Lifecycle Analysis of Space-Based Solar Power

A fact-based study of the green technology for future aviation regarding climate impact, safety, economics, feasibility, and viability by 2050

The University of Texas at Austin

Talia Elkhatib - Environmental Engineering, Undergraduate
Tiffany Huang - Advertising, Undergraduate
Enrique Loredo - Chemical Engineering, Undergraduate
Mariana Ponce Ramirez - Civil Engineering, Undergraduate
Mateo Renaud - Mechanical Engineering, Undergraduate
Dafhne Salvador - Mechanical Engineering, Undergraduate
Christian Claudel - Civil Engineering, Faculty Advisor

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****New Volume includes the following new sections: 3, 3.1, 3.2, 3.3, 5, 6.1, 6.2, 7.1, 7.2, and 8****

Appendix

Table A: Reusable Rocket Fuel Emissions

	Fuel	**CO_2 (tonnes)**	**Water Vapor (tonnes)**	**NOx (tonnes)**
Hypersonix *Delta-Velos*	Hydrogen	0	2	0
SpaceX *Starship*	Methane	4400	29199	1.7
Rockwell International *Space Shuttle*	Solid Fuel + Hydrogen	443	976	7

Table B: Summary of Design Parameters

Item	**Current best performance (2023)**	**Required or assumed performance**	**Current technology readiness level (2023)**
Solar space station			
Solar panel CO_2 equivalent production cost	101 $kgCO_2/m^2$	150 $kgCO_2/m^2$	N/A
Space solar panels (efficiency)	47%	47%	TRL-4[1]
Space solar panels (lifetime)	15 years	15 years	TRL-9
Space solar panels (mass per unit area)	2 kg/m^2	2 kg/m^2	TRL-9
Laser efficiency	81%[2]	81%[3]	TRL-4
Laser mean time before failure (MTBF)	250,000 hours (28 years)[3]	5,000,000 hours[4]	N/A
Laser pointing precision	10 microradian (Starlink)	1 microradian	TRL-9 (Starlink)
Laser divergence	<1 microradian	1 microradian	TRL-9

[1] Alotaibi, G. (2020, December 17). How can Space-Based Solar Power support Earth's Sustainable Development? Space Generation Advisory Council. Retrieved February 27, 2023, from https://spacegeneration.org/space-based-solar-power-sustainability

[2] Wang, L., Qu, H., Qi, A., Zhou, X., & Zheng, W. (2021, June 27). *High-power laser diode at 9xx nm with 81.10% efficiency*. Optics Letters. Retrieved February 27, 2023, from https://opg.optica.org/view_article.cfm?pdfKey=2045964c-4608-44fc-89a7e0fa0de30af8_477280

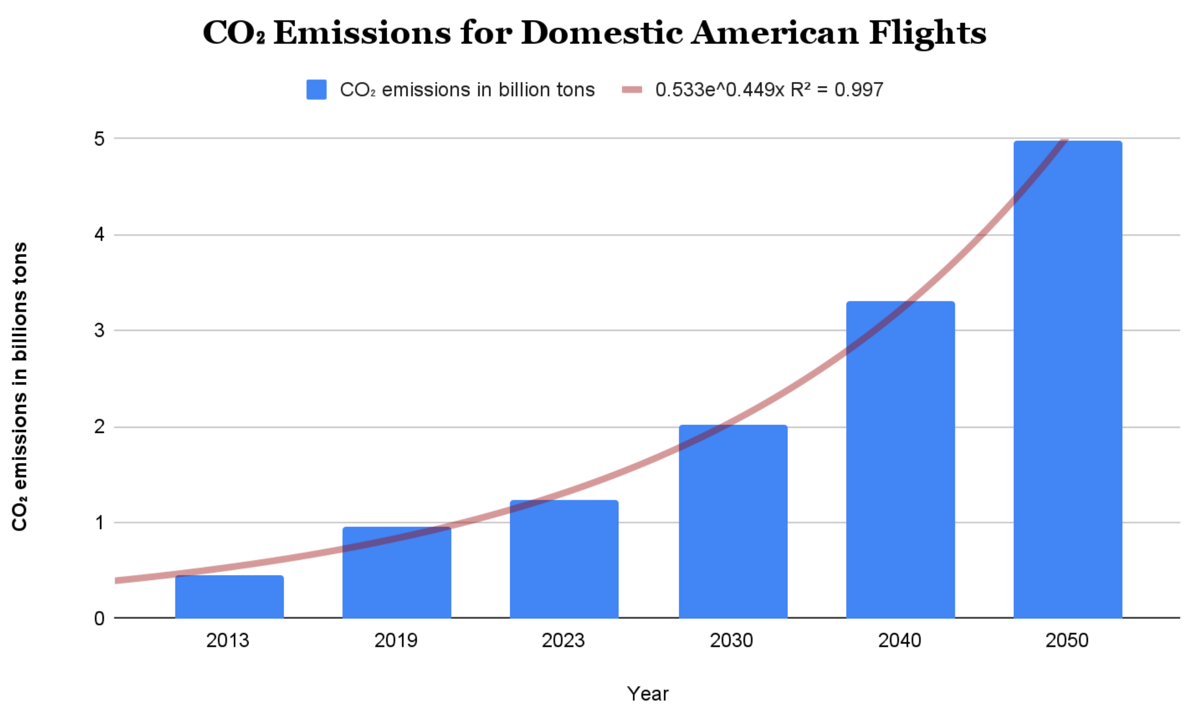
[3] BONATI, I. G., & Gmbh, J. (2003, July). *Exploring Failure Probability of High-Power Laser Diodes*. Photonics. https://www.photonics.com/Articles/Exploring_Failure_Probability_of_High-Power_Laser/a16397

