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The Economic Impact of Space-Based Solar Panel Systems (SBSP) on Energy Markets: A Comparative Analysis with Solar Power Plants

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ABSTRACT The increasing global energy demand, the environmental costs of fossil fuels, and issues related to energy supply security are all contributing to the growing importance of renewable and innovative energy sources. In this context, Space-Based Solar Power (SBSP) systems offer the promise of continuous energy generation and geographic independence by providing extended access to sunlight in Earth's orbit. This study examines the economic impacts of SBSP systems on energy markets within a conceptual framework and analyzes them through a comparative lens alongside existing terrestrial solar power plants. By evaluating factors such as cost, efficiency, risk, and market integration related to the technology, the study highlights both the long-term potential and the short-term limitations of SBSP systems. In addition, the study incorporates projections tied to the development trajectory of the space economy by considering emerging technologies (such as OPVs) and private sector company initiatives. The study concludes that, despite current high costs and uncertainties, SBSP represents a promising investment area for the long-term in terms of strategic energy security and sustainability. It also addresses the potential threat posed by space debris to future SBSP projects.

Keywords
space-based solar power (SBSP) • energy markets • economic impact • solar power plants • space economy

Uzay Tabanlı Güneş Paneli Sistemlerinin (SBSP) Enerji Piyasalarına İktisadi Etkisi: Güneş Enerjisi Santralleri ile Karşılaştırmalı Bir Analiz

ÖZ Küresel enerji talebinin yükselmesi, fosil yakıtların çevresel maliyetleri ve enerji arz güvenliği sorunları, yenilenebilir ve yenilikçi enerji kaynaklarının önemini giderek artırmaktadır. Bu bağlamda, Uzay Tabanlı Güneş Paneli Sistemleri (SBSP), Dünya yörüngesinde daha uzun süreli güneş ışığına erişim sağlayarak enerji üretiminde süreklilik ve coğrafi bağımsızlık vadetmektedir. Bu çalışma, SBSP sistemlerinin enerji piyasalarına yönelik iktisadi etkilerini kavramsal bir çerçevede incelemekte ve bunları mevcut karasal güneş enerjisi santralleriyle karşılaştırmalı olarak analiz etmektedir. Teknolojiye ilişkin maliyet, verimlilik, risk ve piyasa entegrasyonu gibi unsurlar değerlendirilerek, SBSP sistemlerinin uzun vadeli potansiyeli ile kısa-orta vadeli sınırları ortaya konulmuştur. Ayrıca, yeni nesil teknolojiler (örneğin OPV) ve özel sektör şirket girişimleri de dikkate alınarak, uzay ekonomisinin gelişim eğrisiyle bağlantılı öngörüler sunulmaktadır. Çalışma, SBSP'nin hâlihazırda yüksek maliyet ve belirsizlik içerse de, stratejik enerji güvenliği ve sürdürülebilirlik açısından gelecek vaat eden bir yatırım alanı olduğunu ortaya koymaktadır. Aynı zamanda uzay çöplerinin gelecekte SBSP projelerine yönelik taşıdığı potansiyel tehlikelere de değinilmektedir.

Anahtar Kelimeler
uzay tabanlı güneş enerjisi (UTGE) • enerji piyasaları • iktisadi etki • güneş enerjisi santralleri • uzay ekonomisi

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Introduction

The growing global demand for energy, the environmental impact of fossil fuels, and the challenges of energy supply security are increasing the need for sustainable and innovative solutions in energy policies. Within this transformation process, solar energy, which has become a prominent renewable source, has shown significant advancements in production capacity and economic accessibility due to technological developments. However, terrestrial solar energy systems are inherently limited by their dependency on direct sunlight and are unable to provide continuous production due to geographic and climatic constraints, prompting the search for more efficient and uninterrupted alternatives in energy markets. They are also dependent on cleaning technologies because after some time dust and other dirt limits the sunlight so that decreases energy production.

In this context, Space-Based Solar Power (SBSP) systems, which involve placing solar panels in orbit and transmitting energy to Earth via microwave or laser technology, have emerged as a theoretical solution offering longer exposure to sunlight. These systems are claimed to offer continuity in energy production and stability in supply security, which could significantly affect current energy market dynamics (Space Solar, 2024). Nevertheless, their economic feasibility compared to conventional solar power plants on Earth, in terms of cost and efficiency, remains a matter of debate.

This study aims to discuss the economic effects of SBSP systems on energy markets within a conceptual framework. It provides a comparative analysis with existing solar power plants based on installation costs, efficiency rates, risk profiles, and potential impacts on energy prices. The analysis is grounded not in empirical data but in economic theory, conceptual frameworks, scenario-based predictions, and the current state of related companies. The concluding section offers theoretical projections for the future of energy markets and strategic recommendations for policymakers.

Conceptual Framework of Space-Based Energy Systems

Space-Based Solar Power (SBSP) systems are fundamentally designed to collect solar energy in space via solar panels positioned in Earth's orbit, transmitting the collected energy to ground-based stations through microwave or laser technologies. The primary conceptual advantage of SBSP systems lies in their operation beyond the atmosphere, where they are continuously exposed to sunlight. This operational advantage eliminates limiting factors commonly encountered in terrestrial systems, such as day-night cycles, weather conditions, maintenance requirements, and seasonal changes. Thus, they are projected to offer critical advantages such as high capacity factors and uninterrupted energy supply.

To conceptually evaluate the position of SBSP systems within the economics of energy, it is essential to reference several core economic concepts. First, due to their capital-intensive nature, these systems are significantly affected by economies of scale. Although the initial investment costs are substantial, the unit cost of energy may decrease with large-scale production and distribution. This dynamic will be a determining factor for the long-term economic feasibility of the system.

Second, given the potential of SBSP systems to facilitate global access to energy, they theoretically tend to resemble public goods. Although state-sponsored investments and projects are prominent, there is also a perception that such ventures are mainly championed by start-ups. If these systems are managed by states or international consortia, collective benefits in energy supply can be realized. However, if driven by private enterprises, issues such as natural monopolies and high entry barriers could lead to market imbalances.

The growing interest of both public and private sectors in SBSP in recent years offers important insights into the future role of this technology in energy markets. Countries such as China, the United States, Japan, the United Kingdom, Germany, and Russia are making serious investments in SBSP through both government-backed agencies and private sector initiatives. These investments are aligned with strategic goals such as ensuring continuity in energy production, achieving geostrategic superiority, and meeting net zero targets.

Among prominent state-backed institutions is China's China Aerospace Science and Technology Corporation (CASC), with an annual revenue of $46.2 billion. CASC leads not only in defense and space technologies but also in SBSP projects. Through its advanced satellite and energy transmission systems, CASC aims to reduce China's dependence on energy imports and establish global leadership in sustainable energy. Similarly, U.S.-based institutions such as Northrop Grumman Corporation and the Air Force Research Laboratory (AFRL) play pioneering roles in SBSP technological development. AFRL's "Arachne Project" has tested the concept of transmitting energy from space to Earth via microwaves (Air Force Research Laboratory, 2025).

For instance, Japan plans to conduct space-to-Earth solar energy transmission in 2025. Under the project named "OHISAMA", a satellite weighing approximately 180 kilