Space-Based Solar Power as a Dispatchable Power Resource

Abstract

Falling launch costs and rising electricity demand have revived interest in space-based solar power (SBSP). Despite significant public and private investment, however, recent levelized cost of energy (LCOE) estimates indicate that - even under optimistic assumptions - SBSP is unlikely to be cost competitive with the lowest-cost terrestrial electricity generation, often below \$0.05/kWh. While this limits SBSP's near-term viability as baseload energy, credible pathways exist to achieve LCOEs below \$0.20/kWh, at which point SBSP could complement intermittent generation by competing with flexible resources such as gas peaker plants and long-duration storage. We therefore reevaluate SBSP's role in the energy system, reframing it as a dispatchable complement to terrestrial solar in grids with high variable renewable energy penetration. As solar deployment accelerates, intermittency raises integration costs from capacity payments, batteries, and other firming resources. By delivering power when solar is scarce, we show how SBSP could offset these costs, functioning as a globally dispatchable peaker. We conclude by discussing how policy can support architectures that enable this role.

The Impact of Rising Solar Penetration

Electricity demand is rising rapidly, driven by data centers, electric vehicles, and economy-wide electrification (Bin Abu Sofian et al., 2024; Davenport et al., 2024; Li and Jenn, 2024). In 2024 alone, global electricity use grew by over 4%, with projections of sustained acceleration continuing into the future (Çam et al., 2025). Renewable energy sources, particularly solar photovoltaic (PV), wind, and hydropower, are expected to meet approximately 95% of future demand growth, with PV leading the way due to falling capital costs and policy incentives (Bond, 2021; Çam et al., 2025; Skea et al., 2021). In the United States, PV and battery storage accounted for over 80% of planned new electricity capacity additions in 2025, with renewables comprising over 90% of total additions (EIA, 2025).

A major driver of the increasing dominance of PV and other variable renewable energy (VRE) sources is their falling levelized cost of energy (LCOE), i.e., average cost per unit of energy produced over system's lifetime, representing capital, operation, maintenance, and fuel costs divided by total energy output. However, while PV's LCOE has declined sharply, this metric does not capture broader system costs associated with high solar penetration, which requires backup infrastructure to maintain grid reliability during intermittent periods of low irradiation (Holttinen et al., 2011; Loth et al., 2022). In other words, because utilities must ensure a steady electricity supply even when the sun is not shining, backup systems such as gas peaker plants, battery storage, and capacity markets create additional system-wide costs.

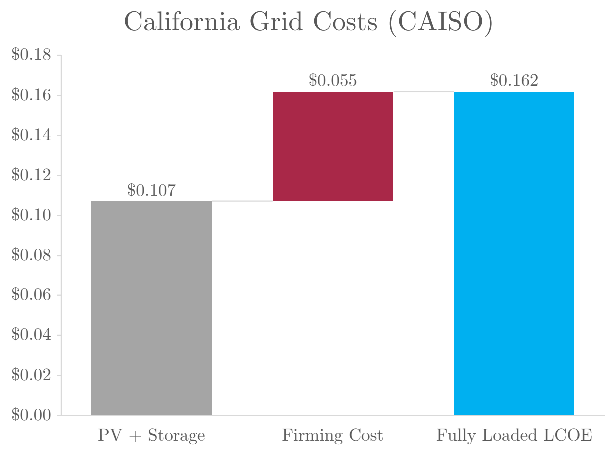
The costs associated with integrating VRE, particularly solar, have been called "firming costs", "system-level costs" "integration costs", or "hidden costs" (Ueckerdt et al., 2013). Because such firming costs are borne by the system rather than the electricity producer, they are excluded from LCOE (Loth et al., 2022). As VRE penetration increases, driven both by increased electricity demand and decarbonization, firming cost increases are expected to rise in tandem as the share of VRE increases (Mills, 2012).

