IAC-21-C3.1.10

Modular Development of an SPS with Electromagnetic Small Satellites

Miles Turner[a], Carson Coursey[b], Ethan Sinclair[c], Thomas Rodriguez[d], Brian Gunter[e]

[a] *Department of Aerospace Engineering, Georgia Institute of Technology, North Ave NW, Atlanta, Georgia, 30332, United States of America,* mturner85@gatech.edu
[b] *Department of Aerospace Engineering, Georgia Institute of Technology, North Ave NW, Atlanta, Georgia, 30332, United States of America,* cdcoursey00@gatech.edu
[c] *Department of Mechanical Engineering, Georgia Institute of Technology, North Ave NW, Atlanta, Georgia, 30332, United States of America,* ethan.sinclair@gatech.edu
[d] *Department of Electrical Engineering, Georgia Institute of Technology, North Ave NW, Atlanta, Georgia, 30332, United States of America,* trodriguez30@gatech.edu
[e] *Department of Aerospace Engineering, Georgia Institute of Technology, North Ave NW, Atlanta, Georgia, 30332, United States of America,* brian.gunter@aerospace.gatech.edu

Abstract

In this paper, the solar power satellite (SPS) builder concept is explored for the building of SPS systems with a low CO_2 footprint. The SPS builder concept uses a modular assembly process called the "free-flyer" approach which has independent small satellites assemble together semi-autonomously to help with the construction and maintenance of a SPS system. A small satellite design called a "builder" satellite is presented as an example satellite to be sent up to space in large numbers to help construct and maintain a SPS system. The suggested set of systems needed for the example builder satellite to build a SPS system are explored, with one key system being the use of electromagnets which are intended for docking and wireless power transfer. Next, a concept of operations is presented to show how through the use of dedicated launches or ride-share opportunities, builder satellites will go from an orbital insertion stage, to a deployment stage, and then an assembly stage to build a SPS system. Afterwards, a case study on an example 1000 m^2 low Earth orbit (LEO) SPS system built using the SPS builder concept is explored to provide context to the estimated cost, CO_2 footprint, the total power generated per hour, and the total CO_2 offset per hour. For the cost and CO_2 footprint, an approximate $363,000,000 and 1600 metric tons are found respectively, largely due to the use of a Falcon 9 rocket as the launch vehicle. For the power receive at a ground location using the model 1000 m^2 LEO SPS system in direct sunlight, 100 kWh of generated power is found if using silicon solar cells or 220 kWh of power is generated if using gallium arsenide with a total CO_2 offset of 40 kg/hr or 90 kg/hr respectively. From these calculations, it is found that it would require 9 years to create a net negative CO_2 footprint if using silicon solar cells, or 4 years if using gallium arsenide solar cells. Overall, the SPS builder concept shows a concept for building future SPS systems if the CO_2 footprint is the driving factor since these solar panels have a suggested life of 20 years. In the case of cost, the SPS builder concept will need further work specifically on spacecraft design since the total cost does not allow for a competitive price per kilowatt hour when compared to traditional methods of energy generation.

Keywords: Solar Power Satellite, Modular Assembly Method

Nomenclature

A – Area of solar panel
CO_2 – Carbon Dioxide
P – Power
G_{sc} – Solar Constant
η – Energy transfer efficiency

Acronyms/Abbreviations

ADCS – Attitude Determination and Control System
COTS – Commercial-off-the-shelf parts
DOE – Department of Energy
ISS – International Space Station
LEO – Low Earth Orbit
MIL-STD – MilSpecs
NASA – National Aeronautics and Space Administration
PV – Photo-Voltaic
RF – Radio Frequency
RTK GNSS – Real Time Kinematic Global Navigation Satellite System
SPS – Solar Power Satellite
SPS-ALPHA – Solar Power Satellite by means of Arbitrarily Large Phase Array
U – Units

1. Introduction

With the transition to alternative energy sources becoming increasingly popular, the focus and development on existing green energy sources such as wind, hydroelectric, solar, and geothermal are also growing. While most of the alternative energy methods have been proven to have the ability to support many communities across the globe, the implementation of these alternative energy systems has primarily been seen in more economically developed countries due to the support from pre-existing infrastructure. Infrastructure such as powerplants, power transfer stations, and power storage facilities is often outdated or not present in more underdeveloped communities, which leads to difficulties in implementing the transition to alternative energy sources. With solar power becoming more economically competitive due to decreased manufacturing costs and increased Photo-Voltaic (PV) cell efficiency, the drive for further development in this source of energy is growing with several new concepts [1].

One concept currently being explored for is solar power generation in space through a network of solar power satellites (SPS). With the continual development of SPS systems since the 1970's the concept of SPS is aimed to help combat the current limitations seen with solar energy production on Earth, such as the intermittent losses in solar energy due to lack of sunlight, losses in solar energy due to atmospheric effects, the inability to build a solar farm due to lack of space, and the failure to direct energy due to lack of infrastructure [2]. The design of an SPS is simple in concept due to each system being comprised of only three major systems: a reflector array, a photovoltaic array, and a power beaming array. From the concept, it is idealized that the use of a reflector array is used to help direct sunlight to the photovoltaic array, the photovoltaic array is then used to collect solar energy and convert it to usable energy, wherein the usable energy is then converted into a more transferable energy and beamed to a specified location to be received. The challenge for SPS arises when attempting to implement the systems in space due to the predicted design sizes of an SPS system reaching scales of 1 km or larger and weighing several thousand metric tons to ensure a megawatt amount of energy generation [3].

Due to the size, weight, and intricacy of a SPS system, the building of a SPS is frequently imagined using a modular design method. The use of a modular design would thus require humans, robotic systems, or both to build an SPS. Traditional methods of space assembly have been seen with the use of element to element mating of two or more independent spacecraft, astronauts in extravehicular space suits manually assembling structures, and the use of astronauts and auxiliary equipment, such as a mobile workstation, robotically assembling structures in space [4]. All cases are proven methods for structural assembly in space, with National Aeronautics and Space Administration (NASA) assembling systems such as simple truss structures to more complicated structures such as the International Space Station (ISS), but with these methods comes the cost of required human interaction and the need of additional systems to complete the assembly of a structure in space.

In this paper, the method considered for constructing and operating a SPS system is denoted as the SPS builder concept. The concept uses the semi-autonomous assembly of preconfigured small satellites, called "builders." Each builder will be task-oriented to a specific section of an SPS system, and through semi-autonomously operations, each builder will assemble with other builders, to build and operate a SPS system. This concept will allow for lower upfront manufacturing and construction costs, and be able to spread out the CO_2 footprint associate with building an SPS system. Additionally, the SPS builder concept will highlight the ease of lifecycle management for an SPS system due to the single task design of each builder.

2. Assembly Method

For the SPS builder concept, the use of the "free-flyer" method is considered for the on-orbit assembly of the SPS system [5]. The "free-flyer" approach consists of each builder being its own independent spacecraft, with its own propulsion system, power system, attitude determination and control system (ADCS), data bus, communication, etc. These flight critical systems allow each builder to have a specified degree of intelligence to allow for the assembly of a large structure in space such as a SPS system.

While the intricacy of this system of satellites may be highly complex, the advantage of the "free-flyer" approach allows for builders to be sent up to space over time with multiple independent launches to spread the costs and the CO_2 footprint associated with the development of a SPS system. The "free-flyer" approach also allows for the maintenance of a SPS system to be completed by sending up builders using ridesharing opportunities. Additionally, since each builder satellite is its own independent spacecraft, a SPS system is capable of manipulating its structural design, if necessary, for future integration or improved SPS system designs.

3. Satellite Design

For the purpose of providing further context to one potential spacecraft design of a builder satellite, the key base subsystems need to perform the "free-flyer" assembly method and the specialized subsystems needed to build a SPS system are as examined.

3.1 Key Base Subsystems

All builders will have similar base system specifications to help with facilitating a simple design for manufacturing high quantities of "builder" satellites. Five key base subsystems with ideal requirements are provided below.

3.1.1 Propulsion

For all builders, the use of cold gas thruster is considered to allow for translational control [6]. Ideally the propulsion system would only be used for initial assembly of the SPS system. With current improvements being made on solar electric propulsion systems, future designs of builders could benefit by using such systems to assist with station keeping or reassembling of a SPS system.

3.1.2 Power System

Depending on if a SPS system is being built from scratch the power system of a builder would most likely be high energy density battery arrays capable of receiving energy from a solar panel unit. If a SPS system is being built with the assistance of pre-existing SPS systems, a radio frequency receiving unit could additionally be attached to each builder to allow for added energy supply [7].

3.1.3 Relative Position Navigation

Due to the necessary success of each builder having to assemble autonomously with other builders, the relative position of a builder to other builders is paramount. The use of a real time kinematic global navigation satellite system (RTK GNSS) receiver board would likely be implemented due to its centimeter accurate results and relatively small size [8]. This would require a visible GNSS antenna to the target location the builder satellites are assembling.

3.1.4 Attitude Determination and Control Systems

For all builders, a three-axis attitude control system is considered using reaction wheels, magnetic torque rods, and integrated control algorithms using the prior mentioned cold gas thrusters [9]. The ADCS used will be required to be able to help counter act the effects of the propulsion system and the magnetic attraction forces between the electromagnets used in the docking system and Earth's magnetic field.

3.1.5 Docking

The use of electromagnets are considered for the docking of builders with one another. This is to allow for the reduction of mechanical connections required to assemble builders into a larger space structure, which can reduce the chances of mechanical failures, and allow for variable control of how builders are connected among each other. This variable control allows for builders to be attracted to each other by increasing the magnetic field being created by the electromagnet or repelled away from each other by reversing the magnetic field created by the electromagnet [10]. Docking with electromagnets would need to be performed within close proximity to the other builder satellites due to the electromagnets only have an effective attractive force at distances less than 2 meter given the size specifications stated earlier for the SPS builder satellite.

3.2 Specialized systems

For the specialized systems, each builder satellite needs to have the capability of integrating specialized systems to enable a builder to perform a specialized task on the assembled space structure. In the case of building a SPS system using builder satellites, these specialized systems are seen follows.

3.2.1 Mirrors

The mirror system is a deployable mirror attached to a builder satellite to help redirect sunlight to a solar panels. With the ability to assemble multiple builders together, large mirror arrays could be constructed like the SPS-ALPHA (Solar Power Satellite by means of Arbitrarily Large Phase Array) described by John C. Mankins [11].

3.2.2 Solar Panels

The solar panel system design is a deployable PV solar array attached on a builder satellite. With the ability to assemble multiple builders together, larger solar panel arrays could be constructed to help collect solar energy for future use by the SPS system or if coupled with an energy transfer system, all collected energy could be redirected to a ground location.

3.2.3 Energy Transfer Systems

The energy transfer system is a deployable system on a builder satellited, such as an radio-frequency (RF) antenna, capable of sending and receiving energy. With the ability to assemble multiple builders together, larger energy transfer receivers and transmitters could be constructed to help redirect energy from a pre-existing SPS system to locations outside of the SPS system's line of sight [12].

3.3 Example Builder Satellite

For the extent of this paper, the following builder satellite has been designed following the guidance of the systems mentioned earlier.
Mass: ~ 200 kg [13]
Size at launch: 1.5 X 0.5 X 0.5 meters [13]
Size at deployment: 1.5 X 1.5 X 0.5 meters [13]
Propulsion: Four cold gas thrusters
Power System: Four high energy density batteries
Data Bus: MIL-STD-1553B
GNS: RTK GNSS receiver board
ADCS: Three-axis reaction wheels/Cold Gas Thrusters
Docking: Four electromagnets

A notable feature about the example individual builder satellite is that the spacecraft has two states; one being the launch state in which the four electromagnets are stored into the body of the of the spacecraft, and the second being the deployment state in which the spacecraft has the electromagnets fully extended and is ready for orbital assembly.

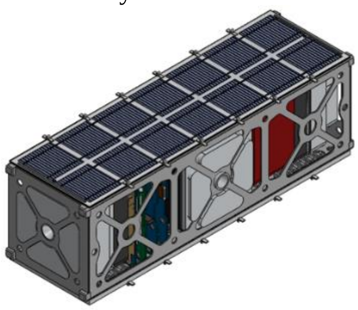

Fig. 1. Launch ready builder with stowed systems

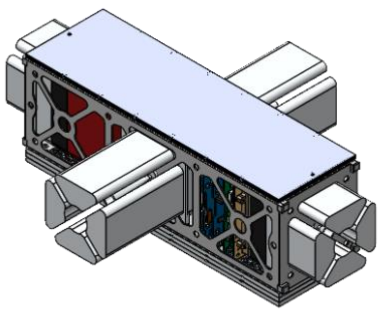

Fig. 2. Builder with four electromagnetic deployed

3.3.1 Electromagnets

One key system that should be noted in the design of this example builder satellite is the use of the four electromagnets. It is believed that using electromagnets, the dependency on heavy, expensive, and complex precision sensors and thrusters commonly used when performing spacecraft maneuvers such as docking could be reduced. Also by using electromagnets, the ability to attract or repel spacecrafts to one another can be completed by varying the electromagnetic field generated by each electromagnet assisting with the assembling and disassembling of spacecraft needed in constructing and maintaining a SPS system. Additionally, it is believed that electromagnets have the capability of offering inductive coupling so that energy could be transferred wirelessly across a large space structure without the need for hard wire connections.

4. Concept of Operations

For the builder satellites, the mission concept is explored in three phases, with first being the orbital insertion, second being the deployment, and third being the assembly of a SPS.

4.1 Orbital Insertion

For orbital insertion, the builder satellites are capable of being sent up on any commercially available rocket. The intent is to have a series of the builder satellites be sent up on rockets that are ready to be deployed and assembled as a structure for solar panels, mirrors, or energy transmitter and receivers to sit upon. With the builder satellites being small, the ability to package several satellites on top of each other into stacks becomes feasible. Depending on the mission, several stacks containing a varying number of the satellites can be sent up on a rocket if the launch is only intended on delivering the builder satellites, or if the launch is specific for another mission that passes the orbit path of the developing SPS structure, a limited number of SPS builder satellites could be sent up along as rideshare opportunity.

4.2 Deployment

With the builder satellites successfully delivered to the desired location, the deployment of the satellites can commence. Using the “free-flyer” approach mentioned earlier, each SPS builder satellite is able to use its cold gas thrusters to move in proximity of other SPS builder satellites and position itself so that the electromagnetic docking sequence can then occur. To successfully position itself in coordination to the other SPS builder satellites, the RTK GNSS receiver board with relay information from each satellite to the others and use predetermined information on the current progress and development of the SPS structure in space.

4.3 Assembling of a SPS

With the SPS builder satellites in the correct position for assembly, the electromagnetic docking sequence can then proceed. By using each of the four high energy density batteries inside each of the SPS builder satellites, an electrical current can run through the electromagnets to create an electromagnetic field proportional to the rate of the electrical current that can then be used to attract to other satellites that are using their electromagnets. By varying the rate which the current is passing through the electromagnet, the attraction force between the two electromagnets driving the two satellites to dock could vary as well, allowing for a more controlled docking procedure with less of a chance for crashing the satellites together. Once docked, a mechanical mechanism would engage allowing for the builder satellites to be secured to one another. This mechanical mechanism would passively engage and disengage when needed for future expansion or integration of the SPS system. This independent disengagement would allow single units to be replaced as discussed from rideshare opportunities.

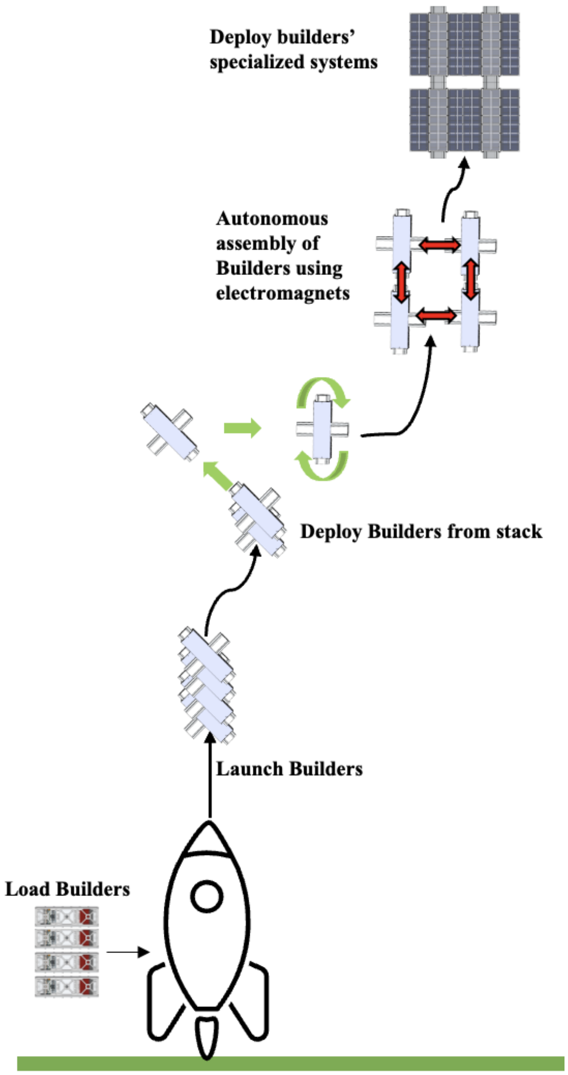

Fig. 3. Concept of operation on how builders would build a SPS system.

5. Case Study: LEO SPS Station

As one potential motivator for SPS energy is the relatively clean environmental impact when compared to other terrestrial sources, such as coal or natural gas, an analysis of the environmental impact to construct a LEO SPS system is conducted. In addition, an approximate cost is found for the building of a low earth orbit (LEO) SPS system using the SPS builder concept. The building of a LEO SPS system is considered for the following reasons:

- The size of the SPS to be built can be reduced since the transmission losses of sending energy to a target location are lower at smaller distances. [14]
- More satellites can be delivered to LEO on a shorter timeline and at a lower cost that other higher orbits. [15]
- The ability to replace and integrate new satellites using LEO ride-share opportunities is more widely available than other higher orbits. [16]

5.1 *Operations of a LEO SPS*

For the case of a LEO SPS, it is assumed that the structure be built in a sun synchronous orbit, SSO, at an altitude of approximately 1500 km [17]. This would allow for the SPS structure to always be in the sun and able to relay energy to any location on earth, but only for a limited time at a specific moment in the space structure's orbit path. With the limitations of only being able to provide a location on Earth energy from a SPS system for a short period of time, multiple SPS would need to be developed at LEO with similar flight paths so that energy could be continuously provided to a specified location.

5.2 *Scale and Design*

The potential viable scale proposed for a LEO demonstration would involve up to an area of 1000 m², roughly 32m x 32m. The proposed SPS concept is shown in Figure 4. This would take 445 units compose into an array of 22 by 22 units.

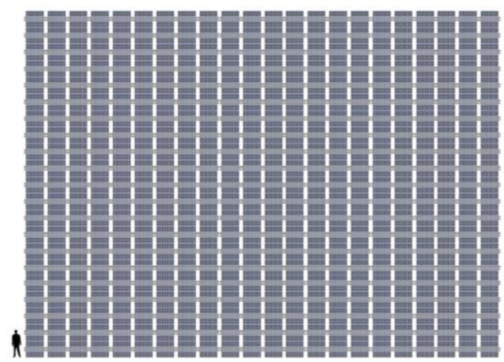
Fig. 4. 1000 m^2 solar power satellite system with person for scale.

Each builder satellite will carry two specialized systems, the first being a solar panel system to collect energy and the second being a RF energy transfer system to relay the collected energy to a designated ground location.

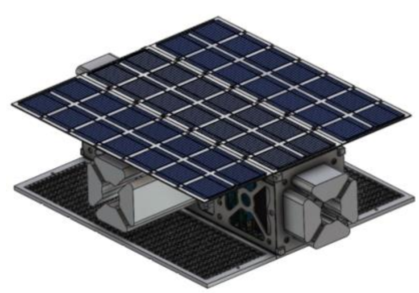
Fig. 5. Builder satellite with solar panel system on the top and a RF energy transmitter on the bottom.

5.3 Manufacturing and Operation

Through the economies of scale, the production cost of each SPS unit inherently reduces as more units are made. Without a complete analysis on the reduction of cost due from the means of scale, commercial-off-the-shelf parts (COTS) and the historical information from existing small satellites are leveraged to estimate costs. An estimation of the cost for one builder satellite as shown in Figure 5 is $250,000 [18]. This value is found by comparing the price of SpaceX's Starlink satellites which are approximately $250,000 and by looking at key base system costs such as, solar panels which are estimated to be $25,000 or lithium ion batteries which are approximately $140 per kilowatt hour [19, 20].

The cost viability that comes with the use of electromagnets is attractive, as the multiple functions of the electromagnets reduces the number of needed systems. Primarily, the electromagnets function as the method for docking as well as 3-axis control for the spacecraft in the manner of torque rods. Additionally, the potential ability to transfer power with the electromagnets can reduce the need for wiring. This contributes to less mass and the cost of launch by mass.

It should be noted that the total CO_2 associated with manufacturing and operation was not considered in this paper due to the CO_2 varying greatly depending on the manufacturing methods used when creating each system within a satellite. For all intents and purposes, it is assumed that the manufacturing and operation of each builder satellite would likely contribute a negligible amount of the total CO_2 footprint associated with building a LEO SPS when compared to the launch phase of delivering the builder satellites to space.

5.4 Launches

After all the builder satellites for a SPS system are manufactured, then the next phase is to consider how to launch the series of builder satellites into orbit around Earth. With the largest contributor to the total costs and total CO_2 footprint being the launch phase, the choice of the desired launch vehicle to send the builder satellites up to space becomes important to keep both factors low. Additionally factors such as timelines for initial launches need to be considered since many launch vehicles are not readily available. Another factor when considering launch vehicles is the availability of rideshare opportunities for replacing single builders since this will help spread out the total cost and CO_2 footprint associated with the maintenance of a LEO SPS system. For the CO_2 footprint and cost analysis of the launch phase of building the proposed LEO SPS system, three rockets are considered, which are, the Falcon 9, Delta IV Heavy, and the Atlas V Medium.

5.4.1 Launch Mass Factor

With the payload masses listed in Table 1, mass is the limiting factor for sending builder satellites up to space. It is estimated that 55 builder satellites can be launched using an Atlas V Medium rocket, 115 builder satellites can be launched with each Falcon 9 rocket, or 140 builder satellites can be launched with each Delta IV Heavy, indicating that it would require 8 launches using an Atlas V Medium, 4 launches using a Falcon 9, and 4 launches using a Delta IV Heavy to send up the minimum of 445 builder satellites to build the 1000 m^2 LEO SPS system.

Table 1. A comparison of three launch vehicles' CO2 footprint per launch, costs per launch, timelines, and number of launches needed to build a 1000 m^2 SPS system

	Falcon 9	Delta IV Heavy	Atlas V Medium
CO_2 / Launch (metric tons of CO2)	441	0	259
Cost (k$/kg)	2.6	12	8.1
Launches in 2020	26	1	5
Payload volume (m^3)	140	145	106
Payload mass to LEO (kg)	22800	28370	11000
Launches/1000 m^2 SPS system	4	4	8

5.4.2 Builder Delivery Launches

In initially building the LEO SPS system, dedicated launches carrying only SPS builders will have to be launched. The CO_2 footprint of launching builder satellites to LEO vastly depends on the launch vehicle chosen. If the launch vehicle is chosen solely based on carbon footprint, United Launch Alliance's Delta IV Heavy or Delta IV could be used, as their exhausts include zero carbon emissions [20]. This is due to their first stage and second stage engines burning cryogenic liquid oxygen and liquid hydrogen. This would result in zero additional carbon emissions resulting from the launch. However, the choice in launch vehicle for a commercially viable SPS constellation is not as simple as only considering carbon costs.

When current options are considered, cheaper and more readily available launch vehicles have larger CO_2 footprints. The Delta IV Heavy, attractive for its low carbon emissions, traditionally cannot operate at a low cost or on a fast timeline, both of which would be attractive to any entity aiming to construct a SPS constellation [21]. If a cheaper launch vehicle with a faster turnaround is chosen, such as SpaceX's Falcon 9, with a launch cost of 2.7k$/kg to LEO and 26 launches in 2020, launch carbon emissions drastically increase[22, 23]. While a Delta IV launch releases zero carbon emissions, each Falcon 9 launch releases 440 metric tons of CO_2 into the atmosphere, which is roughly equivalent to the yearly emissions of 96 gasoline powered passenger vehicles [20,24]. However, this is negligible when compared to the United States' yearly carbon output, especially when the long-term energy offsets are considered [25].

Another approach could be to use a launch vehicle that is a middle ground between the Falcon 9 and Delta IV Heavy. That is, a launch vehicle that is better on costs and timelines than the Delta IV Heavy, but better on carbon emissions than the Falcon 9. A promising candidate to fill this role is ULA's Atlas V, at $8k/kg and 5 launches in 2020, with a carbon footprint of 259 metric tons per launch [20, 21, 26]. It should be stated that while carbon emissions and launch costs are technical, constant features of a launch vehicle, the measure of launch speed, launches in 2020, is not. This measurement does not fully account for demand, as part of the reason that Falcon 9 has so many launches is because SpaceX has an internal motivator to launch Falcon 9s, Starlink which contributed to half of the Falcon 9 launches in 2020 [23].

When launches needed is considered, the Atlas V does not shine. This is due to its smaller payload mass and volume, requiring three launches. Payload mass to LEO is from the launch providers. Payload volume is derived from the published fairing dimensions, given in the form of diameter and height. These dimensions are used to calculate the volume of a cylinder, which a 50% volume loss factor is then applied to in order to account for the loss volume due to the aerodynamic shape of the fairing, any fixtures inside the payload pay, and any volume losses associated with stacking the satellites inside the fairing.

Despite the Delta IV Heavy's zero carbon emissions, when cost and timeline are considered, SpaceX's Falcon 9 becomes the most realistic choice. Given the dimensions of the Falcon 9 fairing, it is again estimated 115 satellites of the size 1.5m x 0.5m x 0.5m can be launched at a time given mass as the constraining factor. In 4 launches of the Falcon 9, 1 SPS system of 1000 m^2 can be launched. This would be with an approximate launch carbon footprint of 1600 metric tons, a cost of roughly $248,000,000 and could reasonably be launched within several months.

5.4.3 Rideshare Opportunity

Although the initial satellites would be inserted into LEO on dedicated launch vehicles, any additional satellites that need to be added as satellites fail would be inserted into LEO using common rideshare opportunities. This spreads out both the CO_2 footprint and cost.

Rideshares spread out the CO_2 footprint associated with SPS system by distributing the responsibility for launch carbon emissions across all the entities in the rideshare. This carbon responsibility can be attributed to each entity by calculating the fraction of the total launch mass their satellite represents and multiplying this by the carbon released during the launched. For example, if a nonexpendable Falcon 9, with a LEO payload capability of 22,800kg, launched one SPS builder, with a mass of 200kg, then the SPS builder would be responsible for just 1.2 % of the carbon emissions.

For the cost of rideshares, SpaceX operates a rideshare program with launches roughly every four months. These currently service SSO, but SpaceX plans to add more frequent LEO capability soon. A slot on a SpaceX rideshare for satellites with a mass of 200kg is currently around $1 million.

5.5 CO_2 Offset

The next step of this case study is to see how much CO_2 and energy can be offset from the power produced by the LEO SPS system. The process for determining the power output was inspired by the work completed by the China Academy of Space Technology which considers critical factors that would contribute to power transfer losses and then using the total power generated to find the total power received by a ground location [27]. Although the paper by China Academy of Space Technology uses a SPS system that is in geostationary orbit, having a LEO SPS system encounter yield similar transfer efficiency factors. These energy transfer efficiencies can be seen in Table 2.

Table 2. Factor efficiencies affecting the power collection and power transfer of a SPS system

Factors Affecting Power Collection	Efficiency
Solar Cell	0.40
Error of Sun-Pointing	0.99
Gap of Solar Cells	0.85
Angle of Sunlight	0.958
Space Environment Effect	0.90
Voltage Conversion in Antenna	0.95
Consumed by Service Devices	0.999
Microwave Generator	0.85
Microwave Regulation	0.98
Microwave Transmission	0.90
Receiving Antenna	0.90
Rectifier Circuits	0.85

Two types of solar cells were compared; one being made from silicon and the other being made from gallium arsenide. By finding the total energy efficiency associated with the SPS system and the chosen solar cell, determining the power that each iterative size of the satellite could transmit to Earth is a fairly simple process, requiring only the system's efficiency (η), the area of the satellite (A), and the solar constant (G_{sc}). The solar constant is the amount of energy per unit area that reaches a surface that is orthogonal to the sun's rays, with a value of 1380 W/m^2 [28]. Equation 1 is used to find the relationship between the satellite area and power received in kW.

$$P_{received\ on\ Earth} = \frac{(G_{sc} * A)}{1000} * \eta \qquad (1)$$

Once the total energy output is known, the total CO_2 offset is found by using a conversion factor of 0.417 kg/kWh which is the average amount of CO_2 produced per kWh in America [27, 29]. It should be noted that while performing these calculations an assumption was made that each builder satellite could collect and store the indicated power calculated within one hour.

5.5.1 Silicon Solar Cells

For the case of solar panels used in these satellites being made using silicon solar cell, an efficiency of about 20% was used, which with including the other associated efficiencies, the overall efficiency of power received on Earth from the power received in space is about 8% [29]. This directly implied that for the case of the one 1000 m^2 SPS system, approximately 100 kWh of energy was produced and received at a ground location. Using the CO_2 conversion factor provided by the United States Department of Energy (DOE) and the calculated total power received on the ground location, it was found that approximately 40 kg of CO_2 were offset per hour.

5.5.2 Gallium Arsenide

Assuming the solar cells used in these satellites would be a thin film gallium arsenic solar cell with an efficiency of about 40% and including the other associated efficiencies, the overall efficiency of power received on Earth from the power received in space is about 15.8% [27, 30]. Using this total efficiency, for the case of the one 1000 m^2 SPS system, approximately 220 kWh of energy was produced and received at a ground location. This directly corresponds to an approximate 90 kg of CO_2 offset per hour using the conversion factor provided earlier by the United States DOE.

5.6 Building Multiple 1000 m^2 LEO SPS systems

By knowing the total power generated per hour and the total CO_2 offset per hour for one 1000 m^2 LEO SPS, a relationship can be found if multiple 1000 m^2 LEO SPS are decided to be built at LEO. By using MATLAB, Figure 6 and Figure 7 were created to show the relationship of the total power receive per hour and total CO_2 offset per hour as a function of the number of LEO SPS systems built in orbit.

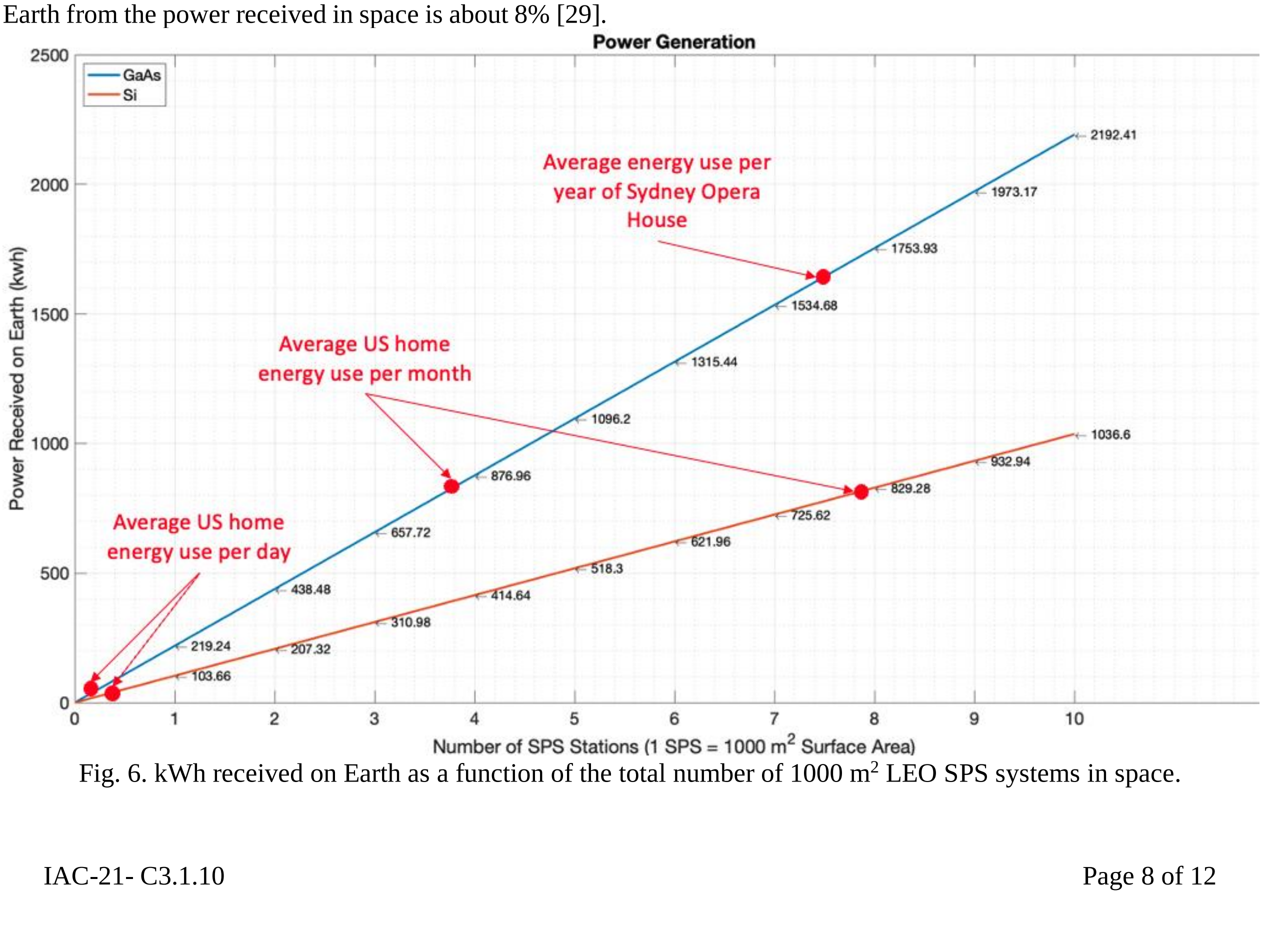

Fig. 6. kWh received on Earth as a function of the total number of 1000 m^2 LEO SPS systems in space.

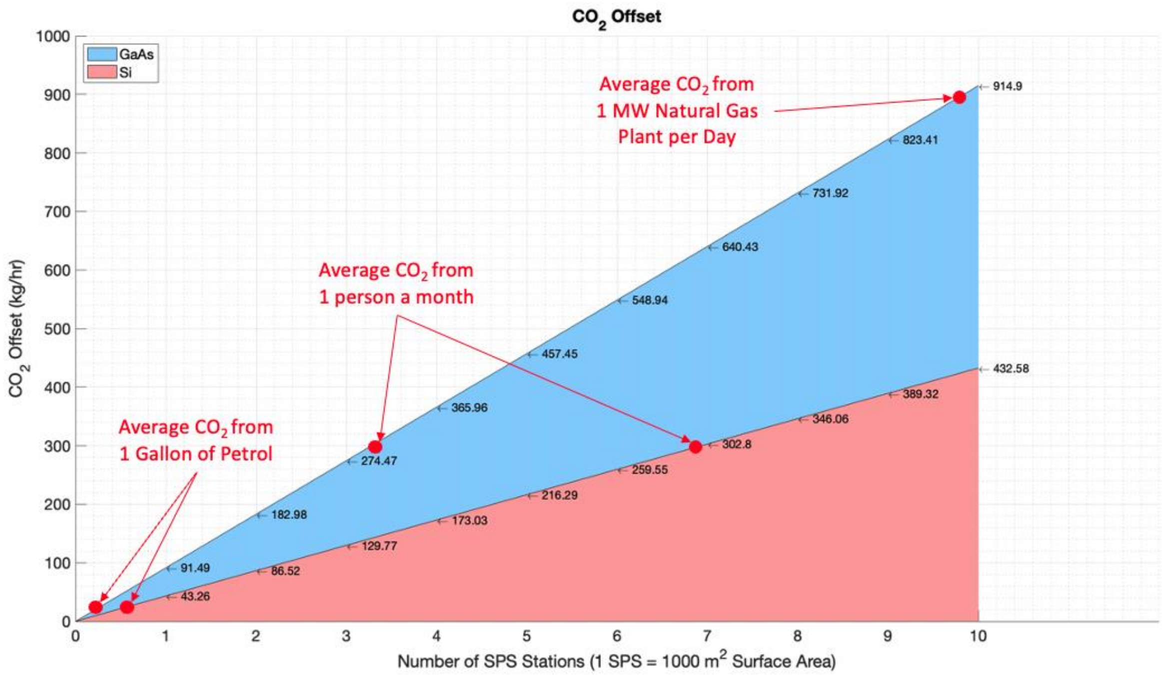

Fig. 7. CO_2 offset per hour on Earth as a function of the total number of 1000 m^2 LEO SPS systems in space.

From Figure 6 and Figure 7, the values for the total power received on Earth and the total CO_2 offset per hour as a function of the number of 1000 m^2 LEO SPS systems can be seen by the black values following the arrow on each figure. It can be seen that the relationship for both the total power received and total CO_2 offset are linear with respect to the number of 1000 m^2 LEO SPS systems placed in orbit, indicating that as more 1000 m^2 LEO SPS systems are added to space, there will be even more CO_2 offset due to the more power generation.

From Figure 6 it can be stated that by building one 1000 m^2 SPS system, enough power would be generated in one hour of direct sunlight to power one US home per day [31]. Whereas by building four solar power satellites using gallium arsenide solar cells, it would be possible to generate enough power in one hour of direct sunlight to power one US home per month [31]. In the case of using silicon solar cells, you would need eight solar power satellites [31]. Then finally you can see that if you were to build eight solar power satellites using gallium arsenide solar cells, you would be able to generate enough power in one hour to power the Sydney opera house for one whole year [32].

From Figure 7 it can be stated that, in an hour of direct sunlight, by building one 1000 m^2 SPS system the power generated would easily offset the CO_2 footprint associated with 1 gallon of petrol [33]. Again if you were to use Four solar power satellites using gallium arsenide solar cells, in an hour, enough power would be generated to offset the CO2 footprint generated by a person in one month [34]. Whereas in the case of using silicon solar cells, again you would need at least eight solar power satellites to achieve the same effect. Finally you can see that if you were to build eight solar power satellites using gallium arsenide solar cells, in one hour of direct sunlight you would be able to offset the CO_2 footprint generated in an average day for a 1 Megawatt natural gas plant [35].