Item	Current best performance (2023)	Required or assumed performance	Current technology readiness level (2023)
Laser power	1 MW	100 kW	TRL-4
Laser beam power density (when received by the airplane)	N/A	30 kW/m^2 (30 suns equivalent)	N/A
Optical beam expander	>1 mm	50-100 cm diameter	TRL-9
Airplane			
Monochromatic photovoltaic cell efficiency (on airplane)	68%	68%	TRL-4
Electric motor efficiency	95%	95%	TRL-9
Propulsive efficiency of fan	80%	80%	TRL-9
Airplane battery energy density	300 Wh/kg	300 Wh/kg	TRL-4
Airplane battery power density	900 W/kg (equivalent 3C discharge rate)	900 W/kg	TRL-4
Launch vehicle			
Reusable rocket (Starship) payload in LEO	150 tonnes	150 tonnes	TRL-7 (not tested yet for Starship, as of 2023)
Reusable rocket (Starship) CO_2 equivalent per launch	4,400 tonnes[4]	4,400 tonnes	N/A
Reusable rocket (Starship) launch rate (steady state)	Multiple flights/day	3-5/day	TRL-1 (concept proposed by SpaceX)
Satellite lifetime	>20 years	10 years	N/A

[4] Calculation derived from measurements of the SpaceX *Starship*

Item	Current best performance (2023)	Required or assumed performance	Current technology readiness level (2023)
Satellite altitude	>36,000 km	1,000 km	N/A

Chart A: Emissions from American Aircraft from 2013 to 2050



Calculations derived from utilizing 17% of global CO_2 emissions[5], as the United States contributes to 17% of all global air traffic.

[5] Graver, B., Rutherford, D., & Zheng, S. (2020, October 8). CO_2 *emissions from commercial aviation: 2013, 2018, and 2019*. International Council on Clean Transportation. Retrieved February 27, 2023, from https://theicct.org/publication/co2-emissions-from-commercial-aviation-2013-2018-and-2019/

Abstract

The aviation industry faces a critical challenge in promoting sustainability efforts worldwide. Extensive changes in our consumption of traditional fueling methods must be made to decarbonize all flights. In addition, planes are expected to contribute 5% of global carbon emissions within the next 30 years (*Airplane Emissions*, 2018), so fuel must lessen its environmental impact. Thankfully, with the rise of greener technologies, industries will significantly reduce aviation emissions by 2050. However, to increase efficiency, further exploration of alternative energy sources must be taken into account. Thus, to combat rising CO_2 levels, we propose using multiple Space-Based Solar Power (SBSP) stations to power airplanes in flight using laser power transmission continuously. The airplanes would use batteries for in-flight emergencies and the following flight-stages: taxi, take off, reaching cruising altitude, and landing.

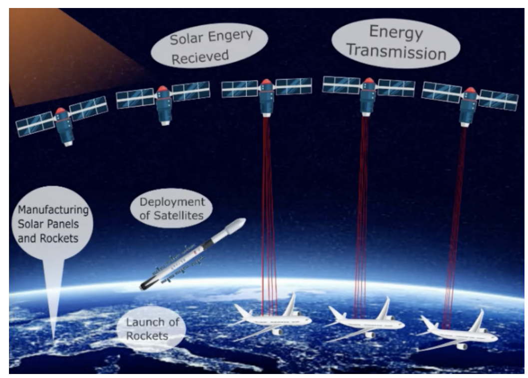
Moreover, the Sun is one of the most significant resources severely underutilized; this massive energy origin could power the globe if the technology is operated correctly. The cost of solar energy has dropped dramatically over the last decade, and utilizing NASA's Technology Readiness Level (TRL) evaluations; the SBSP technology is currently on track to help with worldwide sustainability efforts by 2050. We will explore the energy needed to reposition these stations into space, the materials to construct these stations, and the overall upkeep of such stations. However, it is vital to note that not only would the energy obtained within SBSP stations prove net zero, but it could potentially power all of America's and global aircraft through charging batteries, launching, and inflight in 2050.

1 - Feasibility

The United States aims to bring emissions down to zero by 2050, and solar energy is a promising technology (Penney, 2021). According to a report from Princeton University, the United States will have to speed up building solar panels (Seltzer, 2020). However, as the number of solar panels grows, so does the required land demand. We are looking for clean energy that does not compete with other land uses, so space-based solar power may be the solution to provide aviation energy. Space-based solar power could avoid the problems of terrestrial solar panels, such as atmospheric attenuation. It would solve the problem of transferring this power to airplanes, given the very high geometric horizon of satellites in space, in contrast to ground-based systems. Due to the atmosphere, clouds, gasses, and dust, 55-60% of solar energy is reflected or absorbed to Earth's surface, penalizing energy generation and power transmission to the airplane (Ost, 2023). In space, more energy would be received, and this energy would be transferred more efficiently. The cost of solar energy has dropped 65% in the last 11 years (Fields, 2021); therefore, we can infer that it will continue to drop, and CO_2 manufacturing costs will continue to drop as well.

