THE TECHNOLOGY AND COSTS BEHIND SOLAR POWER SATELLITES

Lappeenranta–Lahti University of Technology LUT

Bachelor's Programme in Technology and Engineering Science, Bachelor's thesis

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Supervisor: Assoc. Prof. Michael Child

ABSTRACT

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The Technology and Costs behind Solar Power Satellites

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A Solar Power Satellite can open new opportunities in space exploration and energy production. Solar power in space is more energy-dense than on Earth and it is always available. This thesis explores different concepts of solar power satellites, obstacles, and major technology segments, and discusses ways to improve them. That is achieved by reviewing relevant literature and studies. In addition, the paper discusses the costs associated with the project, its feasibility, and its practicality. Since microwave-based solar power satellites are more practical than laser-based at this stage, this thesis mostly focuses on microwave power transmission. The LCOE was determined to be $0.35 c/kWh with a ROI of 12 years, and an initial investment of $74.56B, which makes it a high-risk investment. The project has been discussed for decades, and no major breakthroughs are required. The only major obstacle to bringing this project to life is transportation costs, which compose a large portion of the investment and increases the risk of the investment. Pursuing this project gives humankind new possibilities for energy production in space.

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Lastly, I would like to acknowledge Elon Musk for inspiring me to think big, even though he is not a fan of solar power satellites.

Thanks, guys, you’re awesome.

SYMBOLS AND ABBREVIATIONS

Roman characters

A	area	[m^2]
a_n	amplitude	[m]
E_t	energy output per year	[Wh]
F_t	fuel costs	[$]
h	load hours	[h]
H	power density	[W/m^2]
I_t	Investment expenditure in the year t	[$]
M_t	operation and maintenance costs	[$]
P	power	[W]
PR	performance factor	[%]
r	discount rate	[%]

Greek characters

δ_n	phase	[°]
η	efficiency	[%]
η_{pv}	solar cell efficiency	[%]
λ	wavelength	[m]

Constants

c	speed of light	299,792,458 m/s

Abbreviations

AC	Alternating Current
B	Billion
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CPV	Concentrating Photovoltaic
DC	Direct Current
EM	Electromagnetic
GaAlAs	Gallium Aluminium Arsenide
GEO	Geostationary Earth Orbit
GHz	Gigahertz
GW	Gigawatt
ISM	Industrial, Scientific, Medical
kW	Kilowatt
LCOE	Levelized Cost Of Electricity
LEO	Low Earth Orbit
M	Million
mA	milliampere
MW	Megawatt
OCGT	Open Cycle Gas Turbine
PEN	Polyethylene Naphtalate
PMAD	Power Management and Distribution
PP	Power Plant
PV	Photovoltaic

RF	Radio Frequency
SPS	Solar Power Satellite
TWh	Terawatt hours
UV	Ultraviolet
WPT	Wireless Power Transfer

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1 Introduction

1.1 What is a Solar Power Satellite?

A Solar Power Satellite (SPS) is a space-based plant that gathers large quantities of sunlight within space and delivers it as electrical power to Earth utilizing Wireless Power Transfer (WPT). Currently, no SPS is in operation. While all satellites that are currently in orbit host a solar collector, none of them has the primary purpose of harvesting solar energy in space (Flournoy, 2012). An SPS will collect the Sun's energy using arrays of photovoltaic (PV) cells and beam it down to Earth as an electromagnetic (EM) wave, which is the same type of wave that communication satellites have used to deliver data, sound, and video to and from Earth for over 40 years already. However, a highly concentrated energy beam is used in this case. Since solar power and communication satellites are both similar in terms of operational and technological requirements, it is important to note how their markets might converge. While satellites already perform various tasks besides communication such as weather forecasts, navigation, geo-positioning, etc., they only gather solar power to power themselves. On the contrary, an SPS beams the energy to a specific spot, where the energy is received and converted. The realization of an SPS is directly correlated with progress in space commercialization overall.

1.2 Why are they needed?

The power density of sunlight within space is about 1,368 W/m^2 (NESTA, 2012), while 1,000 W/m^2 is generated at noon on a clear day near the equator. Solar arrays on the ground can provide only base-load power if they are integrated with a large energy storage system (batteries, flywheels, pumped water storage, etc.). Unlike other sources of energy, SPS does not emit greenhouse gases, does not produce hazardous waste that must be stored for decades, does not require cumbersome mining operations, and provides large quantities of power 24/7 regardless of wind speed, daylight, weather, and season. In addition, a shift to solar energy on a large scale can reduce competition for the limited supplies of Earth-based energy, which is expected to be the cornerstone for future wars (Flournoy, 2012, p. 7).

1.3 When will it launch?

Most probably, an SPS will not see a launch pad very soon. The size and costs of the technology are tremendous as seen later in this thesis. However, no technological breakthroughs are required as the components and systems have been studied for over 5 decades already since Glaser first proposed the concept of beaming solar energy from space in 1969 (Glaser, 1968). In 2010, Hsu answered the question of whether solar energy from space is feasible by saying “positively and absolutely” yes, explaining that one of the reasons that less than 1% of the world’s energy comes from the Sun is due to the high costs of PV cells and high inefficiencies in energy conversion (Hsu, 2010).

Despite that, several government-based agencies and companies around the world already focus their efforts on bringing the satellite to reality. For example, the Space Energy Initiative is an interesting new project that could see Britain set up the first power plant within space for demonstration by 2030 and it should start supplying power to the grid by 2040. It will be made up of satellites with lightweight PV arrays and mirrors to concentrate the light on the panels, producing around 3.4 GW of electricity. The plan is to have the first generation of this type of satellite in operation by the mid-2040s, which would replace a large part of the electricity generation capacity produced by fossil fuels (Space Energy Initiative, 2022). Regarding Europe’s input in the production of space-based solar power, decisions are currently being made to move forward with the project “Solaris”, which has a goal to prepare to fully start developing the satellite by 2025 by assessing the viability of it in various aspects (ESA, 2022).

1.4 Purpose of this research

The purpose of this research is to assess the feasibility and costs of SPS. The paper takes an insight into the most important technology areas of the satellite and objectively discusses the challenges and possible solutions. It is done by reviewing the literature and making relevant calculations. Different designs of the system were considered as well as emerging cutting-edge technologies that could improve the overall viability of the project. The efficiencies of different system parts were calculated, costs approximated, and overall feasibility and financial viability were discussed.

2 The technology

A solar power satellite is comprised of many subsystems such as photovoltaic cells that collect energy, a wireless power transfer system, power management and distribution, attitude control systems, platform propulsion, and ground interfaces. High efficiency is required within all systems for this project to be economically viable. This chapter discusses recent breakthroughs and possible upgrades that could be implemented to make the satellite more efficient and realizable.

2.1 Obstacles

The most significant barriers are the lack of easy and cheap access to space, inefficiencies of solar cells, wireless power transmission and reception networks, energy conversion, storage, and distribution systems. The lack of a regular transportation system to orbit is thought to be the single biggest reason SPS is still not implemented at any scale. A limited number of rockets are available and they are attributed to a small number of satellites and almost none of them are reusable, which shows that space is underdeveloped as a commercial destination. The fear of space being overcrowded is also present, which can cause satellites to collapse onto each other. These incidents are rare, but they happen. The Space Data Center, for example, works towards reducing the chances of collisions and frequency interference between satellites globally, and it was established after a series of incidents when several satellites collided. Another problem is thousands of space debris pieces that are still orbiting within space. Solar flares and storms can also cause satellites to malfunction by creating static electricity that can discharge or short-circuit electrical components on board. Interference between satellites is a big concern and it has not been studied properly yet. Nevertheless, the signal must be separated from other communications, WPT must be “clean”, and the transmitted energy must not be smeared over a broad range of frequencies (Flournoy, 2012).

For SPS to be economically feasible, it is either supposed to be lightweight or transportation by reusable rockets must be inexpensive. Once the system is deployed, it has to assemble itself at least to some extent, supposedly by intelligent modular systems. The electronics should be able to withstand high temperatures and have high efficiency. For instance, beaming 1 GW of radio frequency (RF) wave with amplifiers of 20% efficiency means 4 GW of waste heat must be removed from the spacecraft, while amplifiers with 80% efficiency will produce only 250 MW of waste heat, reducing the size and costs of a cooling system (Mankins, 2014).

2.2 Designs

A solar power satellite has been discussed for decades and several promising concepts have been considered. They have different operating frequencies, various structures, and slightly different principles of transmission, but they all have one job – to harvest and deliver solar energy.

2.2.1 Reference System by National Aeronautics and Space Administration (NASA) and Department of Energy (DOE), US, 1978

This SPS is expected to output 10 GW of DC power (version of 1979). It has a transmitting antenna (1 km in diameter) on one end that connects with the rectenna[1] on the ground (Figure 1). The power amplifier utilizes more than 100,000 klystrons. The rectenna on the ground has subarray panels with an area of 78.5 km^2. The overall dimension is 5.3 by 10.4 km, and the mass of 31-46 thousand tonnes. The system would operate on 2.45 GHz and have a power

[1] Rectenna - an antenna comprising a mesh of diodes and dipoles for absorbing microwave energy from a transmitter and converting it into electricity.

density of 0.023 W/m^2 at the center of the rectenna, but 0.001 W/m^2 at the edge (DOE & NASA, 1979).

