Abstract
SLEP is an integrated aviation solution employing space-based lasers as the main source to power aircraft flights with the aid of hydrogen for takeoff, landing and emergencies (1-hr energy buffer). Long-distance wireless power transmission is an idea with a long history, which can be traced back to Tesla's era. Today, the US military has been conducting experiments with the goal to power mobile vehicles. However, though limited but meaningful successes had been demonstrated by using drones over shorter ranges, powering a 737-800 class or larger aircraft for a long flight remains very challenging. In this proposal, a space laser-enabled propulsion solution, i.e., SLEP, is described for implementing the vision of pure blue skies. The core of a SLEP aircraft is a novel highly efficient laser jet engine that can convert > 95% of received laser energy into the thrust. Space based solar power stations deployed in the Medium Earth Orbit (MEO) will be responsible for powering the SLEP aircrafts while above cloud altitudes. For ensuring a continuous 15MW power supply, estimated based on 737-800's parameters, required for cruising with a 737-800 sized SLEP aircraft, a SLEP MEO power station will include a 250x250m solar array and a 20 MW laser cluster capable based on fiber lasers. However, with a specialized blended-wing shape allowing higher

altitude operations from greater lift and with the laser ramjet engine, a SLEP aircraft may cruise with only 5-10MW laser power supply.

Impact

1. Environmental impacts:
   SLEP eliminates the existing harmful emissions to the greatest extent and causes no new ones. For a SLEP aircraft, both the core laser jet engine and the auxiliary hydrogen jet engines produce no CO_2, nvPM as well as no new harmful ones. The hydrogen jet engines will emit H_2O which may cause contrails at high altitudes; however, they will be only used at low altitudes for takeout, landing and emergencies to prevent from the generation of contrails. NOx are species that can not be 100% avoided, as the process of heating up and accelerating the introduced air molecules, as a mixture of N_2 and O_2, provides a certain chance for the production of NOx. However, it might be mitigated by adjusting the details in engine or nozzle designs if needed. By adopting space-based solar power stations as the energy source, SLEP offers the greenest energy beamed through the vacuum of space and then the very thin atmosphere where SLEP aircraft spend most of their time cruising. The arrangement uses solar energy, avoids the waste of energy from the ground station caused by clouds and weather and avoids hurting anything that happens across the beam, like birds.
2. Flight experience:
   One of the most interesting applications of long-distance wireless power transmission is to enable super long-range traveling of mobile vehicles. By implementing this proposal, SLEP will realize super long-distance flights of aircrafts. Compared to the current 737-800 which can fly for 5,436 km with 26,022 L fuels (~6.7 hours at the cruising velocity) (Wikipedia), a SLEP aircraft with similar capacity to a 737-800 can easily fly across the oceans or around the world without fuel once at cruising altitude. It will be a breakthrough change in flight and traveling experience as well as affecting the development direction and ecology of the aviation industry.
3. Competitive advantages:
   Finding alternatives outperforming or having a similar energy performance to current jet fuels is a problem that has been

approached with traditional means too many times but remains unsolved. Though it may not be possible to know all competing solutions in development, here we would like to briefly compare SLEP with several known solution types. As the basis for comparison, current jet fuels, such as Jet A (43.02 MJ/kg or 35.3 MJ/L) (Wikipedia), have excellent energy performance in terms of specific energy (MJ/kg) and energy density (MJ/L) (Wikipedia). Certain sustainable aviation fuels (SAF) have been claimed with a similar or higher energy performance (Gevo). However, as they are still carbon-based, SAF may not be considered the ultimate solution to this problem. Other chemical fuels, such as liquid or compressed hydrogen (H_2), methanol (CH_3OH), methylcyclohexane ($CH_3C_6H_{11}$, MCH) or ammonia (NH_3), are either lower in energy density (H_2) or both specific energy and energy density (CH_3OH, $CH_3C_6H_{11}$, NH_3) (Chatterjee *et al.*). It is determined by basic chemical properties and fundamental physical principles. Unless there's a revolutionary breakthrough in the future, aircrafts employing cleaner chemical alternatives may have a very significant short-legged problem. e.g., flying for much shorter with the same weight of fuels or needing to have super large tanks for carrying H_2 for the same distance of flights. Current battery and fuel cell technologies are also known to be unable to have completive energy performance with traditional jet fuels (ChatGPT 1, ChatGPT 2), and it may rely on unexpected advances in material science for further improvement. On the other hand, as a response to the Blue Skies Competition 2023, very interesting solid fuel concepts based on alumina or iron powder combustion and recycling of the oxides were proposed by the Boston University teams. However, our analysis suggests that these kinds of solid fuels don't seem like a viable approach to produce competitive alternatives to current jet fuels (WidgetBlender). From the view of known physical and chemical principles, besides long-distance wireless power transmission, nuclear power may be the only reliable energy source to support aircrafts at the same or better flight performance, if the small modular reactor (SMR) technology gets further mature. However, as nuclear energy itself is controversial, the concept is at an environmental and moral risk much higher than others. Therefore, among competing solutions, SLEP should have a better chance to really deliver the expected impacts on environments, traveling experiences and the aviation industries in a visible future.

