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Comparative Assessment of Space-Based Solar Power and Terrestrial Photovoltaic Systems

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Abstract: Sunlight in geostationary orbit arrives at approximately 1,361 W/m², unfiltered by atmosphere, uninterrupted by weather, and available for roughly 99% of the year. On Earth's surface, the same resource averages 150–300 W/m² at mid-latitudes after accounting for atmosphere, cloud, and the diurnal cycle. That gap, nearly an order of magnitude, is the central premise of Space-Based Solar Power (SBSP): collect energy where it is abundant, transmit it wirelessly to where it is needed. This paper quantifies that premise, challenges it economically, and asks whether it survives scrutiny. Using data from NASA, JAXA, ESA, IRENA, and NREL, we show that GEO SBSP concepts could deliver 6–10 times more annual energy per unit collector area than utility-scale terrestrial PV. The cost gap, however, is just as dramatic, NASA's 2024 baseline LCOE for SBSP sits at $0.61–$1.59/kWh, against a global weighted average of $0.043/kWh for terrestrial PV per IRENA's latest figures. The paper also examines two issues the existing literature tends to treat briefly: the specific debris and collision risks posed by deploying large structures in LEO and GEO, and the cost and power expectations for SBSP systems at different scales. A comparative assessment against conventional and modern generation technologies closes the paper, establishing what, precisely, makes SBSP unique and under what conditions it could become competitive.

Table of Contents

1. Introduction

Terrestrial solar PV has had a remarkable decade. Costs have fallen by 90% since 2010, utility-scale plants now routinely achieve LCOE below $0.05/kWh in high-insolation regions, and solar accounted for a record share of new global generation capacity additions in 2024 [6][4]. And yet, the physics of the atmosphere and the rotation of the Earth impose hard limits that no amount of cost reduction can remove. Fixed-tilt systems in most markets achieve capacity factors of 15–30%. Even with aggressive battery storage, integrating variable solar at penetrations above 40–50% of annual generation raises total system costs substantially [4][5]. The question this paper takes seriously is whether collecting solar power in orbit, above the atmosphere, immune to weather, orientable toward the sun at all times, can eventually address those limits. SBSP was first described in 1968 by Peter Glaser [7][36]. It has been periodically studied and periodically shelved, largely because launch costs made it absurd. Recent developments in reusable rocketry, autonomous in-space assembly, and high-efficiency power electronics have brought it back into credible engineering discussion. NASA published a comprehensive techno-economic assessment in January 2024 [1]. ESA's SOLARIS programme is funding design studies targeting a 2025 down-select [8]. China is planning a megawatt-scale demonstrator for 2035 [9]. This paper therefore treats SBSP not as speculation, but as a long-horizon engineering programme whose economics deserve rigorous comparison with what already works. The analysis covers seven areas: the solar resource available in orbit versus at the surface; atmospheric and weather effects on delivered energy; the full energy conversion chain in both systems; annual yield per unit collector area; economic feasibility from current costs through optimistic 2040 projections; the specific challenges of deploying and maintaining large structures in LEO and GEO with respect to space debris and future launch traffic; and SBSP's positioning relative to conventional and modern power generation technologies.

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2. Review of Related Literature

Solar Resource and Availability

A. Solar Irradiance in Space and at the Surface

The extra-terrestrial solar constant near Earth's orbit is 1,361–1,367 W/m², measured consistently by NASA's TSIS instrument [10][4]. At the surface under clear-sky AM1.5 standard conditions, peak irradiance reaches approximately 1,000 W/m². That 30% reduction is straightforward to account for. What makes terrestrial PV harder to model is everything that happens over time: daily and seasonal solar angle variation, cloud cover, aerosols, and temperature effects together reduce the annual average incident irradiance at a fixed-tilt, mid-latitude array to roughly 150–300 W/m², depending heavily on site [2][4][5]. In GEO, an SBSP collector experiences virtually constant AM0 irradiance throughout the year, with the only interruption being brief eclipse periods near the equinoxes, during which the satellite passes through Earth's shadow for a maximum of approximately 72 minutes per day over a period of roughly 45 days per year [1][11][3]. For the remaining 300-odd days, illumination is continuous.

Table 1 places these irradiance characteristics alongside those of LEO SBSP, a configuration studied as a potential precursor to GEO deployment, where lower launch costs trade against more complex operational requirements [1][10][3].

Table 1. Solar resource characteristics for terrestrial PV and SBSP concepts.

Parameter	Earth Surface (AM1.5)	LEO SBSP	GEO SBSP
Peak irradiance (W/m²)	~1,000	1,361–1,367	1,361–1,367
Average available irradiance (W/m²·year)	150–300	~1,000–1,200	~1,200–1,300
Fraction of time illuminated	10–30%	~90–95%	~95–99%

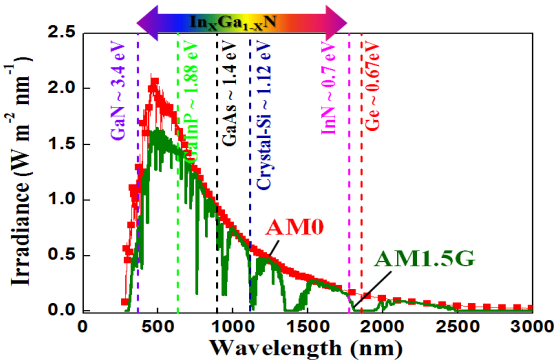

Figure 1. Solar spectral irradiance above Earth's atmosphere (AM 0) and at the surface (AM 1.5), illustrating atmospheric absorption and scattering. Based on standard reference data consistent with NASA TSIS measurements [Source: NASA TSIS / ASTM G173-03 standard data]

B. Atmospheric and Weather Effects

The atmosphere transmits roughly 70% of incoming solar energy to the surface on a global-mean, top-of-atmosphere basis [5]. That figure conceals substantial variability. During heavy overcast or storm conditions, instantaneous PV output can fall by 20–90% [7][5]. Over a year at a real site, cloud cover, aerosol loading, and seasonal angle changes compound into capacity factor penalties that no panel efficiency improvement can overcome. SBSP collectors in orbit are simply not exposed to any of this. Their output variation comes from orbital mechanics, eclipse geometry, pointing accuracy, and hardware degradation, not from weather. This is the single most significant physical advantage of the concept: dispatchable solar power whose availability does not depend on the atmosphere.

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C. Capacity Factor

For utility-scale terrestrial PV, capacity factors typically range from 15% to 30%, depending on latitude, tracking system, and local climate [2][4][5]. A single-axis tracking system in a good desert location might reach 28%; a fixed-tilt installation in northern Europe might deliver 12%. GEO SBSP, by contrast, can sustain capacity factors around 95% once eclipse and maintenance periods are subtracted [1][11][3]. That three-to-one ratio in capacity factor compounds with the orbital irradiance advantage to produce the 6–10× annual energy yield per unit area shown in Section IV.

3. Energy Conversion Chains

A. Terrestrial PV Systems

A utility-scale terrestrial PV plant converts sunlight through four principal stages: the module (photovoltaic conversion), DC collection wiring, the inverter (DC to AC), and grid interconnection. Each stage introduces losses that compound. Modern module efficiencies have improved substantially over the past decade. Standard N-type monocrystalline TOPCon and IBC cells from leading manufacturers now achieve 21–24.8% at standard test conditions [2]. In October 2024, LONGi certified a 25.4% conversion efficiency for its HPBC 2.0 module, a world record for crystalline silicon, verified by the Fraunhofer Institute for Solar Energy Systems [12]. Oxford PV has demonstrated 26.8% efficiency on a commercial-sized perovskite-silicon tandem panel, though mass production of this technology is not expected before 2027–2028 [13]. These figures represent a significant jump from the 19–22% range cited in studies just a few years old, and any comparison that uses the older numbers understates the competitive baseline that SBSP must beat. [14][15][16]

Table 2 summarises the efficiency components for a modern utility-scale PV plant. Note that nameplate module efficiency and system yield are different things; the latter is typically 70–85% of the former once field conditions, soiling, wiring losses, and inverter derates are applied [2][4].

Table 2. Efficiency components of a modern utility-scale PV plant (updated 2024–2025).

Stage	Typical Value	Notes
Module conversion efficiency (DC)	21–24.8% (N-type TOPCon/IBC mono-Si)	LONGi HPBC 2.0 certified world record: 25.4% (Fraunhofer ISE, Oct. 2024) [34]; Oxford PV perovskite-tandem: 26.8% on commercial-sized panels, mass availability expected 2027–2028 [35]
Temperature and operating derates	0.75–0.90 factor	Hot climates reduce output; soiling adds 1–5% additional derate in dusty regions
DC/AC inverter efficiency	96–98%	Modern string and central inverters at utility scale
Wiring, mismatch, BOS losses	2–5% losses	Cables, combiner boxes, single-axis tracker parasitic load

B. SBSP System Stages

SBSP adds three stages that terrestrial PV does not have: converting the collected DC power to a microwave or laser beam, propagating that beam through space and atmosphere, and converting it back to DC at a ground rectenna. Each stage has its own efficiency, and they multiply. Table 3 shows representative values drawn from concept studies and laboratory demonstrations [1][11][3][8]. The end-to-end DC-to-AC efficiency for a GEO SBSP system, from solar conversion in orbit to AC power at the grid, comes out at roughly 13–20%, depending on design choices. That is comparable to a utility-scale terrestrial PV plant, which might achieve 15–18% from sunlight to AC output. The difference is that SBSP runs this efficiency against ~10,500 kWh/m²/year of input, while terrestrial PV works with ~1,700 kWh/m²/year. The numbers diverge because of the resource, not the hardware. [17][18].

Table 3. Representative power-conversion efficiencies for a GEO SBSP system.

Stage	Representative Efficiency	Notes
Space PV array	30–35%	Multi-junction III–V cells; radiation hardening reduces in-orbit efficiency over time
DC-to-RF conversion	70–85%	Klystrons, magnetrons, or solid-state power amplifiers
Beam transmission (2.45 GHz, clear sky)	90–99%	Rain/cloud attenuation minor at S-band; sidelobe control is the primary design constraint
Rectenna RF-to-DC	80–90%	Laboratory rectennas exceed 90% at a few GHz; field arrays slightly lower
DC/AC grid interface	~95%	Comparable to terrestrial power electronics

C. Frequency Selection and Atmospheric Attenuation

Most SBSP designs target 2.45 GHz (S-band) for power transmission. At this frequency, clear-sky atmospheric attenuation from GEO to ground is under 2%, and even moderate rain events add only a few percent [3][5]. Higher frequencies, such as 5.8 GHz, offer smaller transmitting apertures for a given beam intensity, but rain and cloud water absorption becomes more significant, making 5.8 GHz a less reliable choice for a 24/7 power system [1][11][3]. S-band also benefits from existing regulatory allocations used by radars and communications, which simplifies spectrum coordination somewhat, though a high-power transmission system would still require specific ITU approvals and strict sidelobe limits to protect adjacent satellite services.

Beyond atmospheric attenuation, key technical challenges for Wireless Power Transmission (WPT) include maintaining precise beam steering accuracy over thousands of kilometers to ensure power delivery to the target rectenna while minimizing spillover. Rectenna design limitations, particularly in achieving high efficiency across a broad power density range and managing thermal loads, also present significant engineering hurdles. Furthermore, while current research suggests minimal biological impact from microwave power beams at proposed intensities, ongoing safety considerations and public perception remain crucial aspects for any deployment programme [19][20].

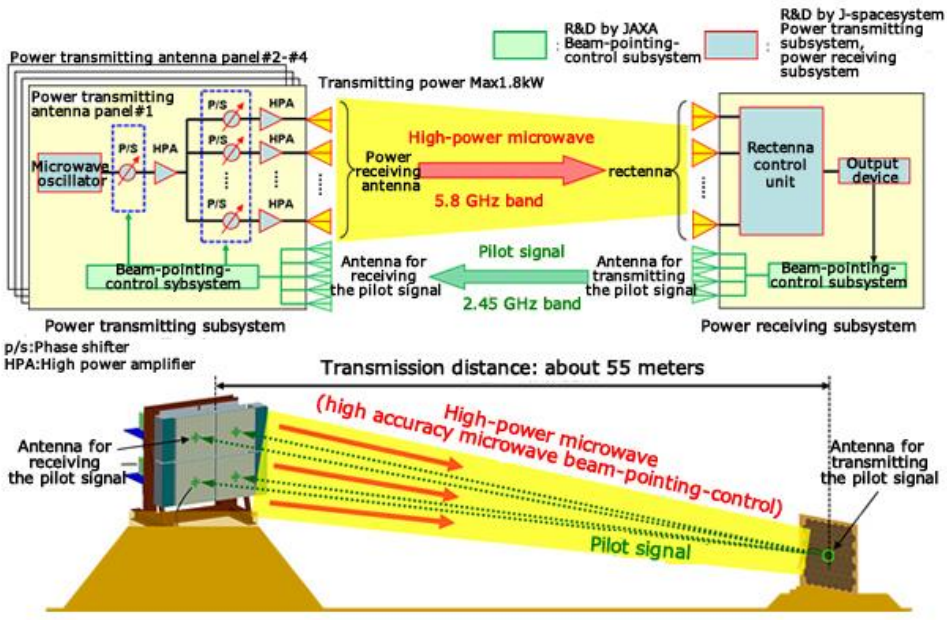

Figure 2. Microwave wireless power transmission architecture for SBSP, showing the phased-array transmitter and ground rectenna configuration (adapted from JAXA SSPS research, 2023). [19][20][21]

[NOTE TO PUBLISHER: Figure 2, Microwave WPT architecture diagram (phased-array transmitter and rectenna). Adapted from JAXA SSPS research. Figure to be provided as separate file.]

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4. Performance Metrics

A. Annual Energy Yield per Unit Collector Area

Table 4 brings together the irradiance data from Section II, the capacity factors from Section II.C, and the system efficiencies from Section III to estimate annual delivered energy per square metre of collector. The comparison is the right one to make when asking about the fundamental resource advantage: how much useful electricity does each square metre of collector produce per year, accounting for all losses in the chain from sunlight to AC grid?

Table 4. Indicative annual energy yield per unit collector area.

Parameter	Terrestrial PV (utility-scale)	GEO SBSP Concept
Average solar input at collector (kWh/m²·year)	~1,500–2,200	~10,000–11,000
Net system efficiency (collector to AC)	~12–18%	~13–20%
Annual delivered energy (kWh/m²·year)	~250–400	~2,000–4,000
Output multiplier vs. terrestrial PV	1×	~6–10×

The 6–10× multiplier for GEO SBSP over terrestrial PV is consistent across recent independent analyses [1][3]. The range within that estimate reflects site quality for terrestrial PV, a desert installation in the Arabian Peninsula performs much better than one in northern Europe, and design assumptions for the space system. What the table does not capture is the economic cost of deploying each square metre in its respective location. That cost is addressed in Section V.

B. Application to Lunar Energy Supply

Lunar surface power is an area where SBSP's advantages are even more pronounced. At equatorial and mid-latitudes on the Moon, the night lasts approximately 14 Earth days, too long for any practical battery system and problematic for any local PV installation that must also survive the accompanying temperature extremes. Dust accumulation on panels is a further complication that has no easy maintenance solution on a crewed lunar base. SBSP in cislunar orbit or on highly illuminated ridges near the lunar poles can beam power to shadowed craters and base sites across vacuum, with no atmospheric loss and no weather, providing near-continuous supply that surface generation cannot match [3][5]. Laser-based optical wireless power transfer is also under investigation for shorter-range lunar applications, trading higher total conversion losses against physically smaller receiving apertures [3][5].

5. Economic Feasibility

A. Current and Projected Cost Estimates

NASA's January 2024 Office of Technology, Policy, and Strategy (OTPS) report is the most methodologically rigorous recent economic assessment of SBSP for civilian power grid application [1]. It analysed two reference designs, an Innovative Heliostat Swarm (RD1) and a Mature Planar Array (RD2), and calculated LCOE under conservative assumptions using 2050 projected technology and Starship-class launch vehicles. The results were stark: $0.61/kWh for RD1 and $1.59/kWh for RD2. Note that these figures already assume a major reduction in launch costs relative to today; using current launch pricing, the numbers would be considerably higher. [22][23]

On the terrestrial side, IRENA's 2024 report provides the most current global data [4]. The global weighted-average LCOE for utility-scale solar PV in 2024 was $0.043/kWh, a 90% reduction from $0.417/kWh in 2010 and a figure that is now 41% below the cheapest new fossil fuel-fired alternative globally. There is meaningful regional variation: China achieved $0.033/kWh, India $0.038/kWh, and the United States $0.070/kWh, the latter reflecting permitting delays, interconnection bottlenecks, and higher balance-of-system costs rather than any fundamental resource disadvantage. Best-in-class projects in high-insolation regions with competitive procurement have recorded LCOE below $0.020/kWh.

Table 5. Economic comparison of SBSP and utility-scale terrestrial PV (NASA 2024 and IRENA 2024 data).

Metric	SBSP (Current Concepts)	Terrestrial Utility-Scale PV
LCOE (USD/kWh)	~0.61–1.59 (NASA 2024 baseline, assuming 2050 Starship-class launch)	Global weighted avg. 0.043; range 0.033–0.070 by region (IRENA 2024) [10]
Dominant capital cost component	Launch and in-space assembly (~70% of lifecycle cost)	Modules and inverters (accounted for 60% of cost reductions since 2010)
Storage requirement	Low, near-continuous output eliminates need for day-night storage	High at penetrations above ~40%; adds $0.02–0.04/kWh to effective LCOE
Site constraints	ITU orbital slot allocation; rectenna footprint (~5 km² per GW)	Land, grid access, permitting, curtailment risk at high penetration

There is a more optimistic line of analysis worth noting. A Frazer-Nash/London Economics study commissioned by ESA places SBSP in the range of €88.5–€155.5/MWh (approximately $0.09–$0.17/kWh) in 2040 price terms, assuming substantial technology development [24]. A 2025 ScienceDirect study of a scalable GEO system generating 76–181 MW concluded the concept could reach economic viability within 10 years under middle-tier cost assumptions, contingent on advancing manufacturing processes and launch capabilities [25]. These projections are more favourable but also more contingent. The NASA figures are conservative precisely because they are not designed to sell the concept, they are designed to inform a government decision. Both ends of the range deserve to be in the analysis.

Achieving these optimistic projections will require not only significant reductions in launch costs, but also breakthroughs in several key areas: advanced in-space manufacturing and autonomous assembly techniques capable of constructing multi-kilometer structures; enhanced space PV efficiency and radiation hardening for long operational lifetimes; and the development of ultra-lightweight structural materials. Furthermore, supportive policy changes, including international agreements on spectrum allocation for power beaming and robust regulatory frameworks for space traffic management and debris mitigation, will be essential before deployment at gigawatt scale is feasible.

B. SBSP Setup Cost by System Scale

A common omission in SBSP literature is a concrete breakdown of what it would actually cost to set up a system at different scales, and what power one could realistically expect from it. Table 7 attempts to fill that gap using current launch pricing, published mass estimates, and standard conversion efficiency assumptions [1][3][9][8].

Table 7. SBSP setup cost and expected delivered power by system scale (order-of-magnitude estimates based on current and projected launch economics).

System Scale	Approx. On-Orbit Mass	Est. Launch Cost (GEO)	Expected Delivered Power
Technology demonstrator (1–10 MW)	~200–2,000 t	$2–20B at current pricing ($10k–$15k/kg to GEO)	~0.6–6 MW at ground rectenna (after conversion losses)
Small commercial (100 MW)	~20,000 t	~$200B current; ~$10–20B under Starship-era pricing (~$100/kg LEO with ion transfer to GEO)	~60–80 MW net to grid
Utility-scale (1 GW)	~80,000 t	~$800B–$1.2T current; ~$80–200B optimistic 2040	~600–700 MW net; ground rectenna (~5 km diameter) adds ~$1B
Utility-scale (4 GW, 1980 NASA reference)	~80,000 t (4×)	~$3–5T current; illustrative only	~2.4 GW net; rectenna array ~20 km²

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The core bottleneck is clear from the table: at today's GEO launch costs of roughly $10,000–$15,000 per kilogram, even a 100 MW system costs on the order of $200 billion to get to orbit. The 1980 NASA reference design for a 4 GW station required approximately 80,000 tonnes of on-orbit hardware [9], an amount that, at $10,000/kg, implies $800 billion in launch costs before a single bolt is assembled in space. SpaceX's Starship targets approximately $100/kg to low Earth orbit; achieving that, combined with efficient ion transfer to GEO, would reduce the launch cost of a 1 GW system to roughly $80–200 billion. Still very large, but within the order of magnitude of major national infrastructure programmes. Ground rectenna infrastructure adds roughly $1 billion per 5 GW of capacity [9].

C. Path Toward Cost Competitiveness

Full lifecycle analyses indicate that simultaneous progress on launch cost, in-space assembly automation, space PV efficiency, and lightweight structure design could push SBSP LCOE toward the $0.040–$0.080/kWh range in aggressive 2040 scenarios [1][3][24]. That would make it broadly competitive with the current global average for terrestrial PV, while offering a capacity factor that no terrestrial renewable can match. The catch is the phrase 'simultaneous progress': if any one of those technical pillars lags, the economics degrade rapidly. The NASA analysis treated these optimistic scenarios as plausible but not certain, and that assessment seems right.

6. Orbital Deployment and Maintenance: Space Debris and Launch Traffic

A. The Debris Environment in LEO

Low Earth orbit, roughly 160 to 2,000 km altitude, is the most congested region of near-Earth space, and the one most relevant to SBSP assembly operations. LEO is where launch vehicles release payloads, where constellation satellites operate, and where the density of debris fragments is highest. The European Space Agency's 2025 Space Environment Report estimated approximately 40,000 tracked objects currently in Earth orbit, along with hundreds of millions of smaller fragments that cannot be routinely tracked but remain capable of causing mission-ending damage, along with hundreds of millions of smaller fragments that no ground-based radar can track but that are energetic enough to disable a satellite on impact.

The risk that compounds over time is the Kessler cascade, first described by NASA scientist Donald Kessler in 1978: beyond a threshold debris density, collisions generate more debris faster than orbital decay removes it, creating a self-sustaining degradation of the orbital environment [26][27]. Current analyses by the Inter-Agency Space Debris Coordination Committee (IADC) project that without active removal measures, the number of trackable debris fragments larger than 10 cm in LEO could exceed 50,000 by 2050, with LEO collision rates increasing sixfold relative to today [28]. An SBSP programme that assembles large structures in LEO over a multi-decade construction period would operate throughout this escalating risk environment. The scale of the structures, potentially square kilometres of solar panel area, makes collision avoidance harder, not easier: large targets are harder to manoeuvre and present more surface area to chance debris impacts.

B. The Debris Environment in GEO

GEO presents a different risk profile. Relative collision velocities between GEO objects are lower, impact velocity peaks at approximately 1.5 km/s, compared with 7–14 km/s typical of LEO collisions [26]. At those speeds, a fragment collision is unlikely to completely destroy a large platform in a single event, but it will certainly damage it and may render it inoperable. More practically, GEO is a finite and internationally regulated resource. The geostationary belt is a finite and internationally regulated orbital resource. The belt has a circumference of approximately 265,000 km, and orbital positions are coordinated through the International Telecommunication Union (ITU). While only several hundred GEO satellites are operational at any given time, the total number of allocated and occupied orbital positions is substantially larger, making long-term congestion and coordination an increasingly important issue [41]. Derelict satellites that run out of station-keeping propellant drift in longitude and inclination at approximately 0.8° per year, with close approaches, within 50 metres, estimated at roughly one per year for any given GEO asset [26].

An SBSP collector with an aperture potentially several kilometres across occupies a position in GEO that simply cannot be protected by Whipple shielding. Solar panels, which must face the sun, cannot be armoured. Even small impacts cause cumulative degradation, the plasma discharge from a micrometeorite impact is an electrical hazard to the panel circuitry independent of the physical damage [26]. A realistic SBSP design must budget for a degradation rate that accounts not just for cosmic ray damage to cells, but for the accumulated physical toll of operating in the orbital debris environment for 20–30 years.

C. Mitigation Strategies

The SBSP engineering and policy communities have identified several mitigation approaches, though none has been validated at the scale required for a multi-gigawatt system [29][30][31]. Active collision avoidance through onboard propulsion is considered essential for any large space asset; the challenge is that a multi-thousand-tonne structure distributed over square kilometres cannot manoeuvre as a rigid body, which points toward modular architectures where individual segments can adjust independently [27]. Active Debris Removal (ADR), demonstrated at small scale by ESA's ClearSpace-1 mission and commercial operators, provides a longer-term remediation pathway, but current methods have only been validated against single, cooperative targets [28]. [32][33][34].

Research is progressing on technologies for capturing or deorbiting larger, non-cooperative debris, including robotic arms, nets, and harpoons, though these remain at low Technology Readiness Levels (TRL) for operational deployment at the scale required by a multi-gigawatt SBSP programme. The economic structure of ADR constitutes a public-good problem: operators who remove debris benefit all satellite operators but cannot recover costs from those who benefit without paying, meaning regulatory intervention is the only route to a functional market [33].

Regulatory frameworks are also evolving. The ITU already requires proof that a satellite can vacate its orbital slot at end of life. The FCC's 2023 consent decree against DISH Operating LLC for failing to properly deorbit EchoStar-7, the first such enforcement action, established that debris mitigation obligations are enforceable, a precedent directly relevant to any future SBSP operator [35]. Under the Outer Space Treaty, States bear international responsibility for national space activities and must take measures to avoid harmful contamination of the space environment [30]. How that obligation applies to a multi-kilometre solar platform with a 30-year operational life is a question that international space law has not yet been asked to answer.

D. Coexistence with Future Launch Traffic

An SBSP system commissioned today would still be operating in the 2050s and 2060s, a period during which the number of active satellites in Earth orbit is projected to grow by one to two orders of magnitude relative to today. SpaceX filed with the FCC in January 2026 for authority to deploy up to one million satellites described as orbital data centres [35]. Coexisting with that density of launch and operational traffic is not a solved problem.

The most practical technical approach for a GEO SBSP system is real-time space situational awareness integrated with automated avoidance capabilities, not manoeuvring the entire platform, but shutting down vulnerable systems and commanding individual modules to safe orientations when a tracked object comes within a defined exclusion zone. For LEO assembly operations, routing launch trajectories through rather than lingering in the most debris-dense altitude bands reduces exposure time. At the policy level, extending ITU-style orbital coordination frameworks to include mandatory proximity management for very large structures would require new multilateral agreements, difficult to negotiate but not without precedent [35][30].

Beyond space debris, a comprehensive assessment of SBSP's environmental impact must also address the energy intensity and resource consumption associated with manufacturing the vast number of components required for orbital deployment, and the environmental footprint of launch operations. Although the operational phase of SBSP produces zero direct emissions, full lifecycle analysis, from raw material extraction through end-of-life disposal, warrants detailed study before deployment decisions are made. Additionally, while current scientific consensus indicates minimal risk, continued monitoring and research into potential long-term effects of microwave power beams on atmospheric phenomena, avian populations, and biological systems at ground receiving sites are prudent for both public acceptance and regulatory certainty.

E. Broader Environmental Considerations

7. Scalability and Long-Term Context

GEO SBSP is, in the long view, a relatively modest step in terms of the scale of energy collection conceivable in space. The progression from a few gigawatts in GEO to a distributed swarm of collectors at various heliocentric distances, the Dyson swarm concept, follows naturally from the same technical capabilities: modular construction, autonomous assembly, and wireless power beaming [36][3][5]. Progress on kilometre-scale structures, in-space robotic manufacturing, and cislunar logistics would each be directly applicable. This does not mean the Dyson swarm is an engineering roadmap, it remains speculative. But it is useful context for understanding why space agencies treat SBSP not just as an energy project but as infrastructure development with a very long return horizon.

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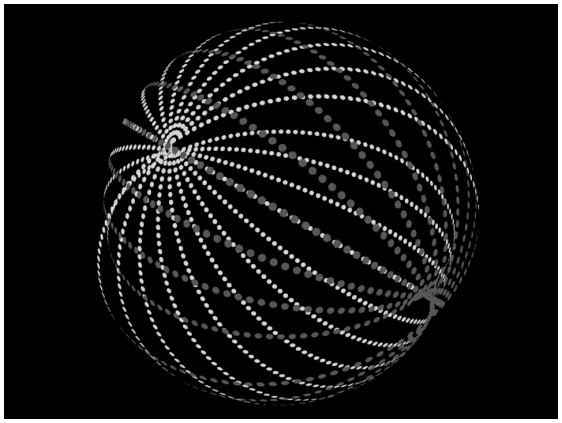

Figure 3. Conceptual illustration of a Dyson swarm of independent orbiting collectors surrounding a star to maximise energy capture (adapted from Wikimedia Commons; Credit: Vedexent, CC-BY-SA 3.0).

8. SBSP's Unique Characteristics and Comparison with Conventional Systems

A. What Makes SBSP Different

Every major power generation technology has at least one of three problems: it emits CO_2 or produces radioactive waste; its output is intermittent or geography-dependent; or it requires large amounts of land that competes with other uses. SBSP, in principle, avoids all three simultaneously. That combination is genuinely unusual. The capacity factor comparison is the most important single number. At ~95% for GEO SBSP versus 15–30% for terrestrial PV, SBSP functions as a baseload generator, not a variable resource that must be firmed up with storage or backup generation. A 2025 European energy system study found that a near-baseload SBSP heliostat design could reduce total European system costs by 7–15%, displace up to 80% of wind and solar variability, and cut required battery storage by more than 70% [37]. No other zero-emission technology on the comparison table can claim that system-level value simultaneously. The delivery flexibility of SBSP is also without parallel. By steering the transmitting phased array, a GEO system can direct power to any ground station within its orbital footprint, without building transmission lines. Remote regions, island nations, military installations, and disaster-relief operations that currently have no access to grid power are potential markets that conventional generation, which requires physical connection to a grid, cannot reach at the same scale. The ground footprint of the rectenna is modest: roughly 5 km^2 per GW, dual-usable with agriculture [9].

A less-discussed advantage is manufacturing independence. Terrestrial solar depends on a supply chain for silicon wafers, inverters, and mounting hardware that is geographically concentrated and subject to trade disruption. SBSP's supply chain challenge is different, launch vehicle availability and in-space assembly robotics, but it diversifies the risk profile in ways that may matter for energy security applications.

B. Comparative Feasibility

Table 6 positions SBSP against the main alternative power generation technologies on LCOE, capacity factor, and key characteristics. The pattern that emerges is consistent: SBSP's technical profile, near-baseload, zero-emission, site-independent, most closely resembles nuclear fission in terms of what it delivers to the grid, but at dramatically higher current cost and with substantially less mature technology.

