Brayton Cycle Conversion For Space Solar Power

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To make Space Solar Power economically viable, the specific power, defined as the electric power generated in space per unit mass placed in orbit, has to reach on the order of 1 kWe/kg. Architectures using photovoltaic conversion are not able to project more than 0.2 kWe/kg, and this value does not rise appreciably with the size of the power plant unlike the case with jet engines. The conceptual design for a converter satellite using an intensified conversion architecture based on a closed Brayton cycle has been shown to surpass 1.6 kWe/kg with conservative technology assumptions. In this paper, we extend the discussion on such satellites, and attempt to reduce the uncertainties in technology projection towards making SSP viable. A primary heater using Hafnium Carbide tubes is proposed, to exceed the target of 3500K. A radiator based on graphene sheets is proposed to exceed the requirements for heat radiated per unit mass. The optimal temperature for the radiator is investigated. Considerations for the design of the high pressure turbine and the electric generators are discussed. Remaining technology needs are listed.

I. Nomenclature

$Girasol$	SSP converter satellite
GW	GigaWatts. One billion Watts
GWe	GigaWatts of electric power
c	Launch cost to LEO, in dollars per kg
k	Viability Parameter for SSP architectures
kWh	kiloWatt-hours.
LEO	Low Earth Orbit
$Mirasol$	Ultralight collector satellite
MW	MegaWatts. One million Watts
P	Price of electric power, US dollars per kWh
PV	Photovoltaic
S	Specific Power, kW to Earth per kg in orbit
SSP	Space Solar Power
SPG	Space Power Grid
TW	TeraWatts. One thousand GigaWatts
η	Efficiency of transmission to Earth

II. Introduction

To make Space Solar Power (SSP) plants viable when scaled up to the level of terrestrial power plants, the cost must be reduced by one to two orders of magnitude from those of architectures considered in the past. The specific power is a primary avenue for the radical improvement that is needed. A tacit assumption is evident in past architectures that conversion of solar power to electricity in Space must use photoelectric effects. However photovoltaic conversion offers no economies of scale in the specific power. The option of intensifying sunlight and using high-intensity solar cell stacks, appears to be of limited utility because

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beyond an intensity of 2 Suns, an active thermal control system required[1] to remove and radiate out the waste heat. This implies that as intensity is increased to high levels, the active thermal control system more than nullifies any mass advantage gained by reducing converter area. On the other hand, Brayton cycle turbomachines used in aerospace propulsion offer specific power values that rise with the level of power. At the scale required for Space Solar Power, specific power above 10 kW/kg for conversion to mechanical power is achievable. Figure 1 shows data on modern jet engines. An approximately linear upward trend is clear. For power levels over 50 MW, the specific power reaches 6 kW/kg.

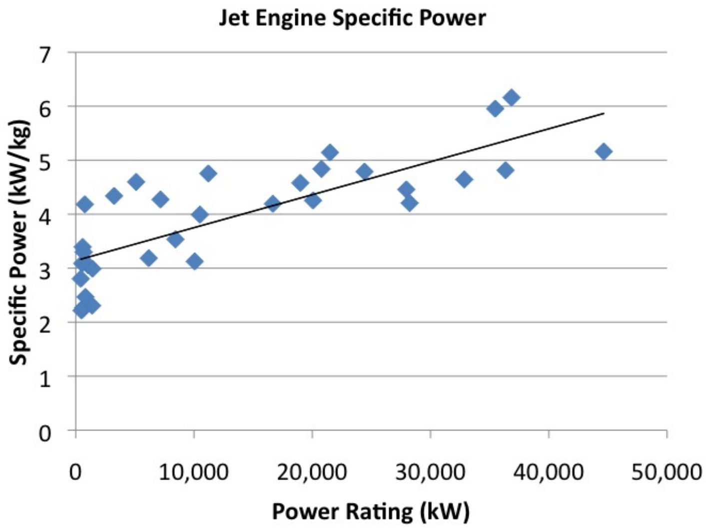

Figure 1. Specific power of commercial jet engines as a function of power level. Data for recent GE and Pratt and Whitney engines.