Our vision for this system is to combine the following recent advances into a single system:

- Large satellite constellations (e.g., Starlink)
- Reusable boosters (e.g., Starship + Super heavy)
- Laser-power transmission to aircraft (e.g., DARPA Persistent Optical Wireless Energy Relay (POWER))
- Space-based solar power with distant laser power transmission (not demonstrated to date, though laser links are used by Starlink satellites for inter-satellite communication)



The design of this system requires the following considerations:

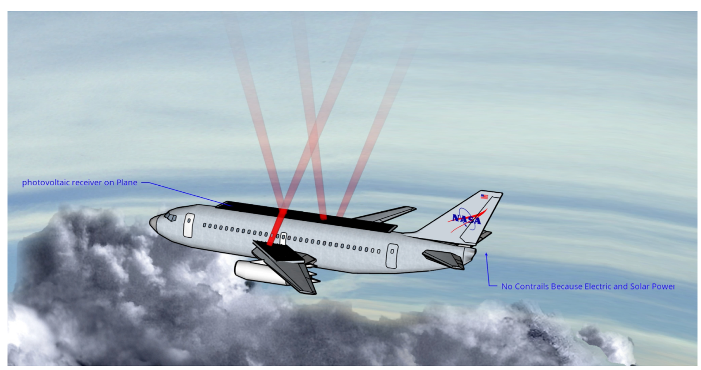
1.1 - Space-based solar panel requirements -
Space-based solar power on current satellites rely on gallium arsenide cells, which can reach 30% efficiency. We can expect to see an increase in efficiency in the future: in theory, Tandem perovskite solar cells are capable of 45% with concentrated sunlight. (Shepard, 2018), with even more efficiency by 2050. Important variables associated with space solar panels include efficiency, rate of degradation (which we expect to be on the order of 1.5% to 20% per year, leading to a useful lifetime exceeding 10 years), and mass per unit area of solar panels (which we expect to be on the order of 3 kg/m^2, though 1.78 kg/m^2 is currently available (*PV Solar Panels 05-20-10.pub*, n.d.)). Thin film (flexible) solar cells have even lower surfacic masses (<0.25 kg/m^2) (Reed & Willenberg, 2004), thus the expected value of 3 kg/m^2 is conservative even with currently available technology. Since most of the mass of the space stations will be from solar panels, this parameter dictates the average power density of the space station (power generated per unit mass).

It is important to note that thin film or lightweight solar panels are more prone to thermal-expansion induced oscillations, which negatively affect the accuracy of pointing a laser at a specific point on Earth. Thus these lightweight solar panels are currently not used for applications that require high precision pointing (such as the proposed system). However, these oscillations could be compensated with fast (high bandwidth) actuators. Such actuators will continue improving over the coming decades, and better electronics and sensors will allow the estimation of these oscillations and their compensation in real-time.

1.2 - Laser power transmission from space stations- The space stations will transmit power to the airplanes through laser beams. The important design parameters of this system are the following:
Laser power, efficiency, and cooling- Lasers have practical power limitations (mostly because of cooling constraints). We envision several ten kW power lasers operating at approximately 81% efficiency (Wang, L., Qu, H., 2022). The solar panels could be used to radiate the excess energy and cool the lasers, with a coolant loop and a slight corresponding loss of efficiency in power generation (slightly higher operating temperature and energy required to operate the coolant loop). High-efficiency lasers would further reduce cooling requirements. Assuming an emissivity of one on the backside of the solar panels and an operating solar panel temperature of 100 ℃, the laser cooling would increase the operating temperature to approximately 105 degrees C, using the Stefan-Boltzmann law.

1.3 - Laser wavelength. The atmosphere is not transparent to all wavelengths. However, the receiver (airplane) would be in the upper troposphere for this proposed system, with considerably reduced atmospheric attenuation of a few percent (Oumbe, A., & Wald, L., 2010). Thus, we can expect that most wavelengths can be used for the laser system. The most interesting wavelengths would be in the red or near IR range and could be optimized for the particular photovoltaic receiver on the plane. Near IR range (1.5 micrometers) would allow the use of "eye-safe" lasers. To minimize risks to humans and animals on Earth, the power sent to a plane would come from many stations in the sky. Any pointing error would have a very limited impact on Earth, given the airplane's speed, the use of eye-safe lasers, the limited power of each laser, and the different directions of arrival. To a user on the ground, being caught in a laser beam from a satellite would result in a brief heat flash, and the energy of this heat flash would be compatible (10x less) with existing laser exposure limits for both eyes and skin.

1.4 - Laser optical and tracking parameters. Pointing the lasers precisely on the airplane's monochromatic photovoltaic receivers is crucial. The operating altitude of the space stations is 1,000 km, and the size of the airplane receivers is on the order of several meters, leading to a required tracking precision of 1-2 microradians. Current Starlink satellites achieve a precision of 10 micro radians or better, and we expect that 1 microrad tracking accuracy will be available by 2050. Furthermore, the beam divergence must also be on the order of 1-2 micro radians, which can be achieved using beam expanders. Using the diffraction limit and assuming a wavelength of 1.5 micrometers, an optical beam expander of 50-100 cm diameter would be required.



1.5 - Satellites as power relays- A limitation of this low-orbit satellite-based power system is that airplanes can only be powered if they are within a sufficient number of satellites given the sun. During the nighttime, power transfer is possible up to about 1,700 km from a satellite with a sun view, assuming beam angles are less than 60 degrees. Hence, the system is usable for 58% of the day/night cycle at the equator. This can be further increased if we use other satellites as power relays, with photovoltaic laser receivers, to receive power from other satellites given the sun. With a single hop, the system can serve approximately 80% of the day/night cycle (depending on latitude and time of year).