Novelty and Description

1. Solution description:

   (1) Overview: As shown in **Figure 1**, a SLEP aircraft employs a combination of long-distance wireless power transmission and liquid hydrogen as the energy source. The core of a SLEP aircraft is a novel highly efficient Laser Engine (LE) that is placed on the tail and can convert > 95% of received laser energy into the thrust. A Hydrogen Engine (HE) or more on each side for 1-hr energy buffer will be added to the SLEP aircraft for the flight at low altitude and emergencies. Power Stations based on large solar arrays and fiber (Wikipedia) or DPSS (diode-pumped solid-state) seed (Wikipedia) laser clusters and deployed in MEO to form a MEO Laser Constellation will be responsible for continuously powering the SLEP aircrafts at cruising. Though other designs are possible, a flat aircraft appearance with blended wings and a ramjet engine is considered the best design that can utilize laser power in the most efficient and simplest way. The exact aircraft designs and the deployment scale of space power stations depends on ultimate system needs.

   (2) Laser Engine: SLEP Laser Engine relies on a Laser Receiver to receive lasers and direct them into the engine. For safety the beam will be spread over a 3-4m diameter then refocus for the Laser Engine (see **Figure 1** and next subsection). For pursuing simplicity and efficiency, Laser Engine will be developed based on the ramjet form (**Figure 2**) (Wikipedia).The refocused laser will be pointed into a heating chamber to create a hot zone (> 2,000ºC). With cold air collected from the air surrounding the aircraft channel into the chamber through small openings, gas molecules will be rapidly heated up and accelerated. Then the hot air exhaust will be exit through a nozzle for generating thrust. Although this will not emit CO_2, water and nvPM, the emission of NOx at a certain level is possible. Modifications of nozzles or other parts might be applied to the engine, depending on testing results. For empowering the flight of a 737-800 class aircraft with turbofan engines,

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based on our analysis, 15MW for the thrust should be ensured (WidgetBlender), which brings the Power Station's continuous target laser power to 15~20MW. However, with the combination of a flat appearance (based on an awarded blended-wing body (BWB) design with an improvement in aerodynamics) (Alcock, Dehpanah&Nejat, Chaturvedi) and the ramjet-based Laser Engine suitable for high altitude cruising, reducing the power requirement to 5MW may be possible.

(3) Laser Receiver: On top of the aircraft, toward the tail, a Laser Receiver is needed to direct the laser power to the Laser Engine. This Laser Receiver uses a 2050 era GPS (and other GPS like system) to find its position within 10 cm. It communicates this every 100th of a second, as well as aircraft attitude within a degree with the laser on the Power Station to assure that the beam is optimally placed. It also senses any drift off center and can command the laser to shut down and the aircraft to switch to the Hydrogen Engines as backup. The laser will only transmit power if the beam is well located. This protects the plane and anyone and anything not on the plane. The top of the receiver is a window that is 99.99%+ transparent to the incoming laser. Inside is a positive meniscus lens that compensate for changes in aircraft attitude (**Figure 3**) as well as focus the beam through a reflective funnel and another transparent window into the Laser Engine (**Figure 4**). The Laser Receiver will also capture a very small fraction of the beamed power with solar cells that will be used to power the electrical systems on the plane during the high altitude cruise.

(4) Laser beam power: Aiming to support the continuous flight of a 737-800 class SLEP aircraft, the space Power Station harnesses the cutting-edge technology of fiber or DPSS seed laser clusters, each generating intense 5~20 MW laser beams (see Laser Engine), with precise optics and beam combining techniques employed to aggregate the individual lasers into a singular high-power beam. The Power Station employs intricate precise optics, including beam collimators to control divergence, and adaptive optics to correct aberrations, ensuring the coherence of each individual fiber or DPSS laser within the cluster. Beam combining techniques involve the use of specialized optics such as dichroic mirrors, phase plates, and diffractive elements to precisely

overlap and synchronize the individual laser beams, creating a single, high-power composite beam. Sophisticated control systems continuously monitor and adjust the phase and polarization of each laser to achieve optimal beam quality and uniformity, while integrated power stabilization mechanisms guarantee a consistent output. These advanced optics and combining techniques are essential for maximizing the overall efficiency and coherence of the laser cluster, enabling the power station to achieve the desired 20MW output with precision and reliability.

(5) Space Power Station: The space Power Stations with laser clusters and solar arrays will be deployed in MEO (see **Figure 1**). MEO (perhaps 10,000 km above the Earth) is chosen for several reasons. First, unlike LEO, MEO stations spend most of their time in the sun. When one does pass temporarily through Earth shadow another station can provide power, which is the second reason for MEO, a wide field of view. A wide field of view allows for many aircraft to have many line-of-sight to these power stations. Third, stations in MEO will be well above areas of highest orbital debris concentration and will not contribute to orbital debris when decommissioned. Finally, with a large solar array, even the trace atmosphere in LEO would lead to the need to station keep. MEO avoids this need. These stations will be large, consisting mainly of a large solar array, radiators for heat management and large lasers for beaming the collected energy to aircraft. It will also have communication, computing and sensing/pointing capabilities. It will have the ability to know its location down to 1m accuracy, much like the GPS satellites in MEO already do. The solar array will be the biggest component.

The analysis suggests that 15MW is needed at the Laser Ramjet Engine. If we assume a fiber laser then 50% efficiently is currently available (IPG). So at least 30 MW needs to be collected in orbit. Add in 10% losses in transmission, then 33 MW. Previous studies suggested that space based solar cells are trending toward 40% efficiency (Li *et al.*) in the 2050-time frame. As solar flux at Earth (in space) = 1400 W/m^2, so at 40% we have 560 W/m^2. For 33 MW an active array of 250x250 m will be needed. It can be scaled up or down depending on ultimate system need of the engine (if only 10 MW, then a 170x170m array should work).

By 2040 SpaceX Starship should be able to place 1 station per mission for $20M launch costs and $400M per station building cost. Space stations, instead of ground stations, are chosen due to several considerations. The problem with ground stations are first clouds and weather weaken the laser beam. Second, a lot of ground stations would be needed since they are Line-Of-Sight for only a few minutes. Third, since the beam will be focused near the sender, that beam is going to cook anything that happens across it, like birds. The MEO power stations, which may require maintenance and replacement every 20 years, get max solar power, then beam through a vacuum and finally through a rarefied atmosphere to aircraft. With careful flight planning, 1,000 stations might support 500 flights that are well spread out over space and time. The greater the concentration of flights (spacewise and/or timewise) the more space-based power stations will be needed.
(6) Hydrogen Engine: Hydrogen Engines will be added to SLEP aircrafts for energy buffer. A 737-800 class SLEP aircraft will carry a Hydrogen Engine on each side. As the Hydrogen Engine has a similar thermal efficiency to the CFM56-7B series used in 737-800 (0.453), ~850 kg of hydrogen is required for a 1-hr buffer that can be used for takeoff, landing and emergencies (WidgetBlender). It will need specific tanks/cylinders of around 12,100 L for storage, if the H2 is liquefied (~0.07 kg/L).

2. Novelty: Including but not limited to:
(1) Laser jet engine: The Laser Engine employs laser energy directly to heat up and accelerate air molecules to generate the thrust, instead of converting the laser energy into electricity, using the electricity to generate heat for accelerating air, and then generating the thrust. The latter is a strategy that a significant energy loss can be expected during the energy conversion processes of laser to electricity and electricity to heat (collectively >> 50%). In contrast, we estimate that a Laser Engine can convert > 95% of received laser energy into the thrust.
(2) Hybrid power layout: SLEP aircrafts employ a novel hybrid power layout which combines laser and hydrogen power. This arrangement takes into account both the needs of medium- to low-altitude flights and high-altitude flights. It can realize super-long-duration flights, while ensuring the safety of takeoff, landing and emergencies, as well as

minimizing harmful emissions to the greatest extent.
(3) Blended-wing design: Though SLEP may work with traditional aircraft shapes, a wide and somewhat flat topped aircraft shape featured by a Blended Wing Body offers the best way to integrate the 4m wide Laser Receiver on top of an aircraft. In addition BWB improved aerodynamic performance may make reducing the power requirement to 5-10 MW possible.
(4) In-orbit power station: SLEP includes a novel plan for deploying Space Power Stations in MEO (**Figure 1**).

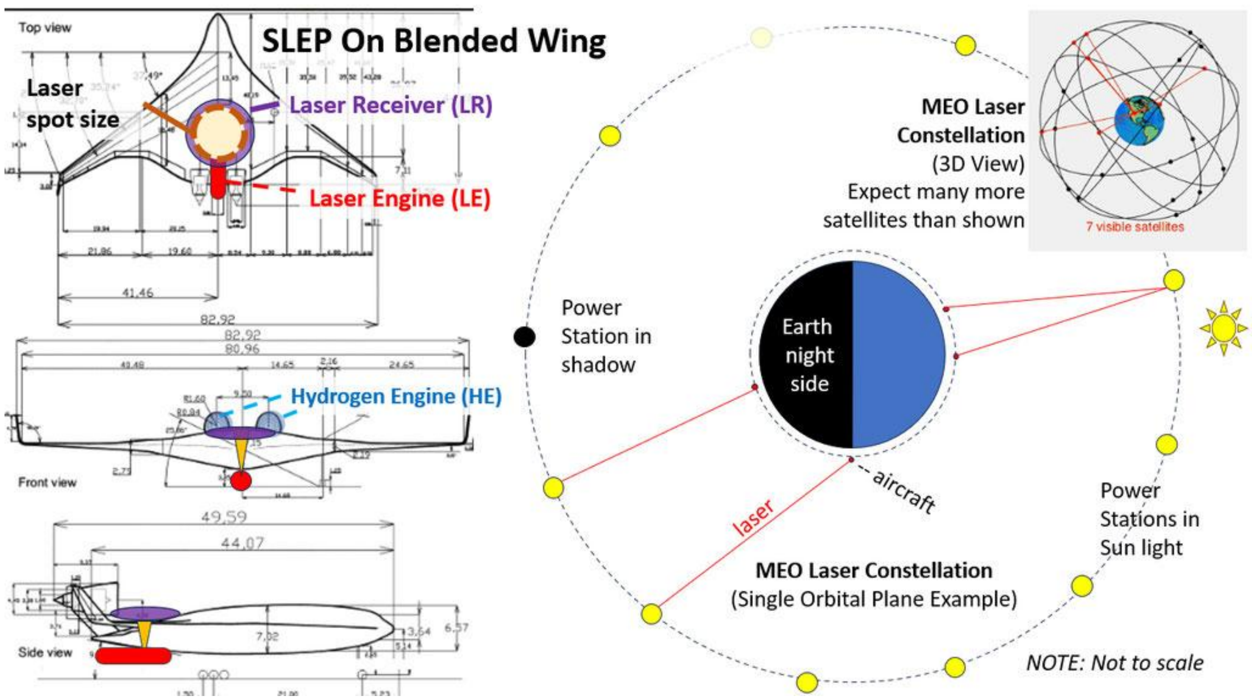

Figure 1. Schematic diagram of SLEP.

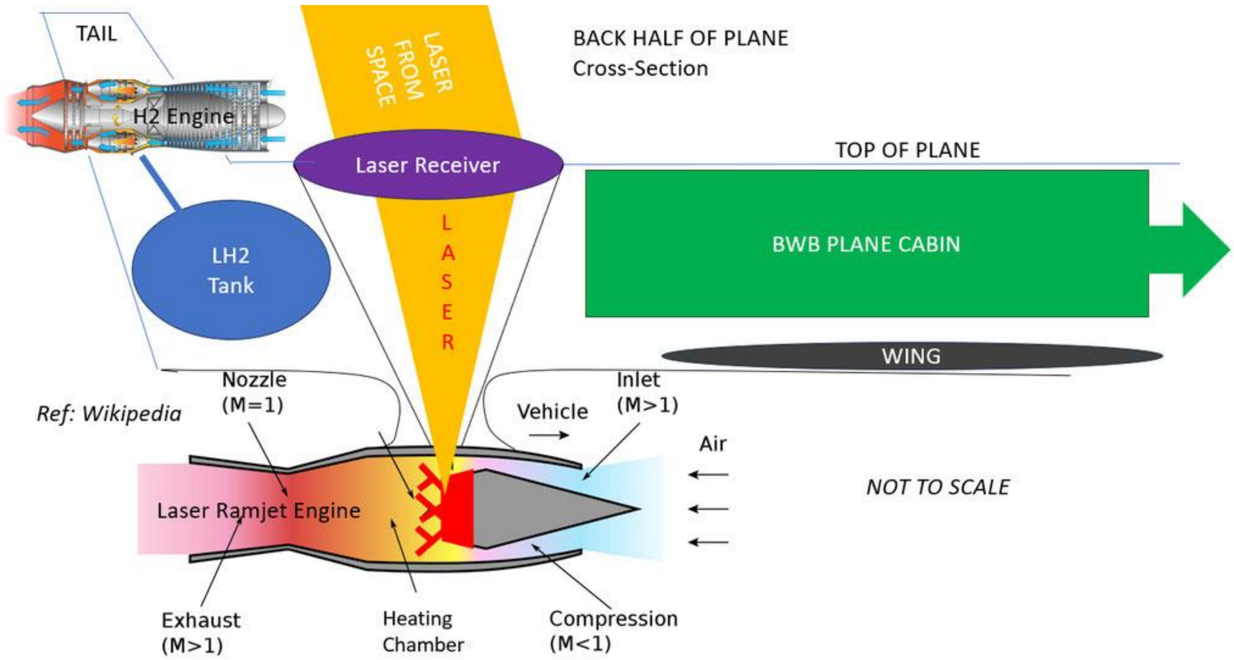

Figure 2. Back half of a SLEP aircraft.