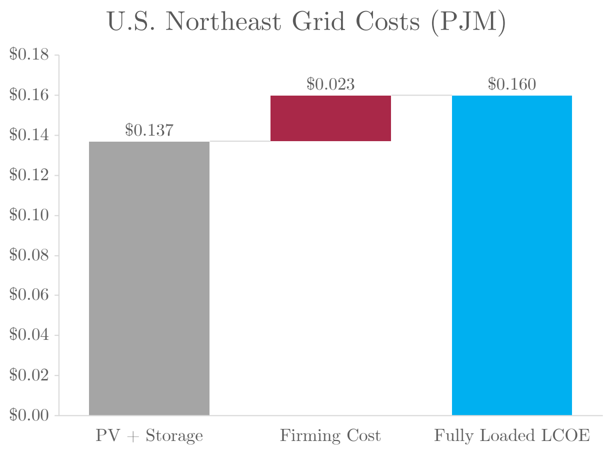
Accurately understanding the specific overall cost of VRE integration is extremely challenging given the many factors that make up grid costs. Nonetheless, in the UK, the Committee on Climate Change (2020) estimates firming costs at around \$0.02–0.05 per kWh for VRE penetration levels of 50–65%, increasing even further at higher penetration (Committee on Climate Change, 2020). This is in addition to the LCOE of solar electricity itself, typically around \$0.03 - \$0.05 per kWh. The OECD (2019) has reported similar findings, estimating system integration costs exceeding \$0.03 per kWh above 50% variable renewable penetration, rising to more than \$0.05 per kWh at penetration levels approaching 75% (OECD, 2019).

Empirically, in some grids where solar penetration is already high such as California, firming costs (including batteries) can exceed the cost of generation itself, effectively doubling the full cost of solar relative to its standalone LCOE (Lazard, 2025). More broadly, while the specific causal relationship is unclear, across OECD countries, higher VRE penetration correlates with higher retail electricity prices across OECD countries (Oosthuizen et al., 2022), and analysis of the "Levelized Full System Costs of Electricity", instead of LCOE, shows that in both Germany and Texas, the full cost of PV is higher than the most expensive dispatchable technology (Idel, 2022)

Figure 1 illustrates the integration costs associated with two U.S. electricity markets: California's CAISO (52% solar-plus-storage penetration) and PJM (7% penetration). Even without accounting for storage, firming costs such as capacity payments and backup generation represent a significant system expense, particularly in California. Moreover, if energy storage is considered part of solar integration, then firming costs account for more than half of the total delivered cost of solar electricity in both CASIO and PJM.

Figure 1 – Comparison of "Firming Costs" Between CAISO and PJM (adapted from Lazard, 2025)





Today, with few grids reaching over 50% VRE penetration, most research indicates that solar's low LCOE has generally outweighed firming costs, meaning that increasing PV penetration reduces costs even after accounting for integration (Gómez-Calvet and Gómez-Calvet, 2025; Quintana, 2024; Stringer et al., 2024). However, even where high VRE penetration lowers overall electricity prices, declining rates can create problems in-of-themselves, resulting in negative feedback loops where low prices reduce VRE profits to the extent that private investment can be crowded out (Christophers, 2022). This is especially a risk when curtailment rises during periods of peak supply, for which operators are not always compensated (Jopson and Stylianou, 2025). In addition, during "Dunkelflaute" - extended lulls in wind and solar - prices can spike dramatically even in relatively low-VRE grids. Even when such events are brief and do not raise average costs substantially, they represent a systemic challenge created by high VRE penetration (Çam et al., 2025; Hirth et al., 2015).

Space-Based Solar Power

As well as catalyzing higher VRE penetration, rising global energy demand has reignited interest in SBSP as a potential source of cheap low-carbon electricity. SBSP refers to the collection of solar energy in space and its wireless transmission to Earth (Bassey et al., 2024). Unlike terrestrial solar, which is constrained by weather and time of day, SBSP operates via satellites collecting uninterrupted solar radiation in space and transmitting this energy to ground receivers, where it is converted into usable electricity (Donchev et al., 2014).