1.6 - Airplane design considerations- We consider airplanes in the same class as the Boeing 737-800, with an empty weight (without batteries or passengers) of 40,000 kg and a take-off weight of

75,000 kg. The airplane would be powered by a prop or unducted fans for increased propulsive efficiency in takeoff and cruise. The important design parameters are propulsive efficiency (which we assume to be 80% in cruise), electric motor efficiency (assumed to be 95%), operating speed (assumed to be Mach 0.75 or 800 km/h), cruise lift-to-drag ratio (assumed to be 17). With these design parameters, at the takeoff weight of 75,000 kg, the electrical power requirements in the cruise are 13.8 MW. Assuming a climb to an operating altitude of 11,000 meters (36,000 feet), during 20 minutes, the total energy required for takeoff and climb is about 6.5 MWh.

1.7 - Laser power reception by airplanes- The laser beams emitted by space stations would target receiving areas on the airplane's upper fuselage and wings. These high-power photovoltaic monochromatic receivers would be tuned to the particular wavelength of the laser to maximize efficiency. Photovoltaic monochromatic receivers have reached efficiencies of up to 68.9% (Bellini, 2021). The energy dissipated by the monochromatic receivers will cause some heating of the wings, the power density (30 kW/m^2) is comparable with that of leading edge wing deicers on the Boeing 787. The temperature rise can possibly require insulation materials between the receivers and the wing, the use of heat tolerant materials for the wing (for example heat resistant carbon fiber), or the use of active cooling for the monochromatic receivers.

1.8 - Airplane battery design requirements- The proposed system will use batteries to power the airplane during the following stages: taxi, takeoff, descent, and landing, but not at cruising altitude. At cruising altitude, we plan to power the flight by "beaming" energy to the plane and using any excess transmitted energy to charge the batteries (it is important to note that the batteries are also serving as a safety measure in case of an emergency). By supplying power to the plane during its cruising altitude we hope to increase the sustainability of the aviation industry as the average plane spends about 60 percent of its operational time at cruising altitude (*Reed,* 2015). It is also important to note that batteries will be utilized for the previously mentioned portions of the flights due to the plane being below clouds where the efficiency of our system would be low. To simplify operations, we propose to use Lithium Ion batteries, though other more favorable technologies could be available by 2050. The important design parameters of the batteries are power density and energy density. The current best commercially available Li-ion batteries reach a 300 Wh/kg capacity. Assuming this capacity and a requirement of 6.5 MWh to takeoff and climb, with an average battery discharge rate of 3C, a total mass of 21,000 kg of batteries is required. This is compatible with an empty mass of 40,000 kg and a take-off mass of 75,000 kg, assuming 180 passengers with an average mass of 75kg (13,500 kg). Further improvements in battery technology should significantly reduce the battery mass. The battery will be partially or fully recharged during flight with the excess power of the photovoltaic receivers, leading to faster turnaround times between flights. It also serves as an energy buffer when fewer or more satellites are in the range of the airplane, or for emergencies.

1.9 - Rocket parameters- In the proposed system, we assume that a booster similar to the Starship-Super heavy launch system is available. The chosen design parameters are a payload of 150,000 kg to low Earth orbit, full reusability (up to 10 times), and rapid turn-around by catching the rocket's first stage after flyback (see side image).

With a circular orbit of altitude 1,000 km, a Δv=210 m/s is required for circularization. Assuming a rocket with specific impulse Isp=380 requires a mass ratio of 1.05; thus, 5% of the total mass boosted would correspond to fuel required for circularization (neglecting the mass of the rocket motor). Hence, the total mass that can be boosted to a 1,000 km orbit is 140,000 kg per launch. The orbit altitude of 1,000 km is chosen for several reasons:

- Orbital lifetime exceeding 10 years, given the expected ballistic coefficient of the satellite (Phipps, 2009).
- Horizon of the satellite (~3,500 km), which ensures that a large number of airplanes can be served by any satellite.

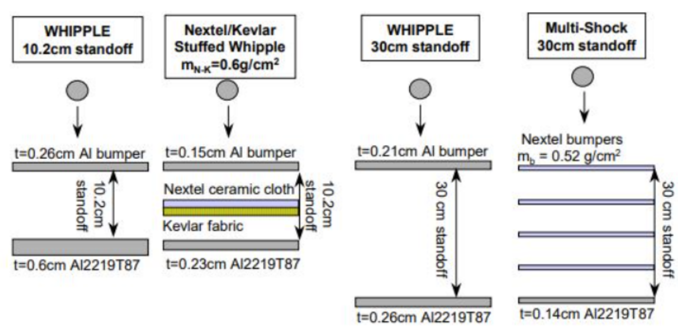
The orbit altitude also impacts the tracking accuracy and beam divergence requirements.

The required orbit inclinations should be computed according to demands for air transportation within a certain latitude band. We estimate that inclinations from 20 to 45 degrees would be sufficient to cover most air transportation demands in North America and the world, given a satellite geometric horizon of 3500 km and a practical horizon (assuming beam angles <60 degrees) of 1,700 km
Space debris control: a small rocket motor can be used to deorbit the satellite at the end of its life. However, we expect that controlling the satellite's orientation overtime during the deorbiting process would allow fine control of its path during the final phases of its orbit.

In order to easily transition from fuel-based energy to Solar Based Solar Power, we plan to send approximately 3 super-heavy launches per day to maintain a steady state system. This is assuming 10,000-20,000 airplanes majority being the Boeing 737 or A320 class are powered by the system worldwide. With the Starship test launch on April 20th deemed as a success, we are hopeful that this is possible to implement this approach. It is mentioned that the CEO of SpaceX's goal is to send 3 starships per day. This was mentioned in 2020 with the goal of being able to send people to Mars. We are able to reason that if it's plausible to send people, then we can send 3 starships per day in order to be able to send solar panels to power the aviation industry for people here on earth.

