largest number of plants, and with all the countries on the list having hot climates.

This paper will focus on Concentrated Solar Power (CSP) technology specifically parabolic trough technology as a solution to the problem of green energy generation and applying this to a satellite in orbit. There have been many designs suggested by different organisations advertising very promising power outputs making this an interesting area to investigate further [6]. Due to being in orbit a Space Solar Power Station (SSPS) would not have its efficiency lowered by cloud cover or day night cycle with the lack of atmospheric attenuation also a positive factor [7,8].

The bulk of research done into the area of SSPS has been into the design of the subsystems with less research done into the combination of this technology into a viable design. This paper aims to further investigate the design of the structure of a SSPS along with the dynamics of that structure as this is an area that has been identified as lacking critical investigation. Previous designs have been large scale, and much too large to be practically built, so an aim of this design is to be more practical to implement in the near future.

The overall research aim of this paper is to examine the dynamics of a SSPS and evaluate different methods of achieving an affective SSPS design. To achieve this, a set of constituent aims have been identified, with each being addressed by a separate section.

The first aim is to review different technologies and methods for the different aspects involved in a SSPS with the objective of finding the most effective combination for a SSPS. (Section II)

The next aim is to design a structure based on the review completed in Section II and complete static analysis on the structure using Solidworks. (Section III)

The third aim is to determine the dynamic forces on an SSPS and develop a code in MATLAB to model this. (Section IV)

The fourth aim is to apply the dynamic forces determined in Section IV to the structure designed in Section II and evaluate the effectiveness of the structure. (Section V)

The final aim is to compare the design to existing designs including terrestrial based designs. (Section VI)

II. COMPARISON OF MAJOR FEATURES

A. Energy Generating System

There are several options for methods of converting solar energy into electrical energy, and these can be broken down into two main categories: Photovoltaic systems and Concentrated Solar Power (CSP). For this design, a CSP is preferred due to the higher end-to-end efficiency, with Peter Fortescue quoting studies that found the conversion efficiency to be approximately 25% greater for CSP compared to photovoltaic systems [9]. There are several types of CSP with the main two being Solar tower and Parabolic trough, between them making up 99.3% of the operational CSP and with 96.3% of all CSP being Parabolic trough collectors [4]. With Solar Tower there would need to be extra structure to accommodate having the tower which is why parabolic trough is the better choice for this design.

B. *Orbit Type*

When considering the best orbit for this design, the time in sunlight, and the time in view of the power receiver need to be considered. The best orbit for time in sunlight would be a Sun-Synchronous Orbit (SSO) as a satellite in this orbit remains in the same position relative to the sun and is a type of Low Earth Orbit. The disadvantage of this orbit is the time for transmitting the power collected is limited and due to the speed the satellite would move across the sky it would not be easy to track from the ground. If the speed of power transmission could be increased in the future this orbit would be ideal for this type of satellite.

A Geostationary orbit (GEO) is an when a satellite is travelling above the equator at the same speed as the rotation of earth, causing the satellite to be in a fixed position in relation to the earth's surface. This has the advantage of being in constant view of the ground station for power transfer with the disadvantage of having less time in direct sunlight for power generation. For this design, the GEO would be the best balance of time in sunlight and time for power transfer. This is reflected in the other SSPS designs as all but one design listed by Xun Li et al. feature a GEO orbit [6].

C. *Attitude Control*

To make sure the efficiency of an SSPS is at the highest rate possible the angle of incidence between the sunlight and the collectors should be zero. This can be achieved using sun tracking and some form of attitude control device to rotate the satellite.

The obvious choice for a design such as this is a momentum or reaction wheel. The long lifetime of a SSPS would make it impractical to use a torque generating device that requires fuel, as it would then require regular refueling trips, increasing the cost unnecessarily. Reaction wheels also offer the advantage of providing continuous torque with precise pointing capability making it suitable for rotating a satellite to follow the sun [9].