We have been exploring the alternative of using conversion to mechanical power using a heat engine, followed by conversion to electric power using a utility-scale generator. Helium Brayton cycles are already used in the nuclear power industry, with the intercooled helium Brayton cycle of the DOE (ORNL) liquid fluoride nuclear power plant cycle.[2] Here we adapt such cycles with the heat coming from solar radiation. Initial cycle analyses show that station thermodynamic states of such a helium gas turbine converter, are well within the range demonstrated by the Space Shuttle Main Engine. Limiting temperature for space engines is already over 3000K. For these reasons, the Technology Readiness Level of this concept may be surprisingly high. With the mass additions needed for radiating waste heat in Space, and a superconducting generator cooled by cryogenic helium, a helium Brayton cycle based 1 GWe SSP satellite could still achieve specific power above 1.6 kW/kg with conservative technology assumptions.

The present paper picks up from our IEEE paper on the Intensified Conversion Architecture (InCA) approach to the 1-GWe SSP satellite.[3] and refines the system design of the satellite, while delving deeper into the analysis of the Brayton cycle converter. Uncertainties are in developing the heat exchanger to achieve turbine inlet temperatures of up to 3,650 K, and in the design of the active thermal control system to remove the waste heat. The issue of optimal power level of individual converters also arises, and involves a tradeoff between assembly, transportation and efficiency scaling issues. Thus the work in progress towards this paper consists of the following:

1. Examine the specific power scaling characteristics of Brayton cycle turbomachines in more detail to determine the relevant scaling law for the space solar power application.

2. Examine the details of the heat transfer system to achieve the required station parameters of the Brayton cycle converter. Carbon-carbon radiators have been proposed for low-mass space use.

3. Devise a low-mass active thermal control system for the Brayton cycle converter

4. Explore the optimal frequency of electric power to generate with the Brayton machine (there is no reason to make this 60 or 50 Hz since it is intended for immediate conversion to millimeter wave power.

5. Refine the layout of the 1 GWe SSP satellite to decide the level of modularity. The present nominal choice is to use an octagonal layout with 8 identical turbomachines, matched in pairs to eliminate net torque or undesirable gyroscopic effects.
6. Refine estimation of the characteristics of the superconducting generator and the cryogenic system needed to operate it.
7. Consider transportation and assembly issues. The role of reusable airbreathing orbital access vehicles becomes more important when one considers the high rate of launches needed to build SSP stations. Thus one issue is the optimal payload for such launchers.

III. Background

A Space Solar Power (SSP) system for Earth will eventually reach over 4,000 GWe of electric power delivered to the surface, to replace present fossil-burning primary power plants. Thus a basic element is likely to be a gigawatt-level converter satellite, of which several thousands must be placed in orbit. To make Space Solar Power (SSP) plants viable when scaled up to the level of terrestrial power plants, the cost must be reduced by one to two orders of magnitude from those of architectures considered in the past. Several difficulties are:

1. A large capture area is needed per unit electric power generated.
2. The waste heat after conversion must be radiated back into Space by a passive and/or active thermal control system.
3. Conversion efficiency is critical to the specific power, because it impacts the capture area and the heat rejection load.
4. Antenna size increases with orbit height and wavelength
5. There must be a reliable space launch system that operates with a high launch frequency and payload.