6. Conclusions

With the assumed cost for each builder satellite being approximately $250,000, the total manufacturing cost to build one 1000 m^2 SPS system would be $115,000,000. With the total launch cost for using four Falcon 9 rockets being $248,000,000, the total cost for building one 1000 m^2 SPS system would be approximately $363,000,000. Then depending on the solar cell used, either 100 kWh of energy is produced in the case of silicon, or 220 kWh of energy is produced in the case of Gallium Arsenide. With the current average price for electricity in the US being 0.13 $/kWh, this 1000 m^2 LEO SPS system would require the price to be 3,600,000 $/kWh using silicon solar cells or 1,600,000 $/kWh using gallium arsenide solar cells making the one 1000 m^2 SPS system comes with a much higher price tag than traditional energy methods for the United States.

In the case of offsetting the approximately 1600 metric tons CO_2 footprint produced with building one 1000 m^2 SPS system being, if using silicon solar cells, which offset 40 kg of CO_2 could be offset per hour, nine years of continuous energy production would be required to achieve a net zero carbon footprint. If using gallium arsenide solar cells which offset 90 kg of CO_2 per hour, approximately four years of continuous energy production would be required to achieve a net zero carbon footprint. With the average life span of a solar panel being approximately 20 years, by using either choice of solar cells, an overall negative CO_2 footprint would be created before the SPS system would require replacement.

While the cost of building the one 1000 m^2 SPS suggested in this paper may seem a bit high in price, it should be noted that these calculations are using cost values associated with the year 2021. With the current trend of there being more launch vehicles using different types of fuel coming to market, the price associated with the launch phase of the builder satellites expected to decrease thus leading to a lower cost per kWh [36]. Regardless, the suggested 1000 m^2 LEO SPS system could still serve as a demonstration of assembling a large space structure, and provide the collected energy to a national defence effort or a humanitarian effort that are operating in energy scarce environments. Additionally, if the driving factor is to keep the CO_2 footprint low when building a SPS system, the one 1000 m^2 SPS system suggested in this paper using the SPS builder concept does provide a potential method to build a SPS system with a negative CO_2 footprint.

7. Moving Forward

While this paper does show one potential concept for how a solar power satellite could be built and a case in which it could prove to be beneficial on maintaining a low CO_2 footprint, many next steps are needed for the development of future SPS systems to become a more reliable and economically viable energy alternative. Three areas currently being researched to expand the SPS builder concept are the focus on developing more LEO SPS systems, new launch vehicles to bring builder satellites to space, and the next iteration of the builder spacecraft design.

7.1 LEO SPS systems

For the case of future LEO SPS system, research is currently being performed on the optimal orbit trajectories in which to provide a LEO SPS system with the ability to collect the most energy and relay the collected energy to a ground location. Additionally, current research is also looking into the total number of LEO SPS systems required to provide constant energy to predetermined ground locations.

7.2 New Launch Opportunities

As the continuing prices of launch costs go down with increased payload capacity and increased rocket reusability, this method of autonomous SPS assembling systems in LEO becomes more and more viable. To name most, future systems such as the Falcon Heavy and extended Falcon 9 fairing, SpaceX's Starship, Blue Origin's New Glenn, and ULA's Vulcan will continue to improve launch costs per mass [37].

7.3 Builder Spacecraft Design

In the case of the builder unit in Figure 5 proposes, several design choices are currently being researched to improve the overall spacecraft design such as the solar panel system incorporated in the current design. Due to the simple design with which the solar panel currently unfolds, only a total surface area of 2.25 m^2 is obtainable per builder satellites. With extensive efforts being made towards unfolding solar panels using origami techniques there is hope that the surface area per solar power satellite could increase leading to larger solar panels and the need for fewer builder satellites to build a SPS system. An example of this technology was demonstrated with the launch of OrigamiSat-1 as part of support from JAXA, which takes a 3U CubeSat of 30cm by 10cm by 10cm and unfolds a 1m by 1m solar panel [38].

By incorporating these new designs of solar panels and expanding the surface area of the solar panels, a new design of the electromagnet system mentioned earlier would be required. This is to allow the electromagnets to extended further than currently designed so that they could attach to other builder satellite without overlapping the larger solar panels. This new electromagnet design is being researched is a method in which the electromagnets will extend from a builder satellites using a boom mechanism, which contains a compact electromagnet on the end with a mechanical locking system. Then by having the electromagnet connected internally to a passively unspooling wiring, power would be transmitted to the electromagnet allow for the creation of an electromagnetic field for assembly and disassembly, as well as means for a method of wireless energy transfer.

In addition to the new electromagnetic design, further experiments are in the works to confirm the validity of using electromagnets in each of the builder satellites for the suggested purposes. For the case of assembling and disassembling spacecraft, work is focusing on analysing the occurrences of any undesired torques that may occur when attracting two or more opposite electromagnetic sources in a space environment. For the case of wireless energy transfer using inductance, further experimentation is intended to analyse the power transfer losses when sending energy from one builder to another builder satellite, and the heat dissipation that is required so that the builder satellite does not overheat when transferring energy.

The final area that is currently being researched and improved upon is the efficiency of the solar panels. Although these efficiencies are already 40% when considering gallium arsenide solar panels, future advancements in the design of solar cells, such as the use of a four-junction, could further increase the efficiency of the energy collection by solar panels [39]. Since the largest contributing factor to the power loss when considering the power received on Earth from the power collected by the SPS system being the solar cell, improvements made on the solar cell will have the single greatest impact on the overall efficiency of a SPS system and ultimately decrease the time to offset the CO_2 footprint and lower the price per kWh associated with building a SPS system.

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