D. *Energy transfer System*

A terrestrial power station is very easy to connect to the cities and town that require the power being generated, even in the case of CSP plants which tend to be in more remote areas due to their large size, and the need for good solar resource in their location. A SSPS however, especially one in GEO orbit, is a large distance from the earth making connecting it to the power grid difficult. There however are several options to achieve this.

The first option would be to have a tethered design [6]. This means there would be a physical connection between a satellite and the ground which could be used for power transfer and any data transfer that would be necessary as well. This would be as energy efficient as current methods of transferring energy using cables with the drawback of a tether being a hazard to other objects in orbit, as well as aircraft within the atmosphere. Whilst satellites in use may be able to avoid the tether, space debris left in orbit or other space objects, for example meteorites, are likely to impact the tether causing damage. If a tether could be designed to absorb or avoid these impacts a tethered SSPS could be viable.

The second option would be to transmit the energy to a ground station via microwave radiation [6]. With this solution there is no need for a physical connection between the SSPS and the ground station. To implement wireless power transfer, the SSPS would have to house a power transmitting array that could transmit towards a ground station with large receiving area to ensure all the transmitted power is received. The large size of the ground station and the transmitting antenna are obvious drawbacks with lower efficiency of transfer also being a negative point.

Due to a tethered design being currently impractical to construct a wireless power transfer solution being the only practical solution to getting the power from an SSPS to the ground despite its drawbacks.

III. STRUCTURAL DESIGN

The structure was designed around the measurements of the Eurotrough parabolic trough collector [10]. To keep the design simple, the satellite is made from arms holding 10 collectors coming from a central structure which contains the main flywheel for energy storage as well as the transmitter for sending the power to the ground station. A code that worked out the effective power producing area for different numbers of arms showed that 16 arms was the most efficient number of arms before the gain in energy producing area is less than 1 percent as shown in Figure 2.