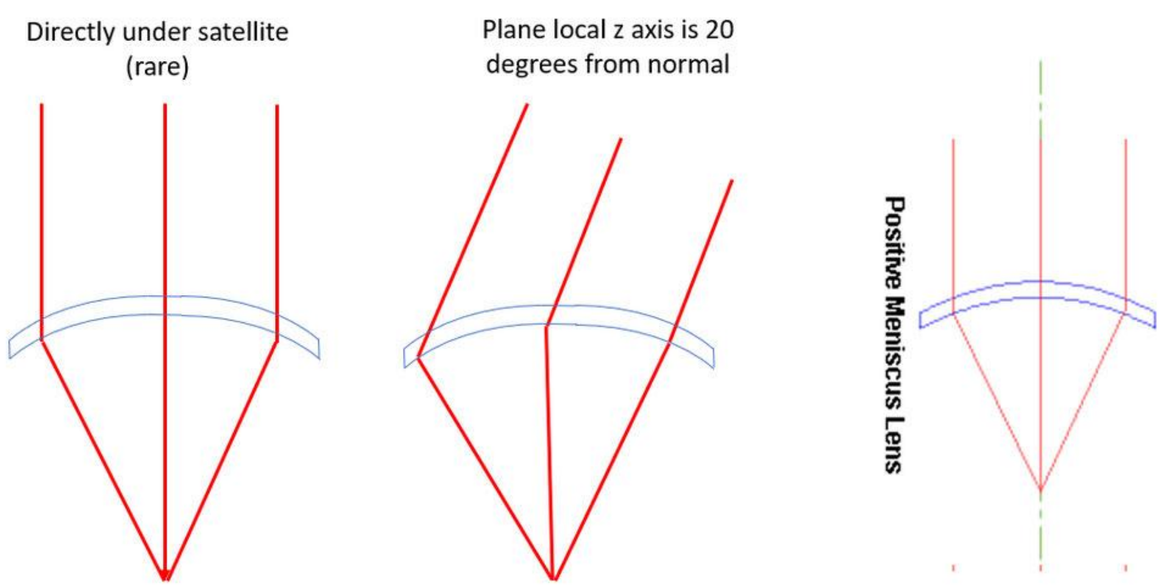

Figure 3. Positive meniscus lens of the Laser Receiver.

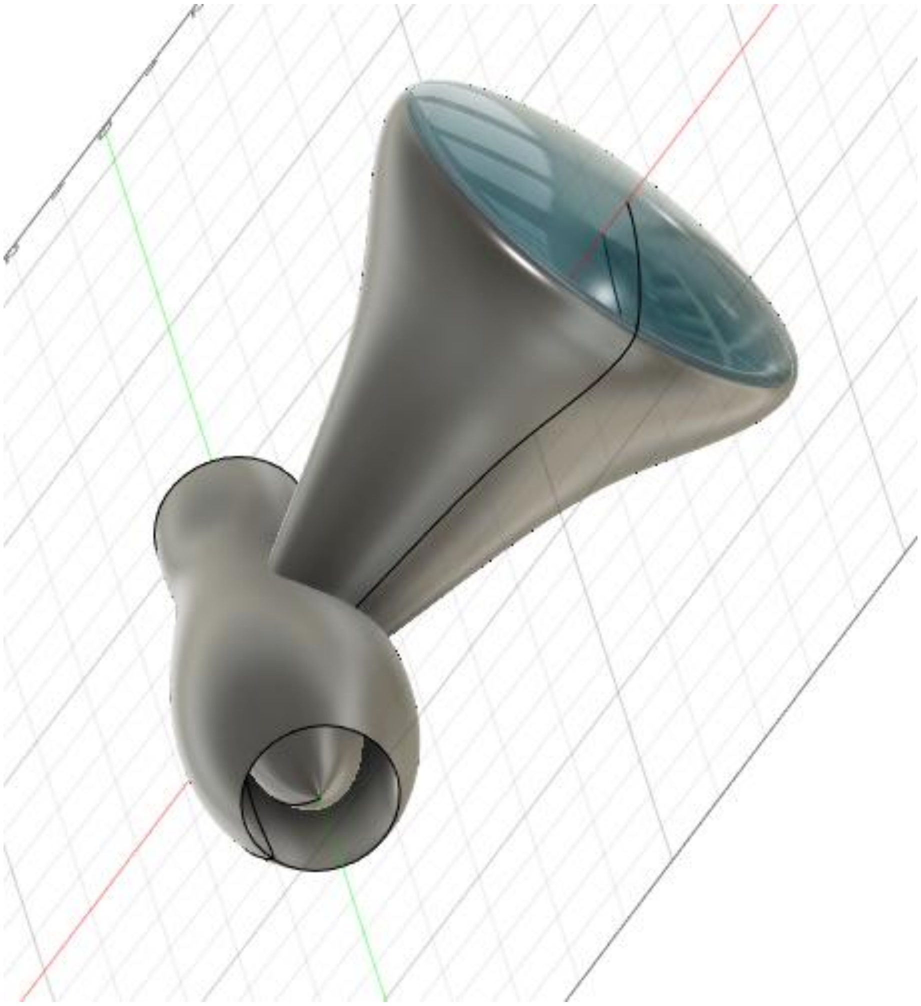

Figure 4. A look of Laser Receiver integrated with Laser Engine.