Although the concept of SBSP has been studied for decades, recent advances have significantly reduced the cost of launch to space, renewing interest in SBSP's economic feasibility (Jones, 2025). SpaceX's Falcon rockets have lowered the price of reaching low Earth orbit (LEO) by more than 95%, from approximately $50,000 per kilogram during the Space Shuttle era to around $1,000/kg today (Bushnell and Moses, 2018; Rodgers et al., 2024). The next-generation SpaceX Starship may reduce these costs further, with projected prices as low as $100/kg - lower than overnight shipping within the continental United States (Fedex, 2023; Jones, 2025).

Historically, SBSP has been understood as a potential source of baseload power, aiming to meet the minimum level of continuous demand on the electricity grid. This framing sets a high bar for economic viability, requiring that SBSP compete directly with the cheapest electricity sources on cost and reliability (see e.g., Glaser, 1968; Mankins, 1997). Understanding SBSP as a baseload energy source also has significant design implications, and several governments are actively pursuing SBSP research based on the assumption that systems may eventually provide continuous power. In the United States, NASA has studied SBSP since the 1970s, most recently publishing a technoeconomic review in 2024 (Glaser et al., 1974; Rodgers et al., 2024). Japan's space agency, JAXA, aims to deploy a working SBSP system in the 2030s

(Government of Japan, 2020). The European Space Agency (ESA) has launched a dedicated initiative to evaluate SBSP's feasibility (European Space Agency, 2022). Other institutions, such as the Korean Academy of Science and Technology, SPACE Canada, and the International Astronautical Federation, are also supporting development efforts (Mankins, 2017). In parallel, private firms and startups have announced plans for commercial SBSP demonstrations in the 2020s and 2030s, driven by declining launch costs and rising global electricity demand.

The Levelized Cost of Energy of Space-Based Solar Power

As interest in SBSP grows, understanding its cost is necessary to assess commercial viability. While SBSP offers ancillary benefits such as delivering power to remote areas or catalyzing a reduction of launch costs through the economies of scale (Wood and Gilbert, 2022), widespread deployment depends on cost competitiveness with terrestrial electricity generation.

In theory, the fundamentals of SBSP create the potential to generate energy more cheaply than is possible via terrestrial solar. Terrestrial systems are constrained by the photovoltaic effect, which imposes fundamental efficiency limits of approximately 30% for single-junction solar cells and 55% for multi-junction cells (Henry, 1980). In contrast, rectennas - rectifying antennas used in SBSP - can achieve high conversion efficiencies at microwave frequencies (Donchev et al., 2014). Practically, however, deploying SBSP at scale remains a substantial technical challenge, primarily due to the mass that must be launched into orbit. In addition, diffraction imposes physical constraints as the minimum beam diameter achievable via SBSP is determined the Airy disk radius equation., potentially In this context, several recent technoeconomic analysis have estimated the LCOE for SBSP, including from academic researchers, national space agencies, and private sector actors.

The Caltech Space Solar Power Project

In 2021, a review study analyzed three medium Earth orbit (MEO) configurations and one geostationary orbit (GEO) system based on the Caltech Space Solar Power Project architecture, each designed to deliver an average of 100 MW to the terrestrial grid (M. A. Marshall et al., 2022). The authors estimated an LCOE of \$2.32/kWh for the GEO system, declining to \$2.15/kWh for MEO constellations as the number of satellites increased and ground station area requirements decreased. These estimates are broadly consistent with a 2022 Caltech study that found an LCOE of \$2.05/kWh for a GEO satellite with a similar architecture (Abiri et al., 2022)

NASA Space-based Solar Power Study

A comprehensive 2024 NASA report assessed two SBSP systems - a heliostat swarm and a planar array - each delivering 2 GW of power from GEO (Rodgers et al., 2024). Under baseline assumptions, the LCOE was estimated at \$0.61/kWh for the heliostat swarm and \$1.59/kWh for the planar array. Launch was the dominant cost driver, accounting for over 70% of total system costs due to the need for thousands of launches, primarily to refuel payloads en route to GEO. In addition, however, the 2024 NASA study showed the potential for SBSP costs to dramatically reduce via improvements across lower launch costs (to \$425/kg), electric propulsion (for orbital transfer from LEO to GEO), longer system lifetimes (up to 15 years), and improved manufacturing learning curves (to 85%). They estimated that improvements could reduce the LCOE to \$0.03–0.08/kWh (Rodgers et al., 2024).