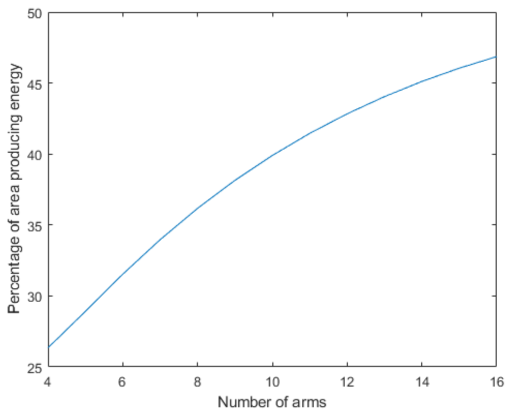

FIGURE 2
PERCENTAGE OF AREA THAT GENERATES ELECTRICITY

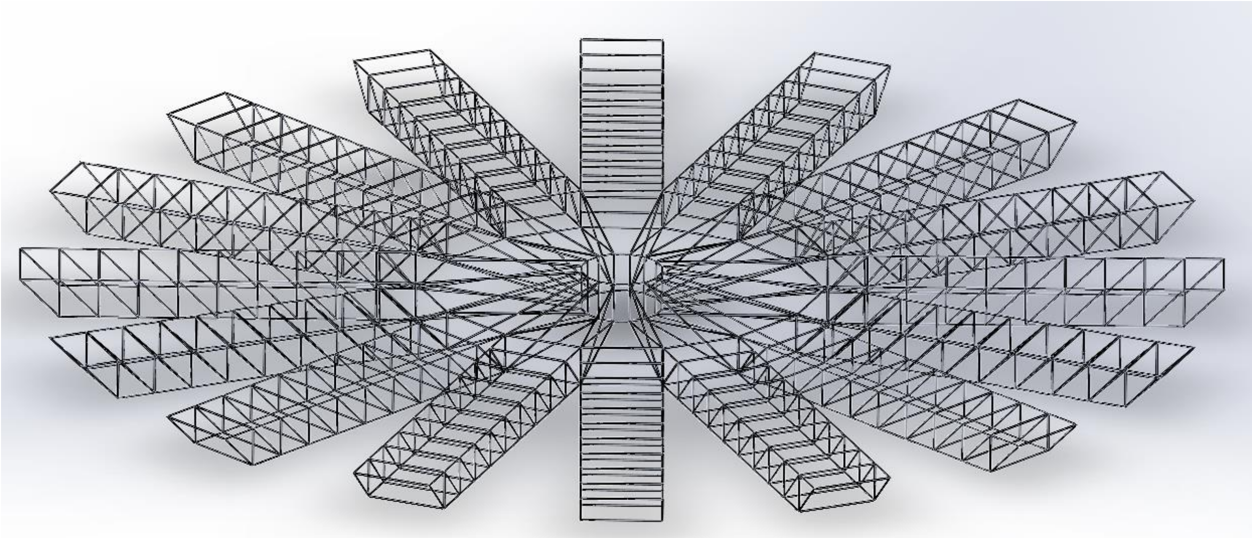

FIGURE 1
IMAGE OF FULL DESIGN

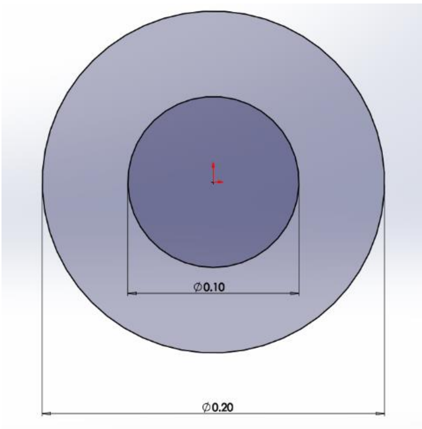

FIGURE 3
IMAGE OF CROSS SECTION OF MEMBER

The structure is made of a frame of circular cross sectioned members as shown in figure 3. The cross section has an internal diameter of 0.1m and an external diameter of 0.2m. This cross section was settled upon after testing the deformation of the structure under load with several different sized cross sections with this cross section having the best performance.

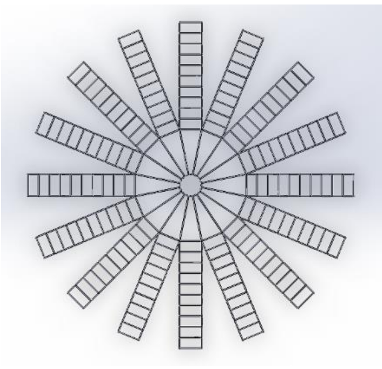

FIGURE 4
TOP-DOWN VIEW OF THE DESIGN

To find the force on the structure due to gravity, the acceleration due to gravity at the altitude of 35786km (GEO altitude) [11]. This parameter can be found by solving the two-body problem.

Taking the two-body problem with Earth at the origin of the inertial frame of reference, the acceleration due to gravity can be calculated using (3.1) as shown in Spacecraft Systems Engineering [9].

$$g = -GM \div r2 \tag{3.1}$$

This gives an acceleration due to gravity of 0.2241 m/s^2.

Using the mass values from the paper Eurotrough design issues and prototype testing at PSA, and the acceleration due to gravity in the chosen orbit the weight of the collectors can be calculated [10].

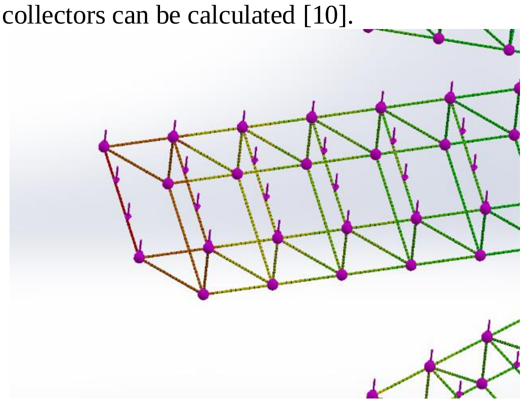

FIGURE 5
IMAGE OF STRUCTURE SHOWING THE DISPLACEMENT RESULTS OF THE SIMULATION

Figure 5 shows the displacement of structure under the weight of the collectors when simulated by SOLIDWORKS. There was minimal deformation in the center. The maximum resultant displacement calculated by the simulation was 0.023399m, which in comparison to the radius of the satellite which is 88.16m, is a negligible displacement. The key values relating to the structure are detailed in Table 1.