Our rule of thumb for viability of SSP, developed from architecture studies is the value of the parameter k, given as

$$k = 25000 P \eta s / c \tag{1}$$

where P is the selling price of space-generated power in \$/KWh, η is the efficiency of transmission to the ground, S (kWe/kg) is the specific power, defined as the power generated in orbit per unit mass mass needed in orbit to do so and C (\$/kg) is the launch cost to low earth orbit (LEO). Here LEO is taken as the energy level where the chemical propulsion launcher leaves the payload, to be taken further by a high-specific-impulse (typically ion) engine. The factor of 25000 simplifies results from detailed architecture analysis and is set so that k 1 is where the architecture is reasonably certain to be economically viable at a large scale. Even with mass-production launch cost to LEO down to \$2000/kg, and power price of \$0.2/kWh, end-to-end efficiency must approach 0.3 and the specific power must approach 2.0kWe/kg for k to approach 1. This is far above the maximum 0.3kWe/kg value projected with photovoltaic conversion. Several schemes count on launch cost falling below \$400/kg with mass operations of reusable launchers.

By coming down from the 36,000 km height of Geostationary Earth Orbit (GEO) to 2000 km polar and sun-synchronous dynamic orbits, and using the 220GHz atmospheric window instead of the 5.4 GHz usually considered, 50 to 100 meter antennae are sufficient. To achieve continuous beaming from low orbits to any given location on Earth, requires a constellation of satellites. This conceptual difficulty is easily removed by realizing that thousands of 1 GWe satellites will be present in a full-scale SSP system.

Large-area ultralight collector/reflectors in high orbits, called *Mirasols* reflect and focus sunlight on to the *Girasol* 1 GWe converter satellites stationed in lower orbits. This separates the large area, constant solar view requirement from the high mass of converters. The Girasol receivers are aligned constantly to the Mirasols. The Girasols carry the equipment to convert the energy and beam it as millimeter waves to terrestrial and space customers. The slow, repetitive sunlight beam pointing problem is seen later in this paper to be easily solvable as the constellation number rises above 20.

IV. Intense, Efficient Conversion Architecture (InCA)

A closed helium Brayton cycle turbomachine was used as the primary power converter. The sunlight received from the Mirasols, already intensified by focusing roughly 1.6 GW of sunlight on to a 300m diameter collector, is further intensified into the feed going into the heater of the machine. With a peak temperature exceeding 3500K, and the sink temperature of approximately 200K, the cycle thermal efficiency touches 80 percent.

Helium closed Brayton cycles have been used ,[5] and recently in the intercooled helium Brayton cycle of the DOE (ORNL) liquid fluoride nuclear power plant cycle.[2] Here the heat will come from intensified sunlight rather than the terrestrial nuclear reactor. Figure **??** shows that station thermodynamic states of such a helium gas turbine converter, are well within the range demonstrated by the SSME except for the heater and first stage turbine inlet. The heater is conceptualized as being built of Hafnium Carbide tubes, heated uniformly by intense sunlight. The first turbine rotor stage may need blade cooling. The operating environment is the zero-gravity, steady orbit, with no substantial accelerations or temperature non-uniformities expected. This fact allows use of high-temperature materials that would be rejected for use in aircraft engines or space launcher pump turbomachines.

IV.A. Cycle Analysis

Table 1 lists the parameter values from a one-dimensional station-by-station analysis of the Brayton cycle power converter. The compression ratio and the initial pressure and temperature are chosen, and the amount of heat added is specified. Component efficiencies are assumed from modern terrestrial jet engine technology.

Some considerations are listed below for the Girasol turbomachine design compared to other designs.

1. Rotation speed of a terrestrial utility gas turbine is limited by the need to match 60 cycles AC generation. In SSP, the power is to be converted to millimeter waves. Hence optimal shaft speed and hence the stage blade sizes are not limited by the matching criterion. Since the Girasol operates at steady state in the calm of orbit, the rotation speed of the turbomachine can reach levels that would not be contemplated for atmospheric turbomachines.

2. Compressor efficiency falls nonlinearly as pressure ratio increases, as is well known. The polytropic efficiency, defined as the efficiency for a differential pressure rise, defines the technology of the compression process. Terrestrial jet engine compressors surpassed 0.93 some years ago. However, helium compressors for power plants are still cited at under 0.92. One strong reason for this is that blade lengths are small, and hence tip losses are much higher. This in turn links to the limits on shaft speed posed by the need to match generator speed. With this constraint removed, we believe that the polytropic efficiency can exceed that of terrestrial air cycle jet engine compressors. A thorough comparison of centrifugal and axial compression for the SSP application, remains to be performed.

3. Unlike a nuclear reactor or combustion-based generator, the heating in SSP can be distributed over several generator modules by suitably directing the intensified sunlight. Distributed placement of several generators is preferred because it minimizes the flow path to the heat rejection radiators, cancels out dynamic effects of rotating machines on an orbiting spacecraft, and is much more convenient for transportation from Earth. Each generator will be large enough to benefit from the scaling of specific power with size, but otherwise be optimized on other considerations. Thus the choice between axial and centrifugal compressors has the additional flexibility of choosing the best size, rather than being constrained by frontal area as in the case of aircraft engines, or single heat source as in nuclear reactors.

These considerations enable the space-based helium Brayton converter to achieve substantially higher values of power per unit mass than terrestrial converters can hope to achieve. The table below presents the station thermodynamic properties of the closed helium cycle converter, along with assumed efficiencies.

IV.B. Girasol Configuration

The initial concept of the Girasol 1GWe converter satellite shown in Figure 2 uses a central 300m diameter inflatable dish reflector to collect and concentrate intensified sunlight into the heater. The heater is at the

Table 1. **Basic One-Dimensional Cycle Analysis**

Station	Parameter Values
Compressor inlet	Station 1
P01	20,000 Pascals
T01	190K
Compressor	station 1-2
Pressure ratio	150
Polytropic efficiency	0.932
Mass flow rate	180 kg/s
Compressor work	1.445 GW
Compressor efficiency	0.846
Start of heat addition	Station 2
P02	3,000,000 Pascals
T02	1642 K
Pre-chiller not used	2-3
P03	3,000,000 Pascals
T03	1642 K
Turbine Inlet	Station 4
Heater pressure loss	10 percent
P04	2,700,000 Pascals
T04	3650 K
Turbine efficiency	99 percent
Turbine exit	Station 4
P05	21,200 Pascals
T05	522K
Turbine work	2.886 GW
Heat removed	Station 6
P06	20,000 Pascals
T06	522 K
High temperature radiator	Station 7
P07	20,000 Pascals
T07	342 K
Heat Rejection work	29 MW
Net work	1.6 GW
Cycle efficiency	0.800

axis. Brayton cycle generators are arranged radially, so that the gas from each machine is routed using pipes through a common heater core around the axis. The turbomachines are shown split into the compressor and turbine sections, instead of being driven on a common shaft. This is partly for convenience in designing the heater and partly because replacing the shaft with an independent electric motor drive for each compressor may make more sense from a mass point of view (remains to be investigated). Each return flow path is enclosed in a radiator, which is nominally shielded from the high-orbit side (and from all sunlight) by the collector above, and from Earth radiation by the transmitting antennae themselves. As on the waveguide satellites, the transmitting millimeter wave antennae are conceptualized as phase arrays placed far enough away from the center of mass to avoid interference, fed by waveguides from millimeter wave amplifiers. The millimeter wave amplifiers are placed along with the superconductor unit, below the turbomachine flow paths. Station-keeping thrusters (not shown) are assumed to be placed on the waveguide arms holding the antennae, to achieve large moment arms. Unlike the waveguide satellites of Phase 1, intersatellite beaming for a power exchange between terrestrial stations is not likely to be a significant requirement for the Girasol. Hence the antennae will be primarily sized to deliver power to ground stations. The waveguide satellites have to carry 4 antennae, each sized to handle 60 MW. Here the Girasol would require only 16 such antennae, sized to handle 62.5 MW each, so the mass requirement is at worst only 4 times that of the antennae on the waveguide satellites. Assembly considerations are discussed later in the paper.