2 - Viability

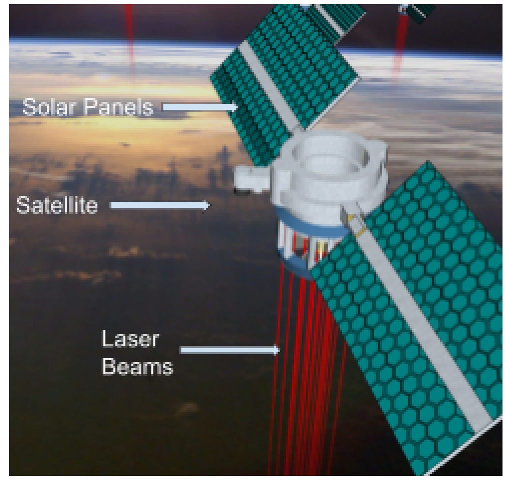
2.1 - Space Debris- A Whipple shield is the primary defense against space debris. It comprises an outer protective layer, some middle layer (i.e., mesh, spacing, and/or shock absorbers), and an innermost protective layer. Different designs are used for different spacecraft components, depending on the component's risk, location, and importance. For this particular project, given the importance of the mass per unit area parameter, the satellite will be mostly unprotected, with the exception of critical elements such as the Lasers and computers.



2.2 - *Solar Radiation and solar panel degradation-* Possibly one of the largest concerns for solar panel satellites is radiation from the sun. However, recent research on self-healing materials against radiation damage is promising. These specific materials (including for example synthesized double perovskite nanocrystals) will be used primarily for solar panels and electronic devices.. A research team at Technion (Israel) has come across double halide perovskites (which are Lead-free). After being hit with electron radiation beams in testing and causing a hole to form, it was found that the material could self-heal to its original state. The double perovskite could “push” the hole formed out to the surface and return to its original state without damaging any surrounding crystal structures. This semiconductor replacement for silicon (the most common semiconductor for photovoltaics) appears to be able to theoretically repair itself indefinitely until a substantial amount of the semiconductor has degraded.

2.3 - Number of Required Satellites and Satellite parameters- We assume that the satellites have the following design parameters:

- Solar panel surface area: 2620 m^2 per satellite
- Satellite mass: 8,000 kg
- CO_2 equivalent cost of manufacturing: 393 tonnes CO_2 equivalent (assuming an average CO_2 cost of 150 kg/m^2)



Satellites within Low-Earth-Orbit at a faster rate than the earth rotates. This means there will have to be a calculated number of satellites within the Earth's orbit to guarantee a minimum number over the contiguous United States to power the flight demand. This calculation was done by calculating the number of satellites required (81,000 satellites) to power all flights in the air within the U.S. at peak travel season (5400 planes) divided by the total area of the contiguous U.S. area (~8 trillion m^2), giving a ratio. Equalling this ratio to the required global satellites divided by the area covered if the contiguous U.S. area wrapped around the Earth (6.946e13 m^2). Giving a final number of 696,320 total satellites in orbit. With the global coverage of satellites, this serves as a global solution as well. Being able to provide power to any point within the band of satellites. For more information relating to space debris pollution reference section 5. With an anticipated satellite lifetime of 10 years, in steady-state operations, 51 new satellites should be launched daily (3 Super Heavy-Starship launches per day) to replace failing/decaying satellites.

3 - Manufacturing

3.1 - Solar Panels - To manufacture solar panels one starts with the raw material that is put through the Czochralski process. This process uses chemical reactions to grow a crystal, the crystal is then cropped, grinded, polished, and glued to glass (NREL). Next the crystal is cut with a diamond wire to produce wafers and a chemical bath is applied to release the glass from the wafers. These wafers are then cleaned, inspected, and used in the solar panels (NREL). Additionally production of solar panels is estimated to emit 50g of CO_2 whereas natural gas produces 117 lbs, petroleum produces 160 lbs, and coal produces 200 lbs of CO_2 (Katelyn, 2023). Solar panels are also shown to have a lifespan of about 40 years allowing for continued use (Katelyn, 2023). As a whole the manufacturing process continues to improve and emissions grow smaller everyday. Recently, increased production has consequently increased the amount of CO_2 produced yet even then photovoltaic production only accounts for 0.15% of total greenhouse gas emissions (Iea).

3.2 - Carbon Fiber - Carbon fiber is difficult to manufacture as it requires chemical and mechanical processes. The first step in manufacturing is to draw out long fibers from the composite material or raw material used for carbon fiber, usually these materials are polyacrylonitrile or rayon precursors (Thuline, 2022). Then this material is carbonized through heat treatment, this process allows the atoms that are not carbon to be taken out of the material leaving behind only carbon atoms(Thuline, 2022). Next the surface of the new fiber is oxidized and this creates a good surface for chemical bonding as well as rough surface for physical bonds with materials such as epoxy. As the fibers are woven into their desired shape the fibers must be coated in binding agents such as epoxy for protection (Thuline, 2022). These processes are energy intensive as they emit 20 tons of CO_2 per 1 ton of carbon fiber (M.