TABLE I
TABLE OF DESIGNS KEY VALUES

Parameter	Value
Material	Aluminium 7075
Mass (kg)	330911.977
Diameter (m)	176.32807
Energy Generating Area (m^2)	11136

IV. REACTION WHEEL DYNAMICS

A. *Code design*

To model the dynamic forces on the satellite due to the reaction wheels a MATLAB code has been developed to simulate the torque required in different load cases. The code is a time-step simulation and uses a set of equations to calculate the motion and torque of the satellite. The code uses a for loop to calculate the parameters of the reaction wheels and satellite for every second over a set period. Due to the design having the reaction wheels placed on the axis the x and y motion of the satellite can be independently calculated.

Before coding, the parameters of the reaction wheels and the satellite need to be set out. The reaction wheels have a radius of 2.5m and thickness of 0.1m. Using Aluminium 7075 the mass can be calculated using a density of 2810kg/m^3 [12]. This mass can then be used to calculate the Moment of Inertia in the x axis using (4.1) [13]. Due to imposing a maximum angular velocity of the reaction wheels based on currently available electric motor maximum rotation speeds, a maximum amount of energy that can be put into the reaction wheels is set at 560000 Joules.

$$I_x = (mr^2) \div 4 \tag{4.1}$$

TABLE II
TABLE OF REACTION WHEEL KEY VALUES

Reaction Wheel Parameter	Value
Mass (kg)	5517.422
Radius (m)	2.5
I_x (kg×m^2)	8620.97

The code functions by matching the angular velocity of the satellite to a required angular velocity input by the user. The angular acceleration required to achieve the required velocity can be calculated. Due to the fact that every time-step is 1 second the angular acceleration required is the difference between the target angular velocity and current velocity.

$$\alpha_{req} = \omega_{target} - \omega_{current} \tag{4.2}$$

Using the angular acceleration required the torque required can be calculated in combination with the moment of inertia in the axis of rotation which in this case is the x-axis [9].

$$T_{req} = I_{x\_satellite} \times \alpha_{req} \tag{4.3}$$

As shown in Figure 6 the reaction wheel placement means that two reaction wheels act on each axis therefore each reaction wheel only has to produce half of the required torque in that axis. Using the torque required of the reaction wheel and the moment of inertia of the wheel, the angular acceleration can be calculated [9].

$$\alpha_{req\_wheel} = T_{req\_wheel} \div I_{x\_wheel} \tag{4.4}$$

This angular acceleration can be used to calculate the amount of kinetic energy added to the reaction wheel as the angular acceleration over one second is equal to the angular velocity [14].

$$E_K = 0.5 \times I_{x\_wheel} \times (\alpha_{req\_wheel})^2 \tag{4.5}$$

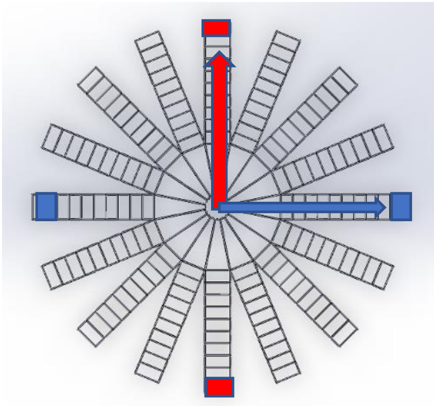

FIGURE 6
IMAGE SHOWING REACTION WHEEL PLACEMENT AND THE X AXIS (BLUE) AND Y AXIS (RED)

After checking that the energy added to the wheel does not exceed the max energy, the angular acceleration produced by the reaction wheel can be calculated and used to calculate the torque produced by the reaction wheel. This can then be used to calculate the change in the angular velocity of the satellite.