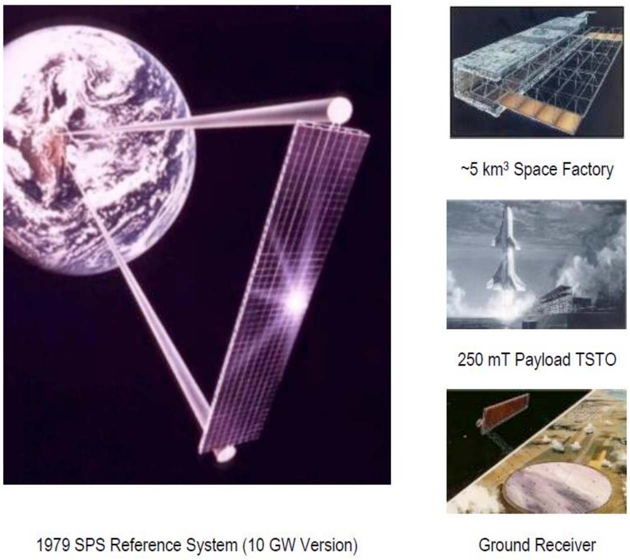

Figure 1. Reference SPS (DOE & NASA, 1979).

Single-crystal silicon and GaAlAs solar cells are considered for energy conversion. An electrical energy storage (around 12 MWh) power system is located on the antenna with a bus connected along the regular network for the system to operate during power-down periods, which can happen during an eclipse, for example. Every subarray has phasing electronics and an RF receiver to process a pilot beam phasing signal that comes from the ground-based receiver. The subarrays form a single coherent beam focused in the middle of the rectenna on the ground. The beam efficiency is around 88%, radius within 5 km, with a 1.2 arc-minute resultant beam width (DOE & NASA, 1979).

2.2.2 SPS2000 by ISAS, Japan, 1993

A saddleback roof-shaped SPS formed by solar panels and the "spacetenna"[2] is built to transmit microwaves to Earth (Figure 2). The shape is meant to simplify the attitude control

[2] Spacetenna - power transmission antenna placed on the bottom surface facing the earth, and the other two surfaces are used to deploy the solar panels. The spacetenna is constructed as a phased-array antenna.

system and avoid using a reaction control system since it utilizes gravity gradient force[3] to stabilize the attitude. It will use a frequency of 2.45 GHz, it will have a power of around 10 MW, a mass of 134,4 tons, a square shape of 132 m by 132 m, and a power density of 574 W/m^2. To minimize the distance of power transmission and transportation cost, an equatorial orbit (1100 km altitude) will be used (Nagatomo et al., 1994).

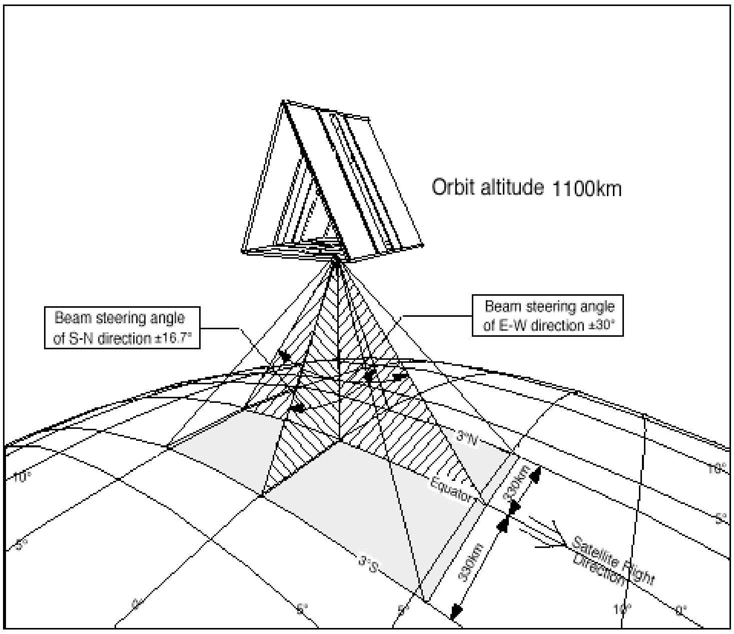

Figure 2. SPS2000 concept (Nagatomo et al., 1994).

A subarray will be composed of 12 solar cells. The array (110 subarrays) is a mechanical element for assembly. The array modules generate 180 A at 1 kV each. Similar to the US Reference System, the mechanical and electrical design of the system is simpler by using square a shape and a single power level. However, microwave power is lower and below international safety standards.

[3] Gravity-gradient stabilization – a method of stabilizing space tethers or artificial satellites in a fixed orientation using only gravitational field and the body's mass distribution.

2.2.3 Sun Tower by NASA, US, 1997

The “SunTower” is another gravity gradient-stabilized RF-transmitting solar power system (Figure 3). It will be made of single satellite/ground receiver pairs of roughly 100-400 MW. The concept will entail relatively small components due to extensive modularity. No concept-unique structure is needed beyond what is required to achieve low launch costs ($200-$400/kg). The concept will transmit at 5.8 GHz from an initial operational Sun-synchronous orbit, at a transmitted power of around 200 MW RF. To transmit that power, the transmitter array elements are roughly 260 meters in diameter and 0.5-1 m in thickness (Mankins, 1997).

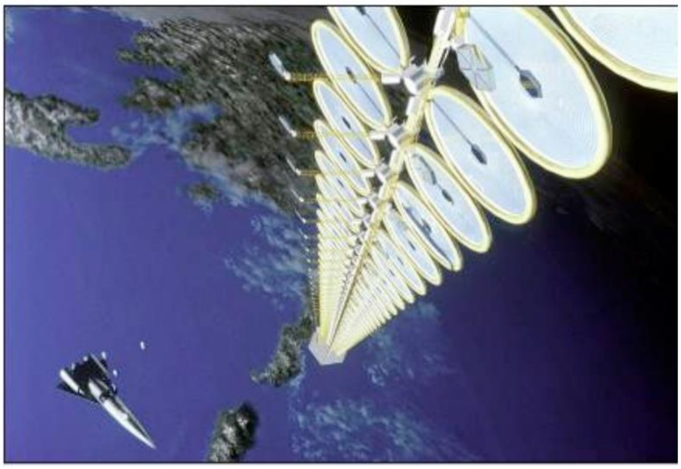

Figure 3. Sun Tower (Oleson, 1999).

Photon-to-electron conversion must be modular and deployable in units with a diameter of 50-100 m and net output of 1 MW. Gossamer-structured reflectors with non-dynamic conversion will be the primary technology. Heat rejection for power conversion and conditioning systems should be modular as well and integrated with power conversion systems. The ground receiver will be 4 km in diameter with direct electrical feed into the grid. No unique in-space infrastructure is necessary for initial deployment, which is located in LEO. Nevertheless, launch systems should include modular assembly-support systems.

2.2.4 Sail Tower, EU, 1990s

Solar sails are large lightweight reflecting structures floating in space that utilize the pressure of photons coming from the sun for propulsion (Figure 4). A solar sail consists of four extremely lightweight carbon fiber-reinforced plastic booms, four triangular sail segments, and one central deployment (Seboldt et al., 2001). Polyethylene-naphthalate (PEN) and kapton are appropriate candidates for the substrates they both have suitable thermal, mechanical, and environmental compatibilities. The films are coated with a reflective material (aluminum) on the side facing the side and emitting material (Chromium) on the other side. Navigation of the sail is achieved through an attitude control system by adjusting the position of the surface relative to incoming sunlight.

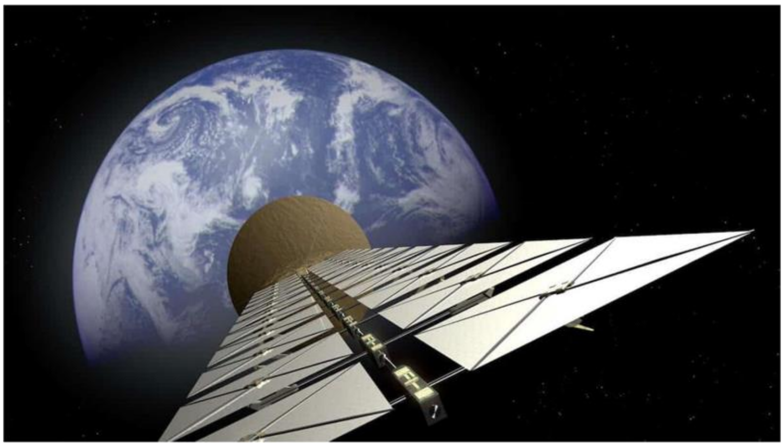

Figure 4. Sail Tower (Seboldt et al., 2001).

Similar to “SunTower”, it has a “central tether” with 120 sun-tracking modules that generate power attached in pairs. It is placed in GEO and has a length of 15 km. The thickness of the coated sail is 12 µm and has dimensions of 150 m by 150 m and a mass of 1,600 kg including mechanisms and deployment module. The system operates at 2.45 GHz and is meant to transmit power of 450 MW. The transmitter makes use of 400,000 magnetrons at around 1 kW each.

2.2.5 JAXA2004 by Japan Aerospace Exploration Agency (JAXA), Japan, 2004

This design does not need to include sophisticated electronics, since the energy transportation will be in the form of light. The Earth-pointing part will take place in the GEO, while the reflectors will use solar pressure to reach the orbits perpendicularly separated from the GEO (Figure 5) (Takeichi et al., 2005). Therefore, the orbits of the reflectors will be parallel to the GEO and have the same period. A configuration like that does not need any large rotation mechanisms, which removes the single point of failure. It will use a frequency of 5.8 GHz and is expected to output 1 GW of power.

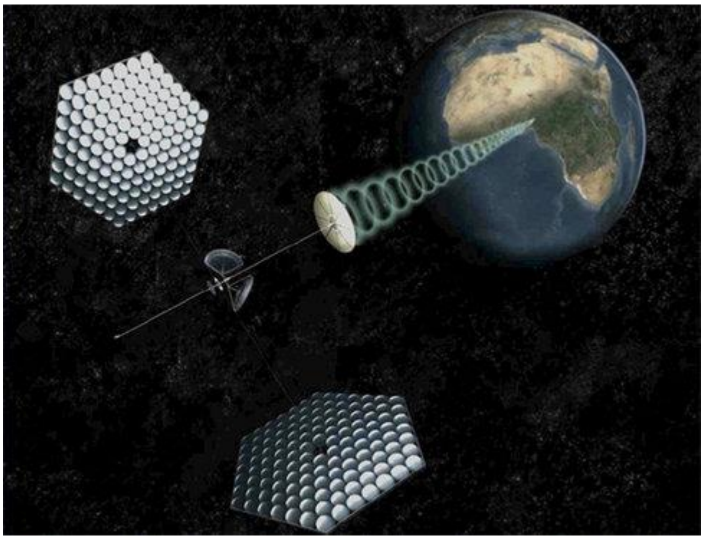

Figure 5. JAXA2004 model (Takeichi et al., 2005).

Formation flying mirrors do not need rotary joints. The size of the primary mirrors is 2.5 km x 3.5 km (2 panels), and weigh 1,000 tons each. The main panel will consist of a solar cell of size 1.2-2 km in diameter, a transmitter of 2.6 km, a receiver with a diameter of 1.9 km, and two secondary mirrors. The expected rectenna efficiency is 89.91% (Mori, Nagayama et al., 2004). The power generated by solar panels will be converted into a microwave beam through a transmitter. Each module is replaceable on a honeycomb frame and control signals are structured independently for a malfunction in one module to not affect other modules.

2.2.6 Laser SPS by JAXA, Japan, 2004

Unlike other designs, this one is a laser SPS, where mirrors and lenses are put into orbit to focus the sun's rays (Figure 6). The solar energy then is sent to a laser generator. The laser beam is produced using the direct solar pumping solid-state laser device. The beam is collected on the ground to produce hydrogen from seawater. The receiver and energy converting station are placed in the ocean, and ships can transport the hydrogen.

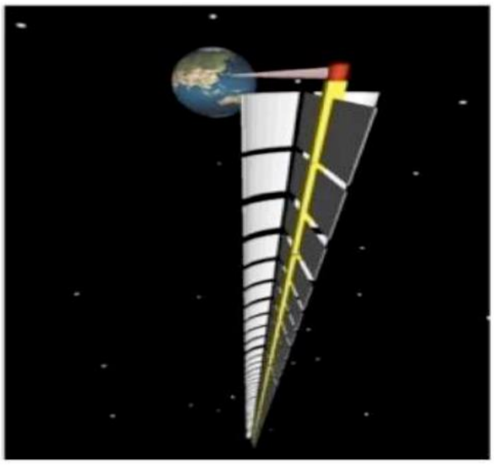

Figure 6. Laser SPS (Mori, Kagawa et al., 2004).

Neodymium-doped yttrium aluminum garnet (Nd : YAG) crystal is the most suitable candidate for the laser medium. The size of the design is 400 x 200 x 12 km with 100 modules and weighs 5,000 tons. The power is transmitted in the range of 10 – 100 MW. The output of 1 GW can be achieved by connecting 100 base units in series. Heat removal is a key issue in this design since the solar concentration is more than a few hundred times. The method to cut some unusable light wavelengths is considered to improve heat control. The assumed wavelength of the laser beam is 1.064 m, however, currently, no photo-catalyst is known for water decomposition into hydrogen and oxygen at high efficiency. The space segment is built within GEO and ground facilities are on seas near Japan (Mori, Kagawa et al., 2004).

2.2.7 USEF2004 Model by USEF/METI Tethered-SPS, Japan, 2004

This system has a large panel suspended by wires and connected to a bus system that is stabilized by the gravity-gradient force (Figure 7). This design has to be based on commercial off-the-shelf products for the system to be realized. The products usually have high performance at a reasonable price. A movable mechanism and active attitude control are considered for the mechanism and structure to be simple and robust. The microwave antennae are typically directed toward the Earth without active attitude control involvement. The power generated varies with local time because the sun’s angle changes.

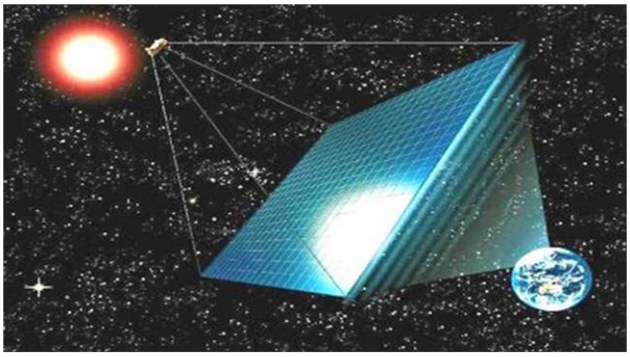

Figure 7. USEF2004 model (Sasaki et al., 2007).

This design outputs 1.2 GW of power and 0.75 GW average power reception on the ground. The panel and the bus system weigh 18,000 and 2,000 tons respectively. The power system consists of individual power generation/transmission modules. Each module generates power through solar cells and converts it into microwave power. The power modules have thin-film solar cells on the upper/lower plane, and a transmitting antenna on the lower plane including microwave circuits, batteries, and a controller between the two planes. It is easy to attach and detach elements for construction and maintenance (Sasaki et al., 2004).

2.2.8 SPS-ALPHA by NASA, US, 2012

The idea of the SPS-ALPHA concept is to form a large, modular system using a minimum number of module types (Figure 8). That modularity depends on in-space robotic assembly at an unprecedented scale. Compared to other designs, this satellite will not be 3-axis stabilized with one or more solar arrays. Instead, this satellite will entail body-mounted, non-moving, solar power generation modules on a gravity-gradient stabilized structure. The concept will involve large WPT transmitter arrays pointed toward Earth, a sunlight-intercepting reflector system, and a truss structure that connects everything else (Mankins, 2014).

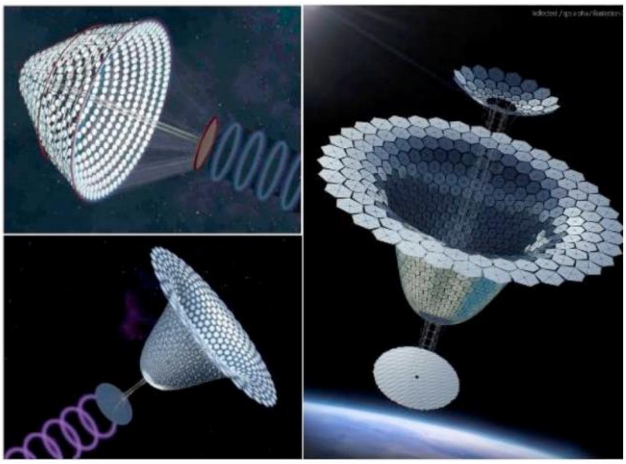

Figure 8. SPS-ALPHA concept (Mankins, 2014).

This architecture will use several emerging technologies, however, no breakthroughs in physics or materials are required. The concept depends on the retro-directive phased array, which is a key concept that occurred in the late 1980s (discussed later). The system does not have to be rigid and can be extremely lightweight since each element in the transmitter can adjust in shape for any local distortion.

2.3 PV cells and optical systems

PV cells are one of the most marvelous creations of engineering that allow us to produce clean energy. However, they have been developing for decades and still have room for improvement since their efficiency is low. An SPS will require more efficient and bigger panels than are currently on the market. According to Hsu, a typical SPS will carry a solar array with an area of roughly 10 km^2 to output around 1 GW of electric power (Hsu, 2010), meaning that a large portion of capital investment will go to the manufacturing of thin, lightweight, and extremely efficient PV cells. Improvements in PV arrays of a solar power satellite also improve the competitiveness of ground-based solar systems, thus questioning the need for the whole project. On the other hand, improved solar cells will reduce the size of receiving antenna and decrease launch costs, meaning SPS systems will still outperform ground-based systems.

Several experimental panels are cheap, light, and have an efficiency of up to 47% (Figure 9). Those panels could be great candidates for the application, however, they have to be tested for reliability since they will be within space possibly without maintenance for many years. Some designs of solar power satellites make use of concentrating photovoltaic systems (CPV) using reflectors and mirrors to increase efficiency and the amount of light converted into electricity.

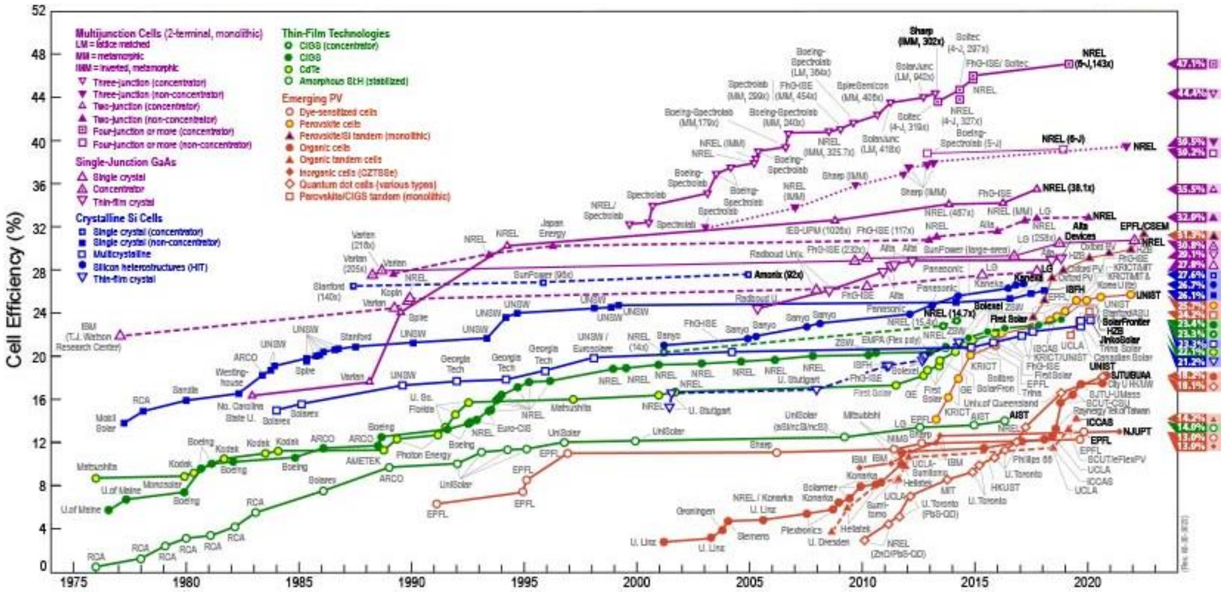

Figure 9. Best research-cell efficiencies (NREL, 2022).

Silicon-based cells are reaching their maximum efficiency, so other options must be considered. A promising candidate would be hybrid organic-inorganic perovskite-based solar arrays. Perovskite materials are cheap to produce and easy to manufacture. In silicon-based tandem cells, the efficiency reached 29.8% (NREL, 2022). However, they are not currently in use due to their quick degradation and lack of sufficient durability. They quickly decompose under influence of temperature and UV light (O'Kane, 2022).

Another candidate for the application is a multi-junction solar cell that is made of various semiconductor materials. The semiconductors allow for the absorption of a broader range of wavelengths, improving the cell's efficiency. The efficiencies reached more than 44% and the performance can be improved by adding an additional p-n junction with an optimum bandgap energy (Frank et al., 2015).

In an application where every gram counts, light flexible thin film solar panels would be a great option. Those panels would be great for "solar sailing", which uses the energy of incoming photons to push themselves. Small satellites that are less than 1 kg use this technology but could be applied to move the parts from LEO to GEO for assembly. However, current efficiency is lower than conventional silicon-based panels, but on the other hand cheaper. The technology has improved over the years and some types have achieved laboratory efficiency beyond 21% (Fraunhofer & GmbH, 2022). Space applications require the reduced weight of the solar panels, especially if a large number of panels is needed. Therefore, advancements in thin film solar technology can create more opportunities for powering a spacecraft.

2.4 Power management and distribution (PMAD).

PMAD is the interfacing technology between the power source and the satellite's components. These interfaces take place on a centralized power distribution board, which includes common components such as voltage regulators, current limiters, shunts, switches, and converters. Source control components include series regulators, shunt regulators, and shorting switch arrays. Power conditioning components include regulators, DC-DC regulators, and DC-AC inverter. Energy storage control components include regulators, and charges (Zhu, n.d.). An example of a power distribution system for the International Space Station can be seen in Figure 10. Since the 1970s, PMAD systems were heavy, which is a significant variable for an SPS. Lower mass could only be achieved with the assumption that high voltages of PV arrays are used, which are thousands of times more than those of typical communication satellites. Thus, if the platform encounters micrometeorites, the platform can be short-circuited and induced array discharged.

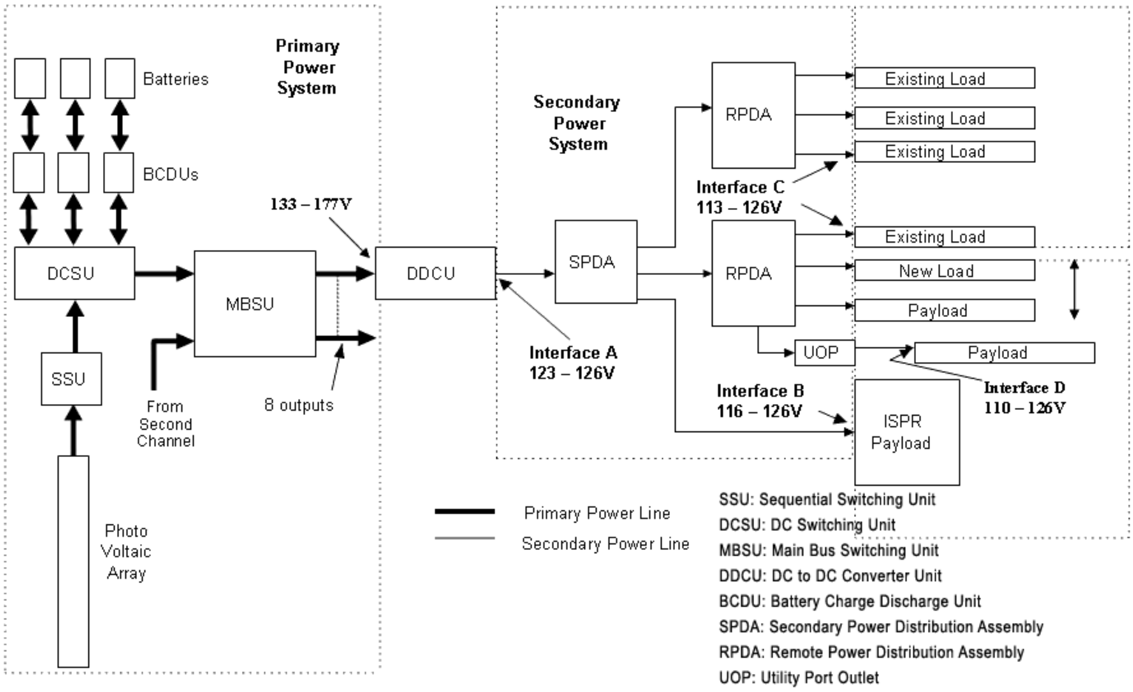

Figure 10. ISS Electrical Power Distribution. Image courtesy of Boeing. (Zhu, n.d.).

Two kinds of PMAD exist: low-voltage local and high-voltage long-distance PMAD. The first kind uses reflectors for linking the sun-facing and Earth-facing parts. The second kind is electrical. An improvement of this technology is required, for instance, high-voltage high-temperature superconductors, or a large and integrated PMAD, as these systems did not progress in the past decades. Advanced concepts like SPS-ALPHA involve lower voltage PMAD. It is achieved by placing solar arrays next to the WPT system. Future development may involve modular wireless micro-inverter architectures that emerged in ground-based solar power generation arrays (Mankins, 2014).

2.5 Transmitters

The transmitter module in an SPS consists of thousands of smaller modules that convert electricity into microwaves and beam down to the Earth on the rectenna. Microwave tube transmitters are vacuum tubes that generate and amplify high-frequency RF electromagnetic waves in the microwave band. They produce a high output, operate under high voltage, and have high-temperature tolerance. Both klystrons and magnetrons are the most popular candidates for the transmission module of an SPS.

A magnetron (Figure 12) is a cross-field high-power vacuum tube and an oscillator that is mostly used in radar applications and microwave heating. A microwave oven magnetron with a frequency of 2.45 GHz is still the cheapest 1-10 kW oscillator in the world (Shinohara, 2018, p. 93). A microwave oven magnetron is able to provide large amounts of power needed in some space applications. In the studies of the NASA/DOE reference system, Brown and Eves (1992) discovered that a conventional oven magnetron can be used as an inexpensive high-gain (30 dB) transmitter in SPS if used with an additional phase-locked control loop (Figure 11). Those amplifiers can be directly used in the radiating modules that make up a phased array. In addition, harmonic filters should be applied to reduce harmonic radiation to very low levels from both the transmitter and receiver (Brown & Eves, 1992).

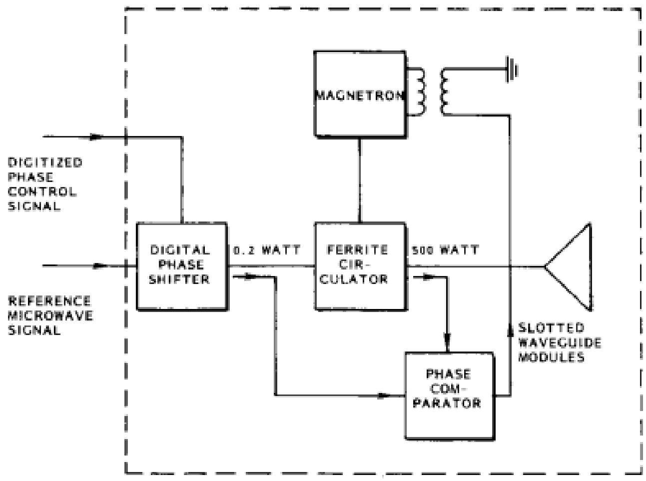

Figure 11. Diagram of radiation module with a phase-locked loop that shows its application to a radiating module in an electronically steerable array antenna (Brown & Eves, 1992).

A klystron (Figure 12) is a linear-beam type vacuum tube that is used as an amplifier in general, while a reflex klystron can be used as an oscillator. Klystrons provide high-power

DC-RF conversion; however, they require more complicated and bigger circuits rather than magnetrons, which have become extremely cost-effective and efficient in previous decades of research (Mankins, 2002). A two-cavity klystron amplifier typically has a gain of 10-15 dB and overall efficiency of 50-70% (Shinohara, 2018). In the original SPS concept, Glaser proposed the use of klystrons with 90% efficiency at a wavelength of roughly 10 cm (Glaser, 1968).

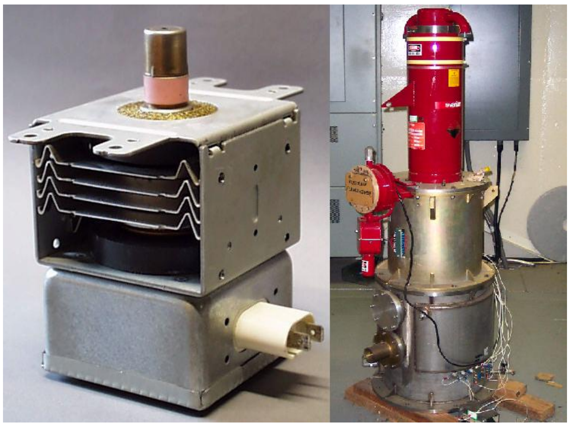

Figure 12. Cavity magnetron (left) and klystron (right) (CDSCC, 2004).

2.6 Phased array antenna

When the position of the receiving antenna changes, the transmitted beam cannot reach it and the beam efficiency drops. The beam direction and optimal form can be controlled using a phased array antenna to avoid that. It is possible to move the antenna mechanically, but controlling it through the phased array (electronically) offers better speed control, higher accuracy of beam forming, and prolonged life of the system compared to the mechanical way. The phased array is comprised of many antennae. The phase δ_n and the amplitude a_n of the radio wave produced by each antenna are controlled by using phase shifters or a beamforming circuit network (Figure 13).

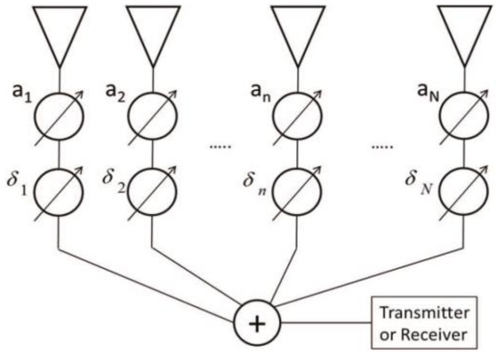

Figure 13. Concept of the phased array antenna (Shinohara, 2018, p. 83).

Each transmitter inside of the phased array antenna has a receiver that picks up the pilot beam for it to be down-converted to a low frequency at each transmit subarray, where the received phased is compared with an internal reference phase. After conjugating the phase difference, it is impressed on the phase of the actual outgoing microwave signal. That practice ensures the high-power beam is focused in the direction of the incoming pilot beam. One study (Rodenbeck et al., 2004) proposed conjugation of the phase of the received beam at RF and retransmitting the conjugated beam instead of converting and conjugating the pilot beam using digital logic. This way is more advantageous since fewer electronic components are required per transmitter, less power is consumed, and the system is less sensitive to thermal fluctuations. In addition, conjugating the signal at RF helps to adjust any misalignment between the transmitter and receiver instantly.

2.7 Wave properties

It might be better for the first couple of SPS to transmit the power wirelessly using a beamed microwave rather than using a laser. In microwave SPS concepts, no energy is lost when transferring it through the vacuum and little is lost in the atmosphere, unlike in laser systems, which have a significant drop in efficiency and power once the laser beam enters the atmosphere. The energy is transferred at the speed of light, the direction of energy can be changed instantly, energy transfer between points does not depend on the difference in gravitational potential, and the mass of power converters can be low since they operate at low microwave frequencies. It can be seen from Figure 14 that the Earth’s atmosphere is opaque to EV waves except for a few wavelengths, where the atmosphere is transparent. Microwave frequencies in the range of 2-10 GHz are considered for the WPT in the satellite application. The frequency of 2.45 GHz is among the most efficient frequencies for the microwave. It is located in the ISM band, uses affordable power components, and is not attenuated significantly by gases and moisture in the atmosphere resulting in a loss of only around 0.05 dB/-1.1445% (Figure 15).

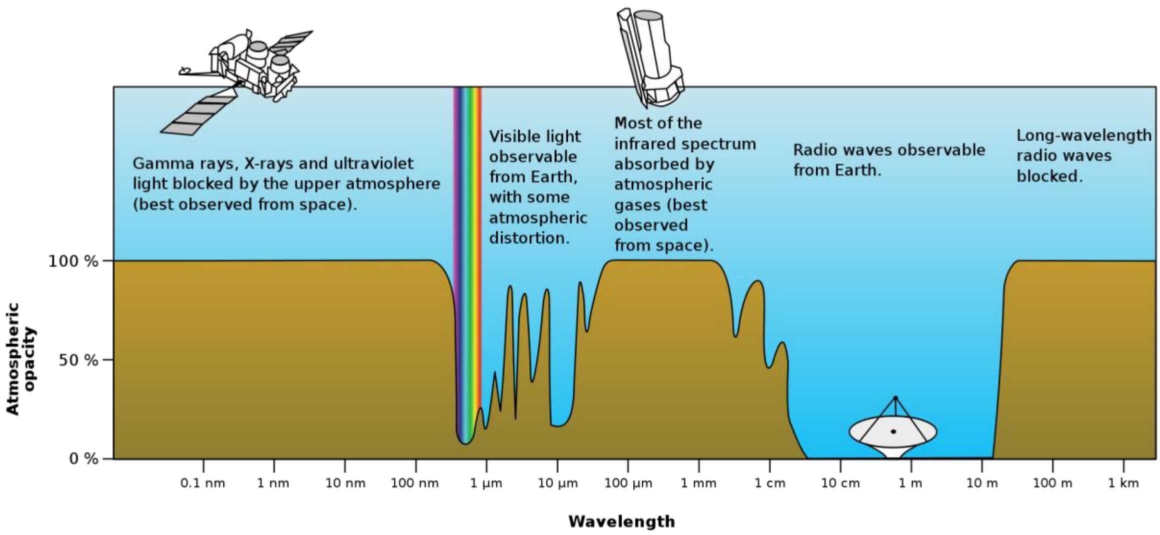

Figure 14. A plot of Earth's opacity to various wavelengths of electromagnetic radiation, including visible light (NASA, n.d.).

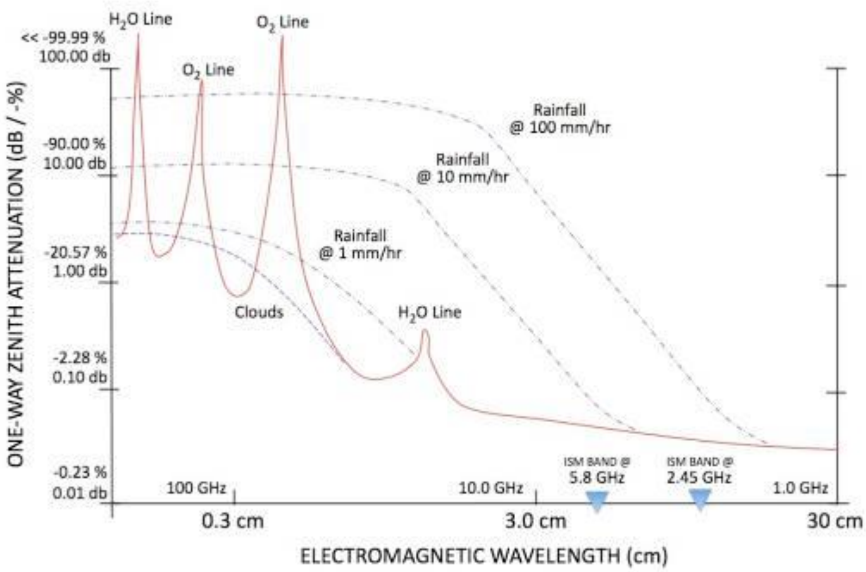

Figure 15. Atmospheric attenuation of RF at various wavelengths (Mankins, 2014).

Interference occurs when two transmissions use the same frequency. SPS concerning spectrum considerations are divided into three categories: WPT receiver emissions, WPT transmitter spectrum management, and SPS operational RF emissions. Whatever part of the EM spectrum is implemented in the space-based SPS, must be separated from other communications. In addition, the transmitted energy must be clean, without smearing over a range of frequencies. Luckily, solid-state WPT RF amplifiers should be capable of satisfying the condition (Mankins, 2014). Two types of RF emissions are expected: the pilot signal and re-emitted harmonics from the incoming WPT. Brown (1973) suggests the pilot beam must be set to a specific wavelength and emitted in a tight band. Re-emission can be avoided by using the right RF filters in each antenna in the receiver (Brown, 1973).

3 Methods

This chapter briefs the reader on the grounds and assumptions that are needed for making calculations and assessing the feasibility of the project in the next chapters.

3.1 Energy output and efficiency

If a standard SPS will require a PV area of around 10 km^2, average energy output can be calculated assuming new p-n junction solar cells with an efficiency of 44% are used (NREL, 2022). One study (Meng et al., 2015) depicted the performance degradation of a triple-junction solar cell by the decay of the output current. The authors of the study did it by analyzing the in-orbit data and taking into account the harsh conditions of space. They discovered that the current of vertical incidence angle declines at smaller rates gradually, from 0.954% in the first year to 0.407% in the third year (Table 1). The performance decline of the cell can be approximated using MATLAB’s linear extrapolation function over 30 years.

Table 1. The predicted results of the current of vertical incidence angle.

Year on orbit	Current (mA)
0	0.1990
1	0.1971
2	0.1961
3	0.1953
4	0.1946
5	0.1939
8	0.1923
10	0.1913

Therefore, the produced energy is calculated with the equation of power for solar panels:

$$P = A * \eta_{pv} * H * PR \quad (1)$$

where A is solar array area [m^2], η_{pv} is total solar cell efficiency [%], H is solar irradiance in space [W/m^2], and PR is performance factor [%]. The power and efficiency of each segment are presented below in Table 2. These variables will produce 5.12 GW of power. Since it is unrealistic for the first version of SPS to output this amount of energy (the size and transportation costs will be too high at this stage), throughout the calculations the nominal power of 2 GW will be used (aperture area of 6.23 km^2 is required).

Table 2. Efficiencies and power of each segment in WPT. Modified from source (Smitherman, 2013).

Segment	Efficiency	Power (W/m^2)	Notes
Sunlight	100%	1368	Maximum on a flat panel in space
PV conversion to DC	44%	601.9	Current efficiency if p-n junction cells are used
PMAD (SPS side)	99%	595.9	
DC-RF conversion	90% (Shinohara, 2018, p. 63)	536.3	Klystrons
Beam efficiency	80%	429	Appendix 1
RF-DC efficiency	90%	386.1	(Shinohara, 2018, p. 140)

DC-AC efficiency	95% (Park, C.-Y. et al., 2020)	366.8	Conversion to grid frequency
PMAD (grid side)	95%	348.5	
Total end-to-end efficiency	**25.5%**	**348.5**	**Best predicted**

Total energy output per year can be calculated using the following equation:

$$E_t = A * \eta * H * PR * h \tag{2}$$

where η is total end-to-end efficiency [%] and h is total load hours [h]. SPS can produce electricity almost the entire year, therefore 99% availability is assumed since satellites are not disengaged when they are maintained.

3.2 Costs, LCOE, and payback period

The levelized cost of electricity (LCOE) is a fundamental calculation that is used to assess and compare various methods of energy production. LCOE calculation includes the costs of building and operating a power plant relative to its energy production, usually excluding costs of transmission and distribution (Ram et al., 2018). Investors use this value to determine whether a power plant will be a worthwhile investment. In addition, LCOE can be thought of as the average minimum price at which the electricity produced by a power plant is required to be sold to offset the total production costs over its lifetime.

Using final values for SPS-ALPHA as a reference (see Appendix 2) (since it is the only concept with publicly available quantitative data), the cost for the hardware is roughly $5.72B when 2 GW reaches the Earth. The rectenna on the ground will cost around $2B (Smitherman, 2013). Transportation costs make up a significant part of the initial investment cost. However, using reusable rockets can greatly reduce the price per kilogram of payload. For instance, in the case of SPS-ALPHA, where the weight of the system is 25.26 thousand tonnes, the total transportation cost for 2 GW will be $66.84B if numerous rockets Falcon 9 from SpaceX are used. The company normally charges $1,200 per pound ($2,646 per kilogram) (Chow, 2022) to transport payload to LEO, from where it can be transported using solar electric propulsion. Since the system is highly modular and should be assembled by itself, the installation costs are not included in this calculation. Thus, the investment expenditures per year (It) will account for $74.56B. Communication satellites have an optimal lifetime of 10 years (Davis, 2018), after which satellite parts are renewed and upgraded with more advanced technology. For an SPS, the optimal operating lifetime (n) should be at least 30 years (Mankins, 2014, p. 523). Ignoring the difference in size between an SPS and a conventional satellite due to a lack of reliable information regarding costs, operation and maintenance costs (Mt) can be assumed $1.5M per year (GlobalCom, 2019). After the end of the 30 years, the satellite is not decommissioned but maintained regularly allowing it to provide energy for a couple of centuries or longer (Mankins, 2014, p. 557). It can be imagined that an SPS will be maintained using remotely controlled robots and software since satellites are not repaired physically in space except for International Space Station and Hubble Space Telescope (Cantieri, 2017). For the calculation of LCOE, fuel cost (Ft) is zero since no fuel is used for electricity generation. The discount rate (r) is assumed 7% (Ram et al., 2018). Knowing the values above, LCOE is calculated using Equation 4:

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad (3)$$

4 Results

Taking into consideration the assumptions and facts from the previous chapter, the necessary factors are calculated in this chapter to objectively assess the profitability of constructing a full-size SPS.

Table 3. Extrapolated data from Table 1.

Year on orbit	1	2	3	4	5	6	7	8
Current (mA)	0.1971	0.1961	0.1953	0.1946	0.1939	0.1934	0.1928	0.1923

9	10	11	12	13	14	15	16	17
0.1918	0.1913	0.1908	0.1903	0.1898	0.1893	0.1888	0.1883	0.1878

18	19	20	21	22	23	24	25	26
0.1873	0.1868	0.1863	0.1858	0.1853	0.1848	0.1843	0.1838	0.1833

27	28	29	30
0.1828	0.1823	0.1818	0.1813

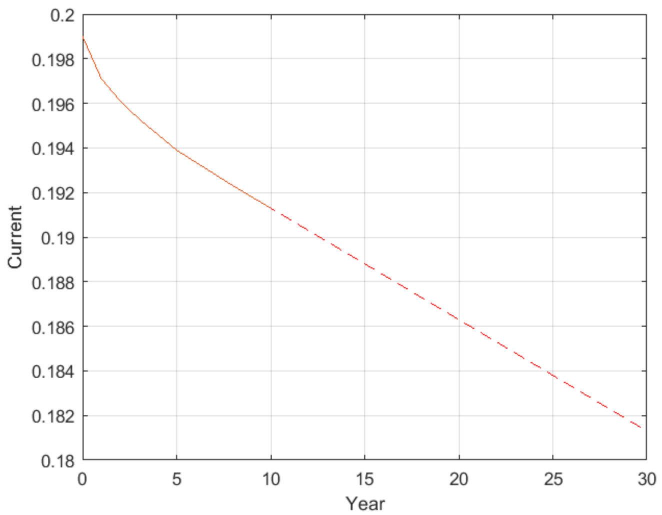

Figure 16. Graph of the extrapolated data.

From Table 3 and Figure 16 the performance decline is observed to be 8%, thus, the performance factor of 0.92 can be assumed. Using Equation 1, one can see the difference between the outputs of standard solar panels (23% efficiency and 77% performance factor (Staff, 2009)) and new p-n junction cells (44% efficiency and 92% performance factor). New p-n junction cells yield more than double of electricity output than standard silicon-based solar panels.

$$P_{silicon-based} = 1 * 10^7 * 0.23 * 1368 * 0.77 = 2.43\ GW \quad (4)$$

$$P_{p-n\ junction} = 1 * 10^7 * 0.44 * 1368 * 0.92 = 5.54\ GW \quad (5)$$

Using the efficiencies from Table 2 and Equation 2, one can calculate the total output energy per year with 99% availability with 2 GW nominal power:

$$E_t = 6.23 * 10^6 * 0.255 * 1368 * 0.92 * 8760 * 0.99 = 17.35\ TWh \quad (6)$$

Results for LCOE calculation are presented in Table 4. A highly modular SPS-ALPHA with cutting-edge PV panels (44% efficiency), beam efficiency of 80%, and reasonably priced components were considered in this calculation. From the calculations performed, it can be seen if this project is realized, there will be a significant return on the investment. LCOE will be 35 c/kWh and the payback period will be 12.3 years if the energy is sold at 35 c/kWh. The payback period is determined by dividing the initial investment by the annual return.