Other Recent Studies

Other studies have similarly projected that SBSP could reach competitive LCOEs under favorable conditions. For example, Mizrahi et al. (2025) evaluate the Caltech Space Solar Power System (CSSPS) under three scenarios. In the present-day configuration - assuming current launch costs, system masses, and rectenna prices - the LCOE is estimated at \$7.77/kWh. A mid-range scenario incorporating improvements over 10 years, including lighter satellite components and reduced rectenna costs, reduced the LCOE to

$0.094/kWh. In the most optimistic case, assuming extensive scaling and asymptotic learning curves, the LCOE could fall to $0.038/kWh (Mizrahi et al., 2025).

CASSIOPeiA

A separate approach is the work led by the UK government, which introduced a system design known as CASSIOPeiA. A 2019 study proposed that by placing a SBSP system in GEO, the addition of fixed mirror concentrators could allow the satellite to receive continuous sunlight while maintaining constant visibility with one or more terrestrial receiving stations. The analysis calculated a simplified LCOE of $0.048/kWh (Cash, 2019). This CASSIOPeiA concept was also evaluated by a UK-government commissioned review (Consultancy, 2021), as well as a 2024 academic article (Alam et al., 2024), who both estimated the system's LCOE at $0.066/kWh), assuming the system is commissioned in 2040.

Commercial Space Companies

In the commercial sector, most companies developing SBSP systems (unsurprisingly) give far more ambitious and optimistic estimates of their medium-term LCOEs at below $0.10 but still above $0.03. In one example the CASSIOPeiA concept developed by the UK is being commercialized via the private company space solar Space Solar, who note on their website that the modelled is "between £37 and £74/mWh [$0.05 and $0.10/kWh]" (Space Solar, 2025). Another company, Virtus Solis, suggests a $0.03/KWh LCOE (Virtus Solis, 2025).

Valuing SBSP as a Dispatchable Power Resource

While prior analyses have largely focused on SBSP as a provider of continuous baseload electricity, this paper evaluates SBSP's potential as a dispatchable complement to terrestrial solar. In this section, we therefore compare the cost of SBSP versus other dispatchable electricity sources such as gas peakers, or, if SBSP is to competes with terrestrial solar, we adjust for the savings it enables.

Formally, if C_{VRE} is the LCOE of terrestrial solar, F is avoided firming costs, and C_{Gas}, is the LCOE of the gas peakers, SBSP is viable if it can deliver electricity at a cost below both benchmarks:

$$\mathrm{LCOE}_{SBSP} \leq \min\{\, C_{VRE} + F,\ C_{Gas} \,\}$$

As discussed, empirical estimates place F in the range \$0.02-–\$0.10 per kWh, C_{VRE} around \$0.02-0.05/kWh, and C_{Gas} between \$0.10 and \$0.20/kWh. Under these parameters, SBSP becomes competitive at approximately \$0.09 – \$0.17/kWh.

To understand the value of SBSP at a system level, we define the value created by the avoided cost of firming during hours of low solar availability:

Let:

- F: Marginal firming cost per kWh
- P: SBSP system capacity in MW
- U: Utilization rate (i.e., average fraction of time the system is delivering power)
- V_{total}: Total value from avoided firming costs (USD/year)
- Hours in a year: 8760

Total value is given by:

$$V_{total} = F \cdot P \cdot U \cdot 8760$$

For example 2,000 MW SBSP system with a 95% capacity factor:

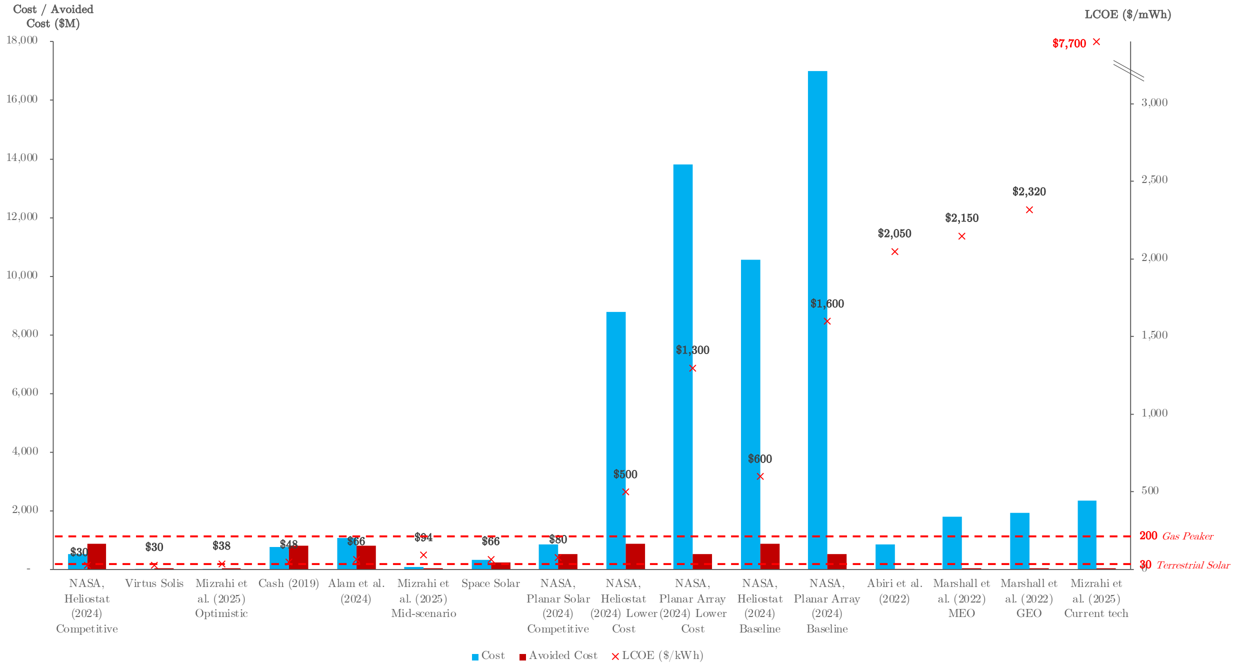
- F: $0.05/kWh
- P: 2000MW

- U: 0.95

$$V_{total} = 0.05 \cdot 2000 \cdot 0.92 \cdot 8760 = \$80.6 \text{ million/year}$$

To assess the economic value of SBSP across different system designs, *Figure 2* combines estimates of LCOE, utilization rates, and system sizes from existing technoeconomic studies. This allows for direct comparison between the total cost of delivering power and the economic value of that power to the grid (primary axis) under the assumption that SBSP is dispatched during high-marginal-cost hours and offsets firming requirements, and LCOE (secondary axis). As can be seen, while most SBSP system estimates remain more expensive than terrestrial solar, many estimates, including from NASA (2024) could be cost competitive with flexible gas peakers.

Figure 2 – Overview of SBSP Net Costs & LCOE



It is worth noting that the cost of gas peaker plants is even higher when accounting for carbon emissions or the cost of abatement. In a study of a net-zero electricity system in the UK, Imperial College London found that SBSP reduces generation operating costs under conditions of low variable renewable energy supply (Strbac, 2024). During such periods, the system would otherwise rely on gas-fired power with carbon capture and storage (CCS) or hydrogen-fueled generation to meet demand.

Technical Requirements of Flexible SBSP

In order for SBSP to function as a flexible source of demand, akin to a global gas peaker, two broad options exist to deliver energy directly to where it is most needed:

1. *Microwave Beaming to Co-located Rectennas*

One potential architecture for dispatchable SBSP involves transmitting energy from space to rectennas co-located with terrestrial solar farms. Rectennas consist of a dense array of dipole antennas coupled with high-speed diodes, which convert microwave radiation into direct current electricity (Donchev et al., 2014). A satellite equipped with beam steering capability could deliver energy to different solar farms across time zones. Rectennas, which are largely transparent to visible light and can be suspended above or embedded alongside PV modules, could piggyback on existing interconnection points from terrestrial solar and thereby avoids long lead times and permitting hurdles associated with new siting.

2. *Direct Photovoltaic Stimulation*

An alternative to microwave transmission is to stimulate terrestrial PV panels directly via orbital reflectors (K. A. Qaid et al., 2024). If light is reflected at wavelengths within the silicon absorption spectrum - approximately 400 to 1100 nm - such beams could activate PV panels even during nighttime or under partial cloud cover. This approach would leverage existing PV infrastructure and eliminate the need for rectennas, potentially simplifying ground system design.

However, reflector-based SBSP also introduces significant challenges. Transmitting a beam from orbit to a fixed terrestrial PV array requires sub-meter pointing precision, which is difficult to maintain given satellite motion and atmospheric disturbance. More generally, compared to rectenna systems, reflection SBSP sacrifices one of the key advantages of SBSP: independence from terrestrial PV constraints. Since the electricity is still being generated through PV panels, the system remains subject to weather-related losses, and therefore could likely not avoid entirely the need for other expensive flexible supply backup.

Conclusions

The analysis in this paper has suggested that, based on current technology, SBSP is not commercially feasible as a competitor to the lowest-cost generation. Existing system architectures remain an order of magnitude too costly and rely on technologies that are unproven at scale in either terrestrial or orbital contexts. Nonetheless, several technoeconomic studies, including NASA's 2024 analysis and work by Mizrahi et al. (2025), show that if launch costs continue to decline, orbital transfer becomes more efficient, and manufacturing benefits from improved learning curves, then LCOEs below \$0.20 or even \$0.10/kWh may be achievable. These assumptions are optimistic but not implausible. For example, electric propulsion is already operational in commercial satellites, and learning rates above 85% have precedent in other space-related manufacturing processes.

At LCOEs below \$0.20/kWh, while still more expensive than the cheapest forms of terrestrial generation, SBSP could become cost-competitive with flexible generation sources and create value for the energy system in the medium-term. By supplying power during periods of low solar output - at night, during seasonal lulls, or under cloud cover - SBSP could reduce the integration costs of VRE. In this role, SBSP would compete with high-cost firming solutions such as gas peaker plants and long-duration storage, instead of low-cost baseload generators or terrestrial solar. This aligns with Che et al. (2025)'s analysis of the NASA designs, finding scope for SBSP to be "complementary" to terrestrial solar (Che et al., 2025),

Several technical requirements are necessary to allow SBSP to function as a dispatchable resource, each with significant implication for system design and therefore the allocation of public funding for research.

First, dynamic beam steering is necessary for flexible SBSP, as delivering power where and when it is most valuable requires systems to redirect beams to geographically dispersed rectennas or solar farms. This necessitates phased-array microwave or laser transmitters with fine control and autonomous alignment.

Second, to achieve high utilization rates, SBSP must be in orbits able to reach disparate geographic areas. Unlike gas peakers, which are idle most of the year, SBSP systems with dynamic beam staring would be able to redirect to anywhere in their geographic reach, amortizing fixed costs over many hours of operation and driving down LCOE. SBSP architectures in GEO or MEO may be better suited to reaching this high utilization than LEO or HEO, as they can maintain line-of-sight with rectennas for longer durations.

Finally, ground systems should prioritize integration with high-VRE grids. Dispatchable delivery is most valuable during periods of high marginal cost or reliability stress. This also implies that grids with high capacity to forecast energy supply and demand, as well as those with dynamic pricing, may offer the most value-creation for SBSP.

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