Table 6. Comparative assessment of SBSP and major power generation technologies (data as of 2024–2025).

Technology	LCOE USD/kWh (2024)	Capacity Factor	Key Characteristics vs. SBSP
SBSP, GEO, current	0.61–1.59	~95%	Only firm, location-flexible, zero-emission baseload option; cost-prohibitive today
SBSP, GEO, optimistic 2040+	0.040–0.155 (ESA/Frazer-Nash)	~95%	Competitive if Starship-class launch costs achieved; requires autonomous assembly
Utility-scale solar PV	0.033–0.070 (avg. 0.043)	15–30%	Cheapest new generation globally; intermittent; land use; storage needed at scale
Onshore wind	0.029–0.034 (avg.)	25–50%	Lowest-cost renewable; site-dependent; transmission required; intermittent
Natural gas (CCGT)	0.065–0.090	50–80%	Dispatchable; CO_2 emissions; fuel price exposure; incompatible with net-zero
Nuclear fission (new build)	0.080–0.200	85–93%	Firm, low-carbon; radioactive waste; construction overruns; 15–20 yr lead time
Hydropower (large)	0.024–0.057	35–60%	Low-cost where available; geography-constrained; ecological impact; drought risk

The nuclear analogy is the most instructive one. Both technologies offer firm, low-carbon power at high capital cost with long lead times and significant technical risk. Nuclear has the advantage of being proven, over 400 GW of operational capacity worldwide, but carries long-term waste disposal obligations and proliferation risks that SBSP does not. If Starship-class launch economics materialise in the 2030s, the cost trajectories of the two technologies could converge within the same decade. At that point, the comparison shifts from 'SBSP versus cheap solar', a contest SBSP currently loses badly to 'SBSP versus next-generation nuclear.' That is a more competitive conversation.

IRENA's 2024 data confirm that solar PV is already 41% below the cheapest fossil fuel alternative globally, meaning cost competitiveness with terrestrial PV is an extremely high bar [4]. SBSP's credible near-term market is not displacing cheap solar in the Sahara. It is: high-value baseload in markets where land is scarce and storage costs are high; remote and off-grid power in regions outside the reach of conventional grid infrastructure; and eventually, if launch economics improve sufficiently, large-scale grid supply for densely populated or persistently cloudy regions where the firming cost of terrestrial solar exceeds the cost premium of SBSP.

9. Conclusion

The physics of SBSP are sound. Orbital irradiance is roughly 8–12 times what a mid-latitude terrestrial installation averages annually and converting that resource at 13–20% end-to-end efficiency still yields 6–10 times more electricity per square metre of collector than the best utility-scale PV plant on Earth. The capacity factor advantage, 95% versus 15–30%, is real and consequential: SBSP would function as a dispatchable baseload generator, not a variable resource. The economics, however, are currently disqualifying. NASA's 2024 baseline puts SBSP LCOE at $0.61–$1.59/kWh, 15 to 37 times the global weighted average for utility-scale PV. The capital required to deploy a gigawatt-scale GEO system under today's launch pricing is measured in trillions of dollars. These are not rounding errors; they are fundamental constraints that require structural change in the launch industry to overcome, not incremental improvement in panel efficiency. The debris and collision challenges are also real, and the literature has not always treated them with full seriousness. Operating a multi-kilometre structure in GEO over a 30-year lifespan, in an orbital environment that is projected to become significantly more congested, requires not just engineering solutions but regulatory frameworks that do not yet exist. The FCC's 2023 enforcement action against DISH signals that the regulatory direction is toward greater accountability, which is the right direction, but the scale of the accountability problem posed by an SBSP platform is qualitatively different from a failed communications satellite. What justifies continued investment in SBSP research, despite all of this, is the combination of properties it uniquely offers: near-continuous, location-flexible, land-free, zero-emission baseload power. No other technology in Table 6 delivers all four simultaneously. Whether that combination becomes economically viable depends primarily on what happens to launch costs in the 2030s. If fully reusable heavy-lift

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achieves the cost reductions its proponents project, the LCOE calculus changes decisively. If it does not, SBSP remains a long-horizon concept with valid physics and invalid economics. The sensible position, held by NASA, ESA, and JAXA alike, is to invest in the enabling technologies now, so that the option is available when the economics catch up.

Data Availability Statement

This paper is a review and comparative analysis; all data sources are cited in the references. No new primary datasets were generated.

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