B. *Code results*

To test the code, it was run with the angular velocity of the sun across the sky as the target velocity. This however was a very small angular velocity and easily achieved, with the disturbing torque of the environment being much larger than the torque required to follow the sun. Therefore, the code was run again with the aim of rotating 180 degrees in the x- axis within 10 minutes.

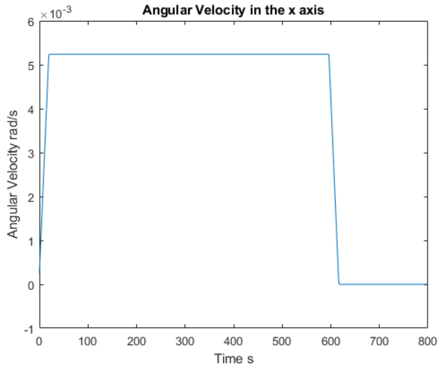

FIGURE 7
ANGULAR VELOCITY IN THE X AXIS

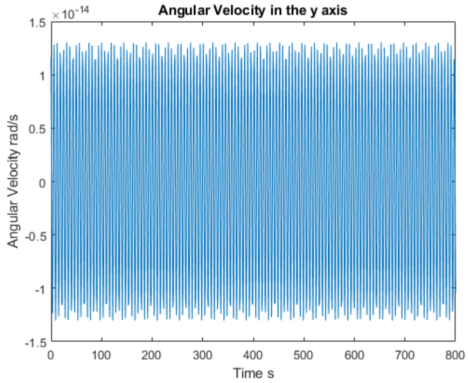

FIGURE 8
ANGULAR VELOCITY IN THE Y AXIS

As shown in Figure 7 the satellite was able to achieve the required angular velocity and rotated 180 degrees in 618 seconds. This is just over the targeted 10 minutes, due to the time taken to accelerate to the angular velocity not being taken into account when choosing a target angular velocity, however this can be made up for by accelerating to a slightly higher velocity.

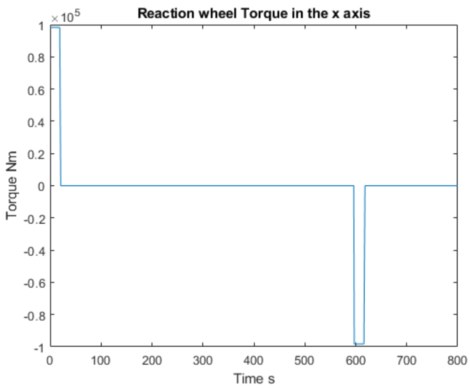

FIGURE 9
GRAPH OF THE TORQUE PRODUCED BY THE X AXIS FLYWHEELS

Figure 9 show the torque produced by each of the reaction wheels in the x axis. To achieve the target angular velocity the reaction wheel produces a pulse of maximum torque for a period before reducing to zero until an equal and opposite torque is required to bring the angular velocity to zero, therefore halting the rotation of the satellite.

V. DYNAMIC FORCES ON THE STRUCTURE

TABLE III
TABLE OF RESONANT FREQUENCIES OF THE STRUCTURE

Mode No.	Frequency (Rad/sec)	Frequency (Hertz)	Period (Seconds)
1	0.17676	0.028132	35.546
2	1.2133	0.1931	5.1787
3	1.2197	0.19412	5.1514
4	1.2221	0.1945	5.1413
5	1.2242	0.19484	5.1324

When in GEO orbit the main forces on the satellite will be gravity and the reaction wheel forces produced by the satellite. It is important that when rotating the satellite the reaction wheels do not excite the structure at its resonant frequency. Using the Solidworks model of the structure the resonant frequencies of the first 5 modes has been calculated so that when the structure is being maneuvered exciting it at these frequencies can be avoided. It is unlikely that any other sources of excitation will be able to excite the structure at the resonant frequency as gravity is constant and solar radiation pressure is also fairly constant.