Feasibility

1. Overview:
   Estimating the overall feasibility of SLEP is determined primarily by five parts, i.e., the feasibility of Laser Engine, Laser Receiver, laser beam power, BWB aerodynamics and Power Station. For the former four parts, they are technically not yet implemented or not yet fully implemented, so their main issues are the technical feasibility. For the Power Station, it is based on solar arrays which have been widely operational on the ground and in space, but it will need a big solar array, so its main issue is the economic feasibility for building and deploying. On the other hand, the Hydrogen Engine is a relatively mature technology, therefore, it's considered feasible. A brief review, identified gaps, and our visions about how to fill in the gaps for each topic are further discussed below.

2. Laser Engine:
   The Laser Engine is the core of a SLEP aircraft. Its conceptual basis is similar to the laser thermal rocket, a thermal rocket in which the propellant is heated by energy provided by an external laser beam (Wikipedia). In SLEP, the beam heats a solid heat exchanger in a ramjet engine design, which in turn heats the introduced ambient air (instead of an inert liquid propellant for the laser thermal rocket), converting it to hot gas which is exhausted through a nozzle. Boeing had patented another laser-powered jet engine concept in 2015 (Anthony), but it relies on laser-induced nuclear reactions to provide energy, so conceptually it's relatively far from SLEP. Key technical issues need to be solved for implementing the SLEP Laser Engine are to ensure the heating chamber can be heated up to the desired temperature (> 2,000°C) that can compete with modern thermal engines and minimize the heat loss from the chamber to the greatest extent. Further studies on optics for directing and refocusing lasers, alloy technology for making the chamber, and composite materials for preventing heat losses are required. We expect to build off a patent that is now in the public domain: (Ram jet powered by a laser beam)
3. Laser Receiver:
   The Laser Receiver requires a positive meniscus lens with a 3-4m diameter, which is larger than the largest lens currently in the world (Guiness) and expected to be expensive. We expect that this issue can be addressed with larger manufacturing machines. While the need is 1,000, 10,000 or more lens, economic factors can drive it happen to offer the lens in an accessible price. On the other hand, the reflective funnel is also needed to be developed. Further studies in the lens and optic or alloy technology for making the reflective funnel are required.
4. Laser beam power:
   Generating high-intensity lasers which are strong enough is the key issue with the highest priority for SLEP. There is still a significant gap between the existing technical level and the desired launch power of 20MW, but a rapid development has been observed in this field. Among laser technologies, fiber and DPSS seed lasers would have the best potential, as they are breaking power barriers all the time. Very recently, in Nov 2023, nLIGHT secured a $171 million defense contract to develop

megawatt-class lasers (nLIGHT). The goal is to enhance the laser power from 300kW to > 1MW in three years. To achieve the desired 20MW power, further studies on fiber or DPSS seed laser methods to enhance the output or optic methods combining multiple > 1MW beams into one high-intensity singular beam, as well as transmission of lasers, are required (Wikipedia, Rubenchik *et al.*).

5. BWB aerodynamics:
   Blended wings are employed with an expectation of utilizing laser power in the most efficient and simplest way with their improved aerodynamic features. Previous studies suggested that BWB aircrafts may fly higher but slower than traditional aircrafts, such as 747, as the blended wing creates more drag but lifts more at slower speeds (Patel). We expect it can be tweaked and optimized. The Laser Engine might be able to push this toward M 0.9. Some of this would need to be wind tunnel tested (Dakka). Flying wings such as the B-2 no longer are a technical challenge, and industry, especially Boing and others are working toward fielding a blended wind aircraft (JetZero).
6. Power Station:
   As aiming to be the greenest, the SLEP space Power Stations are based on solar arrays to collect energy for generating high-intensity lasers. Over decades, solar arrays have been widely used on the ground and in space (Hoffschmidt *et al.*, Patel, Kulu), with a trend toward 40% efficient solar cells. Therefore, a space power station with a 250x250m solar array that can collect 33MW solar energy is buildable. By 2040 SpaceX Starship should be able to place 1 station per mission for $20M launch costs and $400M per station building cost.
7. Others:
   The Hydrogen Engine which is also essential for a SLEP aircraft is a much more mature technology. For example, Rolls-Royce had successfully tested its first hydrogen-powered jet engine in 2022 (Gent).