Shioya , 2014). Additionally it costs up to 10 dollars per pound to produce carbon fiber (Nunna et al., 2019). While the cost and emissions can be high, the benefits are huge as carbon fiber has a high tensile strength, high stiffness, high chemical resistance,and high temperature tolerance while being lightweight in comparison to other materials such as steel (Thuline, 2022). Additionally, future trends demonstrate that the addition of carbon fiber to planes is estimated to reduce emissions by 1400 tons of CO_2 per 1 ton of carbon fiber by reducing the weight of the plane by up to 20% (M. Shioya , 2014).

3.3 - Batteries - Although Lithium-ion batteries are favorable to using conventional jet fuel, there are still sustainability concerns that originate in their manufacturing and sourcing of materials. Lithium provides the advantage of not being scarce which is beneficial as it is an important material for the batteries, but the extraction of the raw material can cause huge environmental and social concerns. Most of the worlds' lithium comes from Australia, China, Argentina, and Chile. Both Argentina and Chile utilize large amounts of water to mine the lithium although being an arid region. Australia and China produce lithium by mining the mineral spodumene and process it by exposing it at 1,000 ℃ and leaching it with acid. Both processes pose issues for the environment through the use of large amounts of water (which will negatively affect both the local human population and wildlife), or with a large energy requirement which is tied to large carbon emissions. However, there are alternatives which are being developed, an example of which is Cornish Lithium's plant using direct lithium extraction technology to produce lithium out of the lithium-rich hot brines (*Sanderson*, 2021). Furthermore, solid-state lithium batteries, lithium-air batteries, and even replacing lithium with sodium or other metals are research areas that are being developed to increase the sustainability of batteries. The manufacturing of Lithium-ion batteries also involves the use of the solvent NMP which raises concerns regarding its harmful impact on the environment and human health (*Toxic-Free Future,* 2022). However, efforts are already being made to reuse the solvent and remove it in an environmentally friendly manner as well as reducing the amounts needed and switching to alternative solvents (*Murata,* 2023). Even with some negative impacts to the environment, lithium ion batteries are still favorable to jet fuel in terms of environmental impact as they will aid in decreasing carbon emissions and with improvement in recycling incentives and technologies, batteries can have a long life cycle. Due to the large size of these batteries even once their energy capacity decreases and no longer meet the requirement for our flight-purposes they will still hold a large amount of energy and can be easily reused by other industries which would increase their lifecycle.

4 - Economics

The economics of this system is highly dependent on the lifetime of the satellites in orbit: the higher the useful lifetime of a satellite, the fewer replacements are needed every day to maintain the number of operational satellites constant. Several factors limit the lifetime of the satellites, including:

- Air drag (satellite ballistic coefficient)
- Solar panel degradation rate and MTBF (Mean time between failures)
- Laser degradation rate and MTBF
- Computer and actuators MTBF

The economics also depend on the cost to boost the required payload, which has gone down substantially in recent years, with the emergence of reusable rockets. With super-heavy reusable rockets, we expect the cost to boost the payload into orbit will further reduce. Finally, the project's economics depend on the ability to extract all resources required to fabricate the satellites economically. We expect some resources to become more scarce, such as Gallium or Arsenic (required for some solar panel designs and the lasers). We anticipate that advances in photovoltaic receivers, solar panels, and lasers will make their construction more scalable by 2050. If not, other options with a very high power-to-mass ratio are possible:

- Concentrated photovoltaic solar power, with lightweight mirrors and lightweight radiators of high emissivity
- Space Stirling engines with concentrated solar power (mirrors), similar to the advanced Stirling Radioisotope generator (*Advanced Stirling)*

It is noteworthy that the total amount of solar panels required to maintain the system (560,000 m^2/day) is well within the manufacturing capacity for solar panels (4,700,000 m^2/day, as of 2021)

5 - Space Debris Pollution

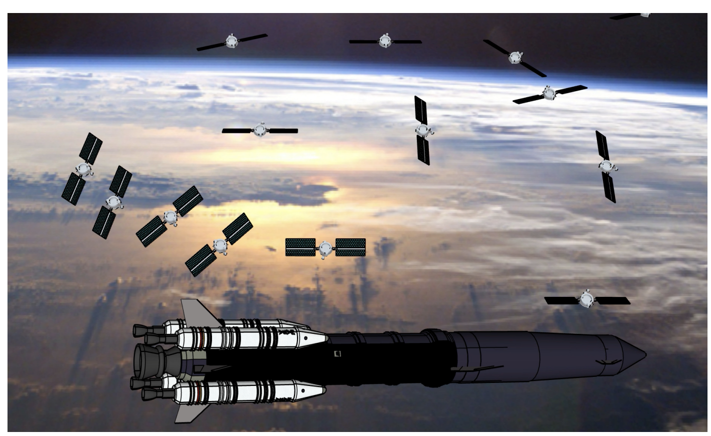
SpaceX's mega constellation of Starlink satellites has sparked a controversy regarding the disruption of the night sky with astronomers and star-gazers. Telescopes have been predicted to move off the planet onto; as well as, possible telescopes on the moon. Starlink utilizes its Visorsat to minimize reflectability and the benefits of SBSP greatly outweigh the disruption of stargazing. There is software, such as AstriaGraph, to track debris in orbit which would allow for minimizing collisions; in combination with maneuvers that are utilized by the ISS to avoid collisions with debris.

6 - Climate Impact

The overall impact of Space-Based Solar Power satellites can be found through the balance between emissions produced and the energy transferred. The energy needed to reposition these stations into space, the materials to construct these stations, and the overall upkeep of such stations require considerable power. However, it is vital to note that not only would the energy obtained within these stations prove net zero, but it could potentially power all of America's planes through charging batteries, launching, and even inflight in 2050. We have designed the system with a conservative estimated lifetime of 10 years/satellite. Even with this satellite's lifetime, this system's CO_2 life cycle emissions are favorable compared to existing hydrocarbon-based fuels.