When adding the maximum force produced by the reaction wheels to the structure, the displacement caused by this extra force can be found with Solidworks simulations. The time-step simulation calculated the maximum force as 1114.51N when performing the maneuver detailed in the previous section. From the Solidworks simulation the maximum resultant displacement was calculated as 0.02354m which means that the extra force only produces 0.141mm of extra displacement. This suggests that the structure is more than capable of being maneuvered by the reaction wheels without major deformation that would reduce the efficiency of the solar energy collectors.

Using the results of the simulations performed it is clear that the structure is fit for purpose whilst not appearing to be overdesigned.

VI. COMPARISON TO OTHER DESIGNS

A. *Energy Production*

To compare the satellite design to previous designs, the estimated energy production needs to be calculated. The useful energy collected can be calculated using (6.1) from Solar Energy Engineering: Processes and Systems [15].

$$Q_u = A_a F_R[G_t(\tau\alpha)_n - U_L(T_i - T_a)] \tag{6.1}$$

This gives a value of 11.2025376 MW for the satellite when the angle of incidence of the solar radiation is 0.

B. *Comparison to other SSPS designs*

The best design to compare this design to is OMEGA as it is the most recent. The OMEGA and this design both use the same orbit as do most of the other designs with the only design not using GEO being the oldest design in the table.

TABLE IV
TABLE OF SSPS DESIGNS

Name	Sun-Tower [16]	Sail-tower [17]	ISC [6]	Tethered [18]	ALPHA [6]	OMEGA [6]	This Design
Year	1995	1999	1998	2001	2012	2015	2021
Organisation	NASA	ESA	NASA	USEF	AIMS	Xidian University	N/A
Power (GW)	0.1-0.3	0.45	1.2	0.75	2	2	0.0112
Orbit	LEO/MEO	GEO	GEO	GEO	GEO	GEO	GEO
Mass (MT)	2000-7000	2100	22463	20000	25260	22953	0.00033
MT per GW	23333.333	4666.667	18719.167	26666.667	12630	11476.5	1.853x10-6

However, this design is a lot smaller and has a lot less mass than the OMEGA, as well as producing less energy. Although the energy produced by this design is much lower than the other designs, the amount of mass per unit of energy produced is much smaller than the other designs showing that this design is more economical in terms of initial cost and cost to launch than the other designs. This mass per energy produced value will increase as the design progresses as the current mass does not take into account the weight of the subsystems such as the main flywheel energy storage and the energy transmission array.

Comparing this design to other SSPS designs is difficult due to the different design philosophy employed in producing the design detailed in this paper. Other SSPS designs have been on a much larger scale and are intended to be more one-off projects, whereas the design in this paper is one a much smaller scale with the hope of it being reproduced many times by countries with limited solar resources within their borders.

C. Comparison to terrestrial designs

With sending large structures into space being very expensive it is worth considering whether the extra money required for a space-based design yields a more efficient design.

The main disadvantage of an SSPS is the large initial cost combined with the increased cost of maintenance. An increased complexity in the design would also require more time and expertise to design combined with more systems that could develop faults. The disadvantages of an SSPS are largely all to do with the cost, therefore as long as the power produced is large enough is this can counter the extra cost out by generating more money coming in.

There are several advantages of having a SSPS over a terrestrial design mostly due to the change in solar radiation exposure due to being in orbit.

The first of these advantages is the increased solar radiation due to none of it being absorbed by the atmosphere. As shown in Figure 10 only 70% of the sunlight comes direct to earth, therefore a SSPS would be able to convert 30% more solar radiation making it more efficient. This diagram is also for a clear sky, clouds will significantly reduce the solar radiation that will be available for conversion by a terrestrial plant. The angle of incidence of the sunlight for Figure 10 is zero, this means as the sun moves across the sky the solar radiation absorbed will increase as the sun light will have to travel through more atmosphere before reaching a terrestrial plant reducing the efficiency at nonpeak hours.