Practical Work to Date and Demonstration Plan

1. Overview: By aiming to be ready for the commercial deployment of SLEP by 2050, major development, verification and demonstration works are

arranged as the following schedule.
(1) By 2025: Propose the Laser Engine, Laser Receiver and BWB designs with details.
(2) By 2026: Build BWB models and perform wind tunnel testing on different BWB designs.
(3) By 2028: Prototype a smaller version of Laser Engine and Laser Receiver and employ a 1MW fiber laser (nLIGHT) to test on the prototype for the thrust that it can create. Verify the laser beam combining techniques.
(4) By 2030: Propose a SLEP aircraft prototype design with the smaller version of Laser Engine and Laser Receiver.
(5) By 2035: Build the SLEP aircraft prototype. Perform power transmission testing on the prototype and an alternative energy source, such as a 1MW laser power on 747.
(6) By 2040: Take stock of the advanced technologies, including our own and commercial products. Propose the full-size SLEP aircraft design and Power Sation with details.
(7) By 2045: Build a full-size SLEP aircraft and Power Station. Launch the Power Station (s) to MEO.
(8) By 2048: Perform systematic testing on the SLEP aircraft and Power Station.
(9) By 2050: Ready for the commercial deployment.
More details about different SLEP parts in this schedule, please refer to the following subsections.

2. Laser Engine: This is the key one as other tech will probably proceed for other reasons. We need to show what a 1MW fiber laser could do for an engine prototype in terms of thrust created. The first prototype is expected to be made by 2028.
3. Laser Receiver: The first Laser Receiver protype should be proposed together with the Laser Engine by 2028 for testing laser refocusing and thrust generation. Regarding precision positioning and communication, for mobile laser mirror applications, the State of the Art lies within missile defense programs and their airborne laser platforms. SLEP would need to invert the technology so it can act as a receiver vs a laser sender. It should be done by 2035.

4. Laser beam power: The highest power laser beam on a mobile platform is a fiber laser with 1 MW output developed by the military (by 2026). This leads us to expect that by 2050 5MW lasers will be available and they can be combined in a set of 3 to become the laser beam solution on the space-based platform. We should be able to handle laser beam combining techniques by 2028.
5. Blended-wing design: The blended wing body is the key element for a SLEP aircraft to have improved aerodynamic features and higher energy utilization efficiencies. We aim to perform wind tunnel testing on it (by 2026) and its combination with Laser Engine and Laser Receiver (by 2028) at very early stages. Based on the testing results, the designs of a smaller SLEP aircraft prototype and a full-size SLEP aircraft can be proposed by 2030 and 2040.
6. Space Power Station: Current State-of-the-Art for space-based solar arrays are the new Roll-Out Solar Arrays recently added to the ISS. Beyond that, solar cells with 40% efficiencies have been achieved. Space Power Stations with a 250x250m solar array that collects 33MW using 40% efficient solar cells will be needed to power SLEP. Thin film technology is expected to improve space based solar array efficiency by 2050, allowing for the construction of a $400 million MEO station with a capacity of 33 MW. This vision requires new launch systems like SpaceX's Starship to enable a very low price per kg to orbit. This seems likely given the mostly successful IFT-2 test of Starship in 2023.
7. Others: The Hydrogen Engine, vital for the SLEP aircraft, draws from a mature technology landscape, exemplified by Rolls-Royce's successful 2022 test of a hydrogen-powered jet engine. This milestone signals a tangible bridge between current realities and SLEP's visionary goals, indicating the commercial availability of hydrogen engines for energy buffers. With this proven technology, the feasibility of integrating hydrogen propulsion systems into SLEP aircraft is enhanced, reinforcing the potential for next-generation solar energy platforms to harness advanced and commercially accessible H2 jet engines for efficient and sustainable operations.