15 satellites are enough to power an airplane of the Boeing 737-800 or the Boeing 737-Max-8 classes, with an estimated fuel burn of 2,000 kg/h, for 10 years. The total CO_2 emissions associated with the construction of the satellites are mainly related to the solar panels, at 256 kg/m^2 (Circular Ecology). Thus, the total lifecycle CO_2 emissions of the 15 satellites required to power one airplane for 10 years are 10,400 tonnes, including approximately 6,000 tonnes of CO_2 equivalent to manufacturing the satellites and 4,400 tonnes of CO_2 to boost these satellites using a rocket similar to Starship+Super heavy.

In contrast, the total CO_2 emissions of a single Boeing 737-Max-8 flying 10 hours per day over 10 years, with an average fuel burn of 2,000 kg/hour, is 230,000 tonnes. Hence, the proposed system has a greater than 10:1 reduction in CO_2 emissions over the lifetime of the satellite system.



As seen in this analysis, the CO_2 emissions associated with the launch are comparable to the CO_2 emissions associated with the manufacturing of solar panels. Advances in manufacturing efficiency would further increase the benefits of the proposed system, as would, higher percentages of renewable power sources used to manufacture these panels. CO_2 launch emissions could also be reduced by using other types of rocket engines, for example, H_2/O_2 based.

Primarily, there is the assumption that the climate impact of operating such stations is based on the demand for flights. The projected traffic growth in 2050 is estimated to support around half a billion passengers flying yearly in America. If the operational efficiency remains the same, almost 5 billion (See Chart A) tonnes of CO_2.will be released. As a harmful greenhouse gas, it is imperative to reduce such emissions, or detrimental environmental damage will linger and fester. This means that more than 192 Billion trees would have to be planted to offset the carbon emissions into the atmosphere (*Calculation of CO_2 Offsetting by Trees*, n.d.). Therefore, society shouldn't have their hopes on environmental adaptations but rather reduce such emissions in the first place. Fortunately, operating a constellation of SBSPs significantly reduces environmental harm and will produce more power.

Moreover, to transfer space-based solar power stations into orbit, rockets need to be constructed explicitly for such purposes. Because it is expected that most of the carbon emissions for the entire system of SBSP will be from transferring the satellites into space, we propose reusable rockets. Fortunately, this technology is already underway. Utilizing improvements with the existing reusable rockets, we can estimate how much carbon emissions will be produced using this transport in 2050. Starship Super Heavy currently exerts 4400 tonnes of CO_2 (Refer to Table A), including fabrication, fuel, and oxidizer separation and cooling, inefficiently reducing greenhouse gas emissions. HYPERSONIX launch systems are the most efficient and only produce water vapor as a minimal byproduct. They expect to generate hydrogen from salt water through solar means.

6.1 - Sustainability assessment for solar panels and heavy launches - We have established two factors for sustainability: Sustainability of Materials extraction and Sustainability of energy use.

With respect to material extraction, we need to use materials and elements that are abundant on earth, to make the system sustainable. Such elements could include: Magnesium, Silicon, and

Magnesium (from structural elements). Magnesium can be extracted from seawater (add source), it is also one of the least dense metals available, with good structural properties. It catches fire easily, but since the missions are unmanned, this would not be an issue. It could be covered with plastic film or paint to prevent oxidation on Earth. Silicon (for the solar cells). Silicon solar cells are mostly silicon (that can be extracted from sand), with additional elements such as germanium. Solar cells usually do not rely on rare earth materials, and their manufacturing processes become increasingly sustainable. The total production of solar panels required for the satellites is only a small fraction of even the current solar panel production. Each day, we estimate that about 400 tons of solar panels will be back on Earth (or 146,000 tons annually). While this is significant, we estimate that solar panel waste will reach 10 million tons/year by 2050, and thus solar panels falling from space would correspond to about 1.5% of the total solar panel waste by 2050, which is sustainable.

Super-heavy vehicles will be highly recyclable after use, their elements can be recovered for the production of new super-heavy vehicles. These vehicles are also mostly made of abundant materials (stainless steel). The fuel and oxidizer of the boosters are also very abundant (methane and oxygen). With respect to energy usage, the system is highly sustainable, as it uses considerably less energy than an equivalent system of airplanes powered by hydrocarbon fuels. The impact of the rock launches and satellites burning in the atmosphere with toxic metals include: Satellite launches create contrails, though much less than the number of contrails generated by the airplanes that they would be replacing since most of the rocket flight is done above the stratosphere. No toxic metals are released during rocket launches in normal operations.

The satellites contain mostly magnesium for structure (which combusts into MgO2 and is naturally present in water), and plastic that burns in the atmosphere. Solar cells mostly combust into SiO2 (sand) with traces of dopants (N and P types), with concentrations on the order of several ppm. The potential toxicity of these elements should not be a concern, and every day, 48 tons of meteoroids fall on Earth. These meteorites contain mostly silicates, or metals, and have not been shown to be a health hazard for the population.

Additionally, the Carbon emissions from creating the stations and upkeep are considered substantial; however, when considering the carbon reduction of solar power, there is less environmental damage in the long run compared to other technologies utilized today.