Table 4. LCOE calculation using Excel.

t	1	2	3	4	5	6	7	8	9	10
I_t **(M$)**	6,009	6,009	6,009	6,009	6,009	6,009	6,009	6,009	6,009	6,009
M_t **(M$)**	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
F_t **(M$)**	0	0	0	0	0	0	0	0	0	0
E_t **(GWh)**	17,350	17,350	17,350	17,350	17,350	17,350	17,350	17,350	17,350	17,350
$(1+r)^t$	1.07	1.14	1.23	1.31	1.40	1.50	1.61	1.72	1.84	1.97

t	11	12	13	14	15	16	17	18	19	20	21	22
I_t **(M$)**	6,009	6,009	6,009	6,009	6,009	6,009	6,009	6,009	6,009	6,009	6,009	6,009
M_t **(M$)**	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
F_t **(M$)**	0	0	0	0	0	0	0	0	0	0	0	0
E_t **(GWh)**	17,350	17,350	17,350	17,350	17,350	17,350	17,350	17,350	17,350	17,350	17,350	17,350
$(1+r)^t$	2.10	2.25	2.41	2.58	2.76	2.95	3.16	3.38	3.62	3.87	4.14	4.43

t	23	24	25	26	27	28	29	30	**Total**
I_t **(M$)**	6,009	6,009	6,009	6,009	6,009	6,009	6,009	6,009	180,256
M_t **(M$)**	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	45
F_t **(M$)**	0	0	0	0	0	0	0	0	0

17,350	17,350	17,350	17,350	17,350	17,350	17,350	17,350	520,500
4.74	5.07	5.43	5.81	6.21	6.65	7.11	7.61	101.07

LCOE	$0.35
Annual return (M$)	6,055
Payback time (a)	12.3
Selling price of electricity (c/kWh)	35
Investment (M$)	74,562
Discount rate	7.00%

5 Discussion

Several variables were assumed for this calculation, as well as approximate values were used because reliable and precise information is unavailable in public access. In addition, many factors were not considered such as salaries for personnel, insurance, debt, etc. However, the calculation gives the reader an idea of what a project of this size can offer. In Table 5, one can see the LCOE values for various types of power plants in both the EU and the US. Comparing the calculated LCOE in the previous chapter with the values in the table, it can be seen that it is higher than any other type of power plant. The high transportation costs substantially increase LCOE and the risk associated with investing in the project. It is predicted that the LCOE of renewable energy and storage will continue decreasing, however, it is recommended to start investing early (Ram et al., 2018). Thus, it would be wise to invest in the project on a smaller scale and increase the capacity as the price of transportation lowers. The correlation between LCOE, discount rate, and investment costs can be seen in Figure 17, Figure 18, and Figure 19. LCOE greatly increases as the discount rate and investment costs (where transportation costs are the biggest factor) increase. However, an increased lifetime, as well as energy produced, tends to decrease the final LCOE value.

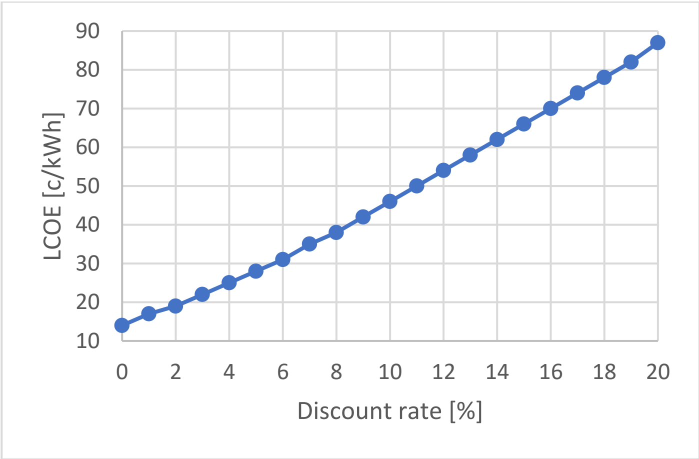

Figure 17. LCOE as a function of discount rate with $74.56B investment.

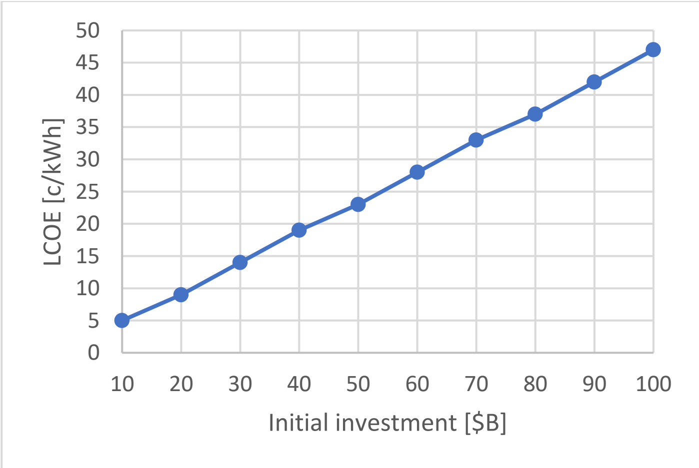

Figure 18. LCOE as a function of an initial investment with a 7% discount rate.

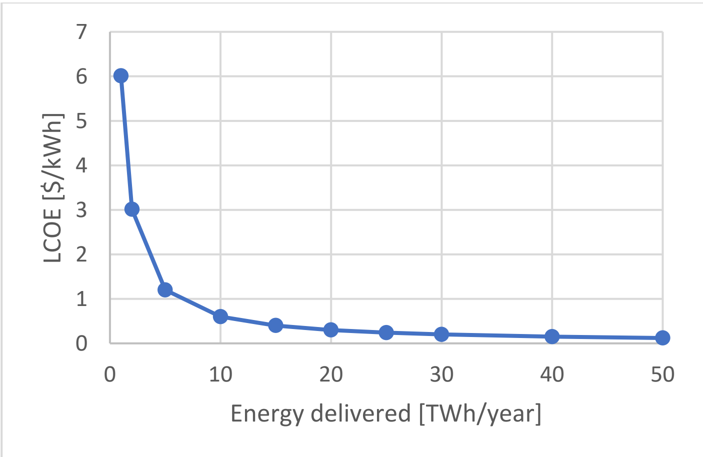

Figure 19. LCOE as a function of energy delivered to the grid.

The author of a new promising SPS design CASSIOPeiA (Cash, 2019) determined its LCOE 4.8 c/kWh, which is significantly lower than the value calculated in this thesis. However, that value comes from low transportation costs, 20 years of operation, and a 3.5% discount rate. The project is supposed to weigh only about 1,800 MT, which seems to be unrealistic even considering the ambitious lightweight structure. Appendix 2 shows that the WPT module of an SPS variant at the same 2 GW power will weigh 12,125 MT alone. ESA's SOLARIS project report also promises lower LCOE than calculated here – 7.3 c/kWh. Their goal is to bring a 1 GW SPS to orbit with an investment cost of $16.6B and a 5% discount rate (LE, 2022). Such a low LCOE also comes from lower weight and, thus, lower transportation costs. Another paper (Marshall et al., 2021) uses a similar approach as presented in this thesis, however, the authors obtained the range of total LCOE of the project between 213 c/kWh and 232 c/kWh, which is substantially higher because individual satellites deliver only 100 MW power to the grid and the solar cell efficiency of 17% is used. In addition, the insurance and possibly failed rocket launches were taken into the account. However, in that case, the transportation costs also have a major contribution – 69% of the total LCOE, while in this research it is 88.6%.

Table 5. Ranges of LCOE values for different types of power plants in the European Union (left) and the United States of America (right) in 2015 (Ram et al., 2018).

Type of power plant	**LCOE (c/kWh)**
Wind onshore	3 – 12
Wind offshore	7 – 20
PV rooftop (5-10 kW)	7 – 25
PV utility (>10 MW)	4 – 12
Li-ion batteries rooftop	11 – 25
Li-ion batteries utility	7 – 25
Coal PP	4 – 12
Coal + CCS	10 – 19
Gas PP – CCGT	5 – 8
Gas PP – CCGT + CCS	8 – 13
Gas PP – OCGT	7 – 18
Nuclear PP	9 - 17

Type of power plant	**LCOE (c/kWh)**
Wind onshore	2 – 6
Wind offshore	5 – 18
PV rooftop (5-10 kW)	14 – 22
PV utility (>10 MW)	5 – 9
Li-ion batteries rooftop	18 – 25
Li-ion batteries utility	8 – 24
Coal PP	5 – 10
Coal + CCS	10 – 19
Gas PP – CCGT	5 – 8
Gas PP – CCGT + CCS	8 – 13
Gas PP – OCGT	7 – 19
Nuclear PP	7 – 12

Deploying a massive satellite in GEO is a reasonable solution to provide base-load power. Although, the idea has many technical challenges since the SPS is gigantic and will be developed for a limited period because the estimated life cycle of SPS is about 30 years unless maintained regularly. In addition, the project requires a significant investment at once, which can be lowered if lighter, more powerful, and more efficient components are used. However, regardless of how impressive the designs for SPS systems are, these concepts and business plans will not be pursued until there is economical, frequent, and reliable access to space. Decreasing the cost of access to orbit is anticipated to precipitate entirely new commercial enterprises, some of which will be transformative for the countries and businesses that pursue them. Advocates of energy from space argue that the new SPS market alone will be sufficiently large to lower launch costs. NSS Executive Committee Chair Mark Hopkins in 2011 noted,

> “The high cost of launch has always hampered the exploration and development of space. With its Falcon Heavy vehicle, SpaceX seeks to achieve a major reduction in launch costs. Such a reduction could enable entirely new categories of space industry.” (Hopkins, 2011)

Lower transportation costs will certainly allow this project to be realized. Despite theoretically near-perfect beam efficiency being hard to achieve, the project still can be applied in space, for instance when humanity will colonize the moon or explore other planets. On the other hand, a fleet of reusable rockets will perform a large number of flights during the transportation process, which means the choice of propellants directly correlates with the amount of impact on the atmosphere.