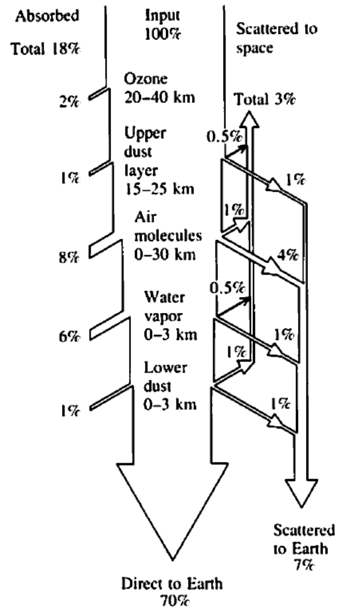

FIGURE 10
DIAGRAM OF CLEAR SKY ABSORPTION AND SCATTERING OF SOLAR ENERGY [19]

The second advantage of a CSP being in orbit is the number of hours in a set period, in this case a solar day, that are spent in direct sunlight, therefore generating power.

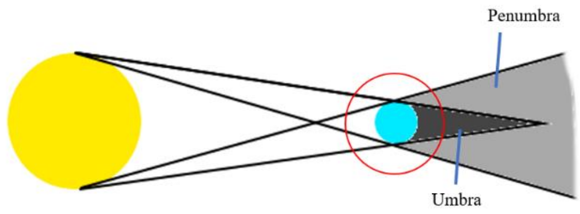

FIGURE 11
DIAGRAM SHOWING THE UMBRA AND PENUMBRA OF EARTH

As shown in Figure 11 a CSP in orbit (shown in red) would spend less time in the umbra than a terrestrial plant. This allows more hours of energy producing time per orbital period.

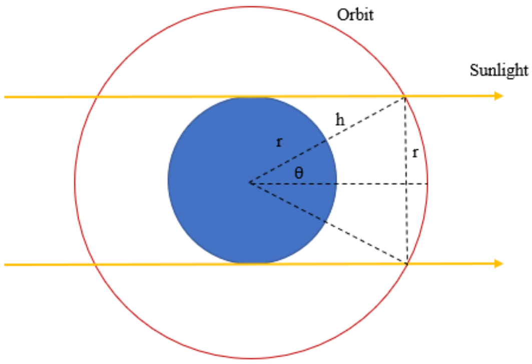

FIGURE 12
DIAGRAM OF EARTH'S SHADOW ASSUMING PARALLEL SUNLIGHT

If it is assumed that sunlight reaching earth is parallel as in Figure 12, the section of the orbit in darkness can be easily calculated using trigonometry. In reality the size of the sun compared to the earth means that the suns light will not arrive perfectly parallel as in shown Figure 11, however the huge distance between the sun and the earth will make this estimate of section of orbit in earth's shadow accurate.

Using trigonometry theta can be calculated and this angle can then be used to calculate the percentage of the orbit in the shadow.

$$\Theta = sin^{-1}(r \div (r+h)) \tag{6.2}$$

This gives a θ of 8.69 degrees which means that the satellite would spend 4.83% of its orbit in earth's shadow.

VII. Conclusion

The aim of this paper and the design detailed within has been to investigate the possibility of a different type of SSPS, a smaller design that could be employed in a wider network of identical satellites, with the ultimate goal of having multiple satellites transmitting to a single ground station.

During the study of the concept some advantages were discovered.

1. The smaller size of this design allows the design to be more easily launched into orbit with current technology.
2. The smaller size allowed the design to be more efficient in terms of Energy produced per amount of mass of the satellite.
3. The use of the reaction wheels to rotate the satellite to follow the sun across the sky allows it to keep the collectors working at the maximum efficiency for the whole day period as the angle of incidence remains at zero.
4. Compared to terrestrial designs, the time being spent in earth's shadow by and SSPS is much lower giving more energy producing time.

There still however is more study on elements of the design before it can get past the conceptual stage.

1. The amount of power that can be transmitted to the surface and what the power transmission system design requires.
2. The design of the parabolic trough collector has not been optimised for use in the conditions found in orbit; a more efficient design for that situation could be investigated.
3. The lifecycle of the design should be investigated looking into issues such as orbit maintenance, redundancies for damaged components and failure due to environmental wear and tear.
4. The design was produced with the assumption that construction would take place in orbit, the actual methods of construction in orbit need further investigation e.g., use of cold welding and other methods.

This paper has shown that the concept of a smaller SSPS is possible and can be a viable source of solar energy. With more work looking into the transmission systems, and how to deploy a wider network of satellites of this type, a viable source of solar energy could be found using a design like the one in this paper.

VIII. References

[1] UK Energy in Brief [Data file]. Department of Energy and Climate Change;July 2014. [25 Jan 2021]. Available from: https://www.gov.uk/government/statistics/uk-energy-in-brief-2014

[2] UK Government. New plans to make UK world leader in green energy [Internet]. Gov.uk;6 October 2020 [cited 25 Jan 2021]. Available from: https://www.gov.uk/government/news/new-plans-to-make-uk-world-leader-in-green-energy#:~:text=The%20government's%20plan%20for%20renewable,build%20back%20greener%20from%20coronavirus.&text=The%20government%20has%20raised%20the,ready%20to%20meet%20the%20challenge.

[3] Burnett D, Barbour E, Harrison G P. The UK solar energy resource and the impact of climate change. Renewable Energy. 2014 June 13;71(2014):333-343

[4] Garcia I L, Alvarez J L, Blanco D. Performance model for parabolic trough solar thermal power plants with thermal storage: Comparison to operating plant data. Solar Energy. 2011 October;85:2443-2460

[5] Jebasingh V K, Joselin Herbert G M. A review of solar parabolic trough collector. Renewable and Sustainable Energy Reviews. 2015 Nov 11;54:1085-1091

[6] Li X, Duan B, Song L et al. A new concept of space solar power satellite. Acta Astronautica. 2017;136:182-189

[7] Space-based Solar Power [Internet]. European Space Agency;2013 Apr 15 [27 Jan 2021]. Available from: https://www.esa.int/gsp/ACT/projects/sps/

[8] Role of Clouds [Internet]. NASA;2004 Apr 22 [28 Jan 2021]. Available from: https://www.nasa.gov/audience/forstudents/5-8/features/F_The_Role_of_Clouds.html

[9] Fortescue P, Swinerd G, Stark J. Spacecraft System Engineering. Fourth edition. Chichester: John Wiley and Sons; 2011.

[10] Lüpfert E, Geyer M, Schiel W, et al. EUROTROUGH DESIGN ISSUES AND PROTOTYPE TESTING AT PSA. Proceedings of Solar Forum 2001:

Solar Energy: The Power to Choose; April 21-25 2001; Washington DC.

[11] Types of orbits [Internet]. 2020 Apr 30 [cited 2021 Apr 6]. Available from: https://www.esa.int/Enabling_Support/Space_Transportation/Types_of_orbits#GEO

[12] MatWeb Aluminum 7075-O [Internet]. [cited 2021 Apr 20]. Available from: http://www.matweb.com/search/DataSheet.aspx?MatGUID=da98aea5e9de44138a7d28782f60a836

[13] Serway R A. Physics for Scientists and Engineers. 2nd Edition. New York: Saunders College Publishing; 1986.

[14] Larminie J, Lowry J. Electric vehicle technology explained. Second edition. Chichester: John Wiley and Sons; 2012.

[15] Kalogirou S A. Solar Energy Engineering : Processes and Systems. London: Elsevier Science & Technology;2009.

[16] Mankins J C. A TECHNICAL OVERVIEW OF THE "SUNTOWER" SOLAR POWER

SATELLITE CONCEPT. Acta Astronaut. 2002;50:369-377.

[17] Seboldt W, Klimke M, Leipold M, Hanowski N. European Sail Tower SPS Concept. Acta Astronaut. 2001;48:785-792.

[18] S. Sasaki, K. Tanaka, K. Higuchi, N. Okuizumi, S. Kawasaki, N. Shinohara, et al. A

new concept of solar power satellite: tethered-SPS. Acta Astronaut. 2006;60:153–165.

[19] Hu C, White R M. Solar Cells: From Basics to Advanced Systems. New York: McGraw-Hill Book Company; 1983.