6.2 - Thermal Impact - The impact of the presence of the satellites on Earth climate is negligible. Indeed, the total surface area of all the satellites is about 0.00001% of the cross section area of the Earth. Thus, the satellites would block 0.00001% of the incoming solar flux, which has a negligible impact on climate. For example, the impact of periodic solar irradiance cycles (+/- 0.1%) is 10,000 times larger than the impact of the satellites on Earth climate. The radiative impact of rocket launches on the thermal balance of Earth is due to cirrus cloud formation and greenhouse gas emissions. The mass of cirrus clouds from the Super Heavy contrails is estimated to be less than that of the contrails generated by a regular long distance passenger flight (less than the equivalent of burning 92,400 kg of fuel, based on the fuel flow of 33 raptor engines at full thrust, for a flight duration of 20 s in the altitude range 8-12 km). Thus the existing airplane fleet generates considerably more contrails. In addition to CO_2 emissions, rocket launches also emit other greenhouse gasses such as NO, CH_4 and CO, though their concentrations are extremely low (and their impact on climate negligible).

7 - Safety

In this section, we discuss the safety of this system. The primary safety problem associated with the proposed aircraft type is the safety of the batteries used for takeoff, reaching cruise altitude, and emergencies. The weight of this battery will be driven by power density considerations rather than energy density considerations. Thus, we expect significant heating to occur during these phases. The airplane should be designed with these cooling constraints in mind, possibly by distributing batteries across the fuselage and wings

By design, the proposed system minimizes other safety hazards. The laser wavelength (1.5 micrometers) is eye-safe, and the laser beam power density is only 10-100 times that of the sun. Any pointing errors from the satellites would cause a brief flash of energy on the ground (<0.05 seconds), which would not cause any injury (including eye injury) or distraction, given the very high speed of the aircraft.

In cruise, the system is highly redundant (each airplane requires 250 laser beams for level flight at cruising speed and altitude). A few failures in lasers, satellites or airplane photovoltaic receivers should not cause many problems, as other satellites could beam power to airplanes. In case of massive satellite failures, a partial reduction in available power can be offset by flying at a lower speed and lower altitude, reducing the power needed to fly. The airplane's battery can also be used as a “buffer” for about 20 minutes at cruise power. In the unlikely case of total power loss (satellites + onboard battery), the airplane can still glide to a landing point, setting its propfan in a slight reverse (windmill) to generate power for its control surfaces and subsystems or using a RAT for emergency power, as in existing airplanes.

7.1 - Cybersecurity - This would be a main concern for the satellite constellation. It's important to acknowledge that this constellation of satellites would have the potential to be used as a weapon (directed energy) if a large number of lasers focus energy on a particular target. For example, if a very large number of lasers are focused on a single airplane, they could heat up its structure beyond its design limits and possibly destroy it, leading to a crash.

In recognizing that this technology could be used as a weapon, we take the same approach that is applied to implementing cybersecurity towards atomic weapons. Atomic weapons are known to be the most threatening weapon to human existence that was created by humans. Therefore by implementing similar applications of cyber security to our satellites, we are able to assess that it would be safe by approaching it as if it were the worst case scenario.

7.2 - Solution to Cybersecurity - When it comes to addressing cybersecurity issues for SBSP, it's important to perform risk management. This includes:

- Identifying the risk: Potential weaponization of lasers via manual or remote operation, risk of unauthorized use, risk of miscalculations, risk of reduction in confidence on lasers.
- Assess the risk: Lasers can cause catastrophic damage if the flight is not powered and if lasers are aimed at the wrong location.
- Treat risk: Several options are available to mitigate risks. First, each satellite should be designed with an internal mechanism (hardware or software) that is not remotely accessible, that would prevent the pointing of the laser at targets that move at a speed less than the minimum speed of an aircraft. This would prevent the use of the lasers on any land or sea based target. Other methods could involve forcing bi-directional communications between the satellite and the aircraft in order for power to be sent, with a physically limited number of channels to prevent more than a given number of lasers to be pointed on an airplane at any given time.
- Monitor and report risk: Continue to evaluate the risk and report what has worked and what hasn't in order to make adjustments.

8 - Conclusion:

With Solar Based Solar Power, we are able to provide a near global solution. This application is able to be used by any length of flight time but is especially beneficial for long term flights. Long term flights are anywhere between 6 to 12 hours, contributing to approximately 60% of total flight emissions (Ritchie, 2020). With this approach, we are aiming this method towards a market that has no direct solutions but is contributing the most impact. Boeing produces about 500 737's a year, this means that the limiting factor for us is the production of the planes rather than how many starships we are able to send. With this in mind, we plan to send between 1-2 starships a day, this will allow us to be in sync with the production of the planes. After a year, we will have 500 planes built specifically for this source of energy and enough solar power to be able to power these planes with constraints. The Constraints being that there will be limited operations hours until the required number of satellites are set in place. At this rate, it will take approximately 10 years to adjust to this type of energy source with those constraints, having produced 5,000 planes (the maximum number of flights during peak travel in the US) and 75,000 satellites. It's important to note that we are reducing the number of CO_2 emissions by 99%. A regular fuel based plane burns an average 6340 kilograms an hour while in flight, while our method will only be approximately 64 kilograms an hour. Comparing this per passenger, assuming 130 passengers on the plane, 48.76 kg/hr per person of a jet powered plane and 0.5 kg/hr per passenger.

The Sun is the most significant resource available to us and it will be the driving force that helps us reach our goal of becoming proven net zero. Our civilization is bound to harness this important energy source, it's just a matter of investing the right energy and time in addition to keeping the main goal in sight, to become a net zero civilization.

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