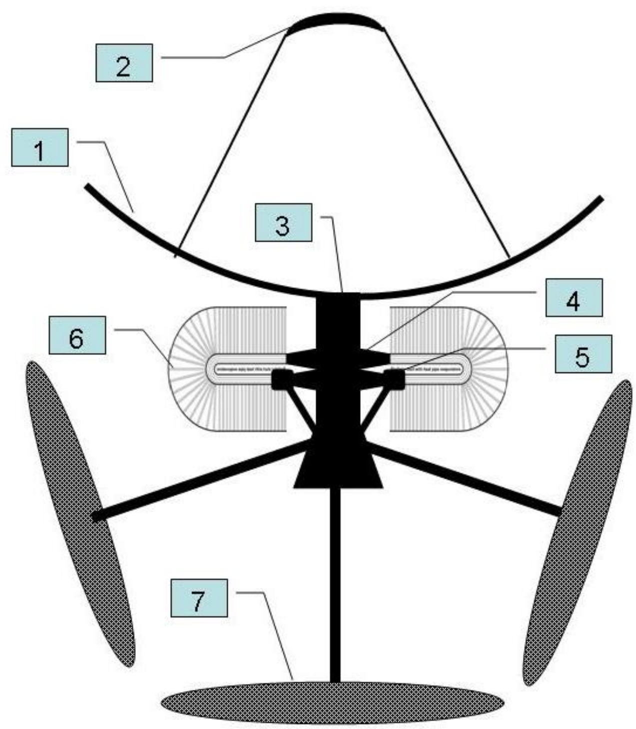

Figure 2. Conceptual sketch of the Girasol satellite. Not to scale. Numbers denote (1) 300m collector receiving intensified sunlight from Mirasol collector satellite (2) Intensified feed (3) Heater (4) Compressor (5) Turbine and Generator (6) Radiator (7) Phase Array Antenna

The 1-Sun collection is done in high orbit using the Mirasol and the intensified conversion using the Girasol at a 2000 km orbit. The 34,000 to 40,000 km transmission between these orbits is conducted using optical frequencies (i.e., raw sunlight) rather than RF. The lower limit on size is the intensity, rather than the diffraction-limited spot size. An equivalent mass per unit area of 0.2 kg per square meter for this collector was used, which is quite conservative and can be reduced in detail design. The mass of the Brayton cycle converter was estimated from turbomachines proposed for a Two Stage to Orbit vehicle,[6] averaging results obtained by scaling based on frontal area, and then on mass flow rate and providing a 25 percent margin. Secondary power systems routinely used in terrestrial power plants to increase thermal efficiency, may become possible to include in later states of SSP, when there is profit generation and infrastructure to deliver more mass. The ATCS design was allotted a specific mass of 400 kg/MW, making the ATCS a strong driver of the overall mass. The conversion from mechanical to electric power now occurs with over 99 percent efficiency mpoweruk-2011energy. Unlike terrestrial utility generators where current thinking finds it hard to justify the energy spent and the cost-effectives of the superconductor system,[7] here reducing mass of the windings dictates use of high-temperature superconductors. Barnes[8] describes portable military power packs with compact, lightweight superconducting generators. They cite a value for mass per unit power of 0.05kg/kW with all-cyrogenic generator. A margin of 20,000 kg was allotted to account for the cryogenic system, plumbing and associated peripherals. Since the AC power frequency need not be low and the ultimate objective is millimeter wave beamed power, the generator speed may be substantially higher than those of terrestrial utility generators.

IV.C. Millimeter wave generator, waveguides and antennae

Unlike most millimeter wave generation schemes for use with nuclear fusion research, radar and astronomy applications, the interest here is entirely in one narrow frequency band (a single line), and so resonant components can be used. Power amplifier efficiencies for the 220 GHz regime are well above 90 percent. Using technology from 1997, the mass needed per unit power conversion to millimeter waves (32 GHz) was given as 0.537 kg per square root of watts. The power amplifier mass is thus estimated to be under 17,000 kg. Corrugated waveguides are already available for the millimeter wave regime.[9–11] General Atomics Corporation[12] presents 63.5mm diameter aluminum waveguides that offer losses under 0.001 dB per 10 meters at 220 GHz. These can take up to 100 MW of power each in vacuum. Thus the Girasol will require 10 to 12 parallel channels of such waveguides to accomodate 1.2 GW of transmitted power. The millimeter wave transmission system in the final satellite design will be a scaled-up version of that used on our Waveguide satellites, which transact 60 MW of beamed 220 GHz power. In fact, techical risk may be minimized by using several units, each a derivative of the 60MW system, which will be already proven on the Phase 1 Space Power Grid system before the Girasol has to be built. The size is limited by beam spreading, not by intensity, and hence the antenna mass is not expected to be significantly higher with this system. However, for this conceptual stage, we used a liberal allotment of 20,000 kg for the antenna system.

The obvious technology challenges are in component design for high peak temperature, conversion to millimeter waves, long-term reliability, and assembly in orbit. Interesting solutions exist. For instance, Tantalum Hafnium Carbide Ta4HfC5 has a melting point over 4680K. A detailed design will help to identify the components that require advanced materials. The rest of the turbomachine stages, for instance the low speed compressor and turbine stages, may be transferrable directly from terrestrial jet engine technology, opening up some other interesting possibilities listed in the discussion section below.

In addition, the architecture requires the Mirasol large-area collector craft in a high orbit. We have not revisited the design of this craft; however we note that the improved conversion efficiency of the Girasol over previous PV-based architecture, means a substantial reduction in collector area needed. The mass estimate[3] for the Mirasol was 53,000 kg. This gives a specific power value of 1.61 kWe delivered on Earth per kg placed in orbit.

The mass budget is given in Table 2

V. Work Underway for Final Paper

V.A. Main Heater

The main heater section is being detailed. The helium leaving the compressor is fed through a bank of tubes that transition in the heater to tubes of Hafnium Carbide. The highly intensified sunlight comes in along the axis of the Girasol,, and is absorbed by the tubes in succession. The mass of the heater section is thus approximated by the mass of the tubes and the reflector duct surrounding the tubes, through which the sunlight streams in.

Table 2. Mass budget for the Girasol 1 GWe Space Solar Power Satellite

Element	Mass, kg	Percent
Collector	3,534	0.92
Cooling System	168,000	44.0
Brayton Cycle	20,000	3.91
AC generator	50,000	9.79
Cryogenics	20,000	3.91
220GHz Amp	17,000	3.00
Antennae	20,000	3.53
Propulsion	170,300	30.00
Misc.	30,930	5.45
Structure	56,700	10.00
Total Girasol	567,000	100
Total Mirasol	53,000	
Total Mass	620,000	

V.B. First stages of the turbine

The pressure and temperature distribution through the turbine is being calculated, to assess the need for blade cooling, and estimate the turbine mass.

V.C. Main radiator

The helium is directed through a tube bank whose walls circulate an active cooling fluid, assumed to be ammonia as used in the International Space Station. This fluid is driven through thin-walled metal ducts between leaves of Graphene which serve as the final radiator. A calculation is underway for the mass of the radiator, and the optimal temperature of the radiator in its different sections. The final portions of the radiator must bring the helium temperature down to 200 K, requiring that the sink temperature be the 4K of deep Space, well-shielded from any view of the Sun, Earth or Moon.

V.D. Optimal frequency of electric power to generate with the Brayton machine

Work underway at this writing, seeks to identify the optimal frequency of electric power that should be generated, bearing in mind that the power is to be converted to 220 GHz power. This process starts from two sides: The efficiency of conversion to 220 GHz on the one side, and the shaft rpm of the generator on the other.

V.E. Modified layout of the 1 GWe SSP satellite

The satellite layout is being reconsidered at this point, from points of view including those of transport, assembly and long-term maintenance. The improved layout will be presented in the final paper.

V.F. Launch and assembly considerations

Once the power level has been scaled up to the point where the specific power levels off in Figure 1, modularity may be considered. From jet engine technology, it appears that a level of 125MW is quite sufficient for the specific power to reach a plateau. Thus the 1 GWe Girasol may be conceptualized as being built of eight identical sectors of a circular cylinder or an octagon, as shown in Figure **??**.

The total mass of the Girasol is given above as 567,000 kg. An assembly sequence might start with pairs of turbomachine systems being joined at the axis, the superconductor and millimeter wave converters being attached below, then the transmitting antennae, and finally the collector in packed form, and the sunlight feed. The collector would then be deployed. Given that each sector has a mass of roughly 71,000 kg, it appears likely that 8 launches carrying 100,000 kg payload each, would suffice to transport the components for a Girasol, along with secondary payloads. The Girasol components are all well within the capacity of present-day launchers, and can be pre-built on Earth for relatively simple robotic assembly in orbit. The Mirasol has a very large deployable solar-sail type collector in addition to focusing, propulsion and control components, but its total mass is only 53,000 kg, amenable to being accomplished with a single launch. Summarizing, a total of 9 launches will be needed per Girasol-Mirasol pairing. Once a design is fairly standardized, expansion of the Space Solar Power System will involve 4000 to 8000 such pairs, meaning 36,000 to 72,000 launches. It is our view that this market justifies establishment of an airline-like infrastructure for large runway-based airbreathing Space access systems. The individual gas turbine components are small enough to be placed in launch vehicles with slender fuselages, that may use runway-operated aerodynamic flight segments, however the flow path will require assembly in Space. This is consistent with removal for maintenance as well. One may imagine that with the demand to assemble and maintain thousands of Girasols, there will be a market for an enterprise that develops and operates dedicated assember robot craft as well.

Recent work by students at our institution has started examining the issue of runway-based airbreathing Space access with such large payloads. The decision on whether to use 3 stages or 2 stages appears to be veering towards 3 stages, which makes it somewhat easier to set up optimal break points between the stages. Two different concepts have been advanced. Both appear to achieve feasible values for the size of the takeoff package. These results will be presented in the final paper.

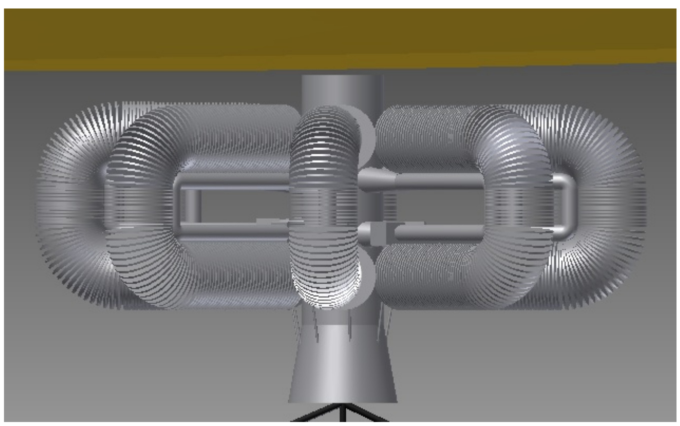

Figure 3. The Girasol may be built of eight identical gas turbine systems arranged in sectors around the central feed duct for intensified sunlight.

V.G. Outstanding Uncertainties

1. The primary objection cited so far against Brayton cycle primary conversion for SSP, is technical complexity. The prospect of high-speed rotating machines and sealed fluid cycles with extreme temperature variations, operating for 20 or 30 year design lifetimes in relatively low Earth orbit, certainly gives pause. But one must remember that turbopumps operating with even more extreme requirements, have been used with human-carrying space launchers for any decades.

2. Access by robotic maintenance vehicles is an assumed certainty with full-scale SSP systems, given their massive size and cost. Micrometeroid impacts and general failures of the rotating machines may be expected to occur, and hence visits by repair vehicles is essential here as they will be with any other SSP system. Access is considerably easier with LEO than with the GEO locations of other proposed PV-based systems. Rendezvous and part exchange have already been demonstrated under the DARPA

Orbital Express[?,?] initiative.

3. Intensifying solar power to the level needed to maintain nearly 4000K continuously for several years, is a major technical step. The level of difficulty in achieving this is not known. Long-term survival of materials under these conditions is an area of uncertainty.

4. Achievement of a closed gas cycle with the projected extremes of temperature is an uncertainty. Achieving the level of heat transfer effectiveness needed to reach 200K on the cold side and 3600K on the hot side, will pose challenges.

5. The operation of a superconducting generator system over long periods in Space is also an area of uncertainty, however, research on terrestrial utility power generators provides a good initial knowledge base in this area.

6. In addition, the uncertainties of millimeter wave conversion to 220 GHz and phased array antenna operation in that frequency regime with high efficiency for power levels of over 60 MW remain, as discussed with the design of the waveguide satellite.[4]

However, none of these appear to be show-stoppers, and in fact appear to be demonstrable in the near term.

VI. Conclusions To-date

Space-based solar power generation must reach several Terawatts to replace fossil-based power generation on Earth. Our prior work showed that with the use of dynamic beaming from low orbits, and advances in millimeter wave technology, the size and efficiency of power beaming could be brought into a regime where space solar power could be made economically viable. The Space Power Grid approach established a synergistic route where terrestrial renewable power plants exchange power through Space, establishing the technology and market before space-based power generation begins. Space-based generation is conducted using high-altitude ultralight, large-area collector-concentrator spacecraft that beam sunlight down to Gigawatt-sized Girasol spacecraft in 2000 kilometer orbits. The Girasol spacecraft is considered as a standard element of a space solar power system. Prior work showed that a specific power of 1 kW per kg for the orbiting mass of the SSP system would enable economic viability of SSP at moderate prices and reasonable long-term launch costs. In this paper, we show that at such levels, photovoltaic conversion of broadband sunlight is not the best option, since it does not offer an adequate increase in the specific power, if high Brayton cycle efficiencies and specific power values can be achieved. The option of using a Brayton cycle as the primary converter of solar power in Space is examined, for the case of a satellite designed to generate and beam 1 GW of electric power to Earth. Specific conclusions follow.

1. By separating the solar spectrum, narrow-band photovoltaic conversion can be used to extract roughly 14 percent of the total solar power as direct current.

2. Narrowband conversion of the pre-separated spectrum minimizes the active thermal control requirement.

3. A closed Brayton cycle can achieve over 80 percent conversion of the remaining solar spectrum to AC electrical power.

4. Given the high Brayton cycle efficiency and high specific mass of the mechanical to electrical converter, it is not cost-effective to use narrow-band photovoltaic conversion.

5. Superconducting generators will be needed to achieve the high power per unit mass needed for mechanical to electric power.

6. The Intensifed Efficient Conversion Architecture with a Brayton cycle converter and superconducting AC generator offers specific power of over 1.6 kW per kg in orbit, with conservative estimates. This compares to less than 0.2kW per kg for photovoltaic architectures.

7. With future improvements and refinements of mass estimates, the specific power could reach over 3.4 kW per kg, with revolutionary impact on the near-term viability of Space Solar Power as a global renewable energy supply option.
8. Shoud roadblocks be encountered in reducing generator and heat rejection system masses, spectral separation and narrowband conversion using photovoltaics should offer specific power of nearly 1 kW per kg in the near term.
9. Since the Brayton cycle converters have many similarities in components with terrestrial gas turbine propulsion systems, it may be useful in a future mass-production system, to design single-use single-stage-to-orbit launchers whose gas turbine propulsion elements may be dismantled in orbit and used for the low-pressure/ moderate temperature parts of the SSP Brayton cycle converters. The required meeting of design processes may be feasible.
10. The turbine inlet temperature of 3500K needed to achieve 80 percent cycle efficiency is achievable using tubes made of Hafnium Carbide
11. A highly efficient, low-mass radiator design can be accomplished using a structure based on Graphene sheets.

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