At first, SPS will utilize the same private, commercial, and government rockets that are used to lift communication satellites from Earth to space. Some plans (see section 2.2 Designs) involve assembling the satellites from components transported by medium-power rockets into LEO at a very low cost, possibly using the International Space Station as a staging area, and later transporting the assembled unit into its final position in a geosynchronous, geostationary or Sun-synchronous orbit. Other plans propose deploying solar spacecraft and their large PV arrays directly into the designated orbit using more powerful thrusters.

SPS will positively affect poor and developing countries, where electricity prices are high. In addition, the satellites will be able to spread various communication networks. That, in turn, will greatly benefit those countries and lower poverty due to exposure to advanced technologies. Rectifying antennas will capture the transmitted signals of the satellites and convert them into electricity. In this respect, SPS receivers will resemble the passive early television receive-only Earth antennas of radio and television, capturing the energy instead of information.

Possible negative health and environmental effects are a matter of public concern that could affect the feasibility of the project. Mistakes can occur during the launch of transporting rockets, misdirection of the beam, etc. The main concern about microwave transmission is the heat produced by it. However, the research conducted by Betancourt notes that microwaves do not bring any harm even to high-flying birds, and the power density is within safe limits at the Earth's surface, however further studies are needed. In addition, for the minimum risk of weaponization of SPS, the peak power intensity clearly should be much less than the ignition point of any material (Mankins, 2014).

> "Microwaves used in space power have no ionizing effect, and there is no danger of cancer or genetic alterations due to microwave radiation. The potential danger of microwaves, like energy from the Sun and from artificially light sources, relates directly to the energy's density in a given area. The design of SBSP systems calls for power densities well within safe limits at the planet's surface." (Betancourt, 2010)

It is important to note that companies must create their own laws to regulate private companies to protect themselves if a company causes any kind of damage. Unless such regulations are created, countries can be discouraged from allowing a private company to explore space because of the fear of international liability. The international authorities should further develop the framework for determining liability for any damage to protect investments and property of companies and countries around the world (Betancourt, 2021).

As mentioned in the calculations and the discussion above, the way the hardware is transported drastically affects the feasibility of the project. However, two ways exist to reduce that price – to either reduce the weight of the hardware or completely step away from the concept of using a large number of rockets with chemical propellants. The satellite can be assembled on the Moon and transported from there using solar electric propulsion or any other method that does not necessarily involve rocket fuel. Researching and advancing a rocket engine to improve the whole system is also an option. Many things can be done to achieve improvement in access to space. However, like any other project involving space exploration and its applications, they require rigorous preparation, funding, and commitment.

6 Conclusions

A solar power satellite with efficient and high-power components has the potential to change the way we produce energy. To achieve that, extensive collaboration between several private companies that are responsible for the production of different parts and governments is required. From the author’s point of view, now is the time when technology companies partner to produce products that help humanity on a much larger scale. To build an SPS, a PV panel manufacturing company needs to work together with, for example, a microwave company that produces hundreds of thousands of magnetrons. This research proved that space-based solar power would be a great investment that brings adequate amounts of clean inexpensive energy. However, high investment costs on transportation prevent the project from becoming a reality by making it a high-risk investment since transportation costs account for almost 90% of the costs. On the other hand, the first SPS is going to be much more expensive than the following versions of it as it is a new and unknown type of power plant we have not built yet. Therefore, it is hard to predict how it is going to behave and operate. That is why it is crucial to continue developing this project and start launching smaller versions of an SPS to prove its concept.

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Appendix 1. Beam efficiency

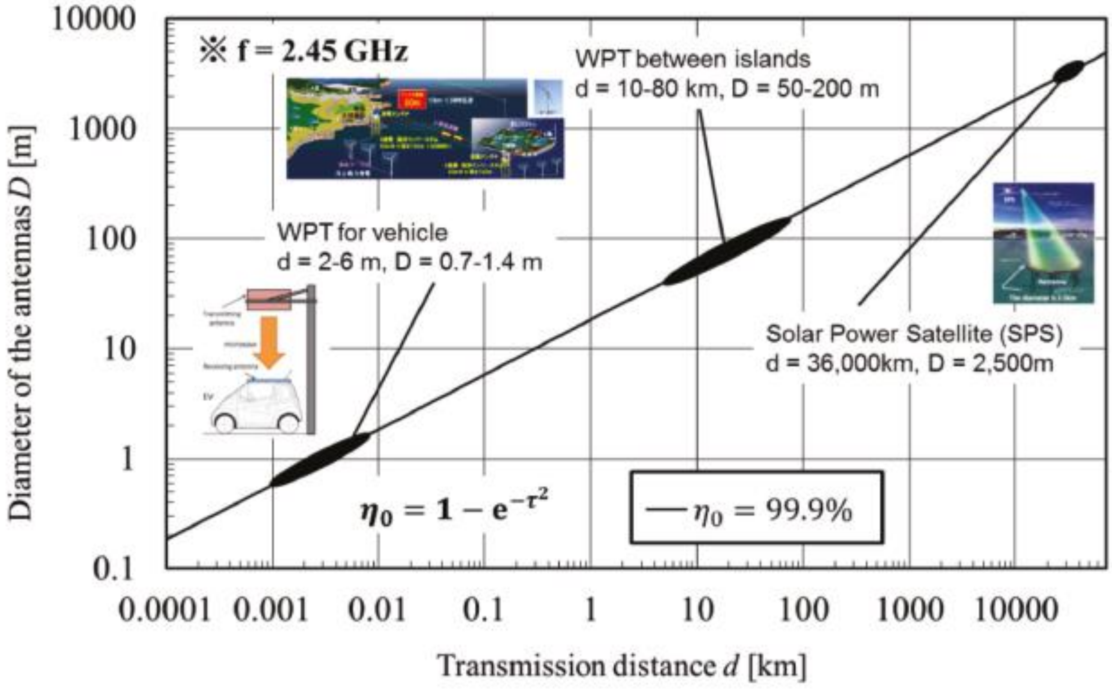

Figure 1.1. The theoretical relationship between the diameter of the antenna and transmission distance at 2.45 GHz with 99.9% beam efficiency (Shinohara, 2018).

Beam efficiency is one of the most important parameters in wireless power transfer, which is the efficiency between transmitting and receiving antennae. It is calculated by using the Friis transmission formula:

$$\eta = \frac{P_r}{P_t} = \frac{G_t * G_r}{4 * \pi * d^2} = \frac{A_t * A_r}{(\lambda * d)^2} = \frac{G_t * G_r}{(\frac{4 * \pi * d^2}{\lambda})^2}$$

where P_r, P_t, G_r, G_t, A_r, A_t, λ, d are the received power, transmitted power, and the antenna gain of the receiving antenna, the antenna gain of the transmitting antenna, aperture area of the receiving antenna, aperture area of the transmitting antenna, wavelength, and the distance between the antennae, respectively.

The wavelength is calculated by diving the speed of light c by frequency f:

$$\lambda = \frac{c}{f} = \frac{299{,}792{,}458\ m/s}{2.45 * 10^9\ Hz} = 0.1224\ m\ \approx 12\ cm$$

Assuming that the entire areas of both transmitter and receiver are utilized as aperture areas, one can calculate the aperture areas using the formula for the area of a circle. For instance, if the diameters for both transmitter and receiver are 2,000 m and 2,500 m respectively, the aperture areas are the following:

$$A_t = \frac{\pi d^2}{4} = \frac{\pi(2000)^2}{4} = 3141592\ m^2$$

$$A_r = \frac{\pi(2500)^2}{4} = 4908739\ m^2$$

The distance *d* between the Earth and GEO is 36,000 km. Thus, the beam efficiency is 79.4%:

$$\eta = \frac{A_t * A_r}{(\lambda * d)^2} = \frac{3141592 * 4908739}{(0.1224 * 36000000)^2} \approx 0.794$$

Appendix 2. SPS-ALPHA mass and costs

Table 2.1. The initial version of SPS-ALPHA hardware cost estimation results (2GW @ Earth) (Mankins, 2014, p. 235).

Sensitivity Outputs	**Unit Mass ($/kg)**	**Number of Modules**	**Total Mass (MT)**	**Final CER ($/kg)**
HexBus Modules	20	337,330	6,770.6	~200
Interconnects	1	2,023,650	2,023.7	~200
HexFrame Structures	43	19,878	856.9	~200
Reflector Deployment Module	79	4,662	368.3	~400
Solar Power Generation module	8	327,891	2,623.1	~200
Wireless Power Transmission module	37	327,691	12,124.6	~200
Propulsion & Attitude Control module	472	200	91.4	~6,000
Modular Autonomous Robotic Equipment	10	5,190	51.9	~700-1000
0.5-Year Propellant Load	1,737	200	347.4	250
Total	N/A	~3,000,000	25,260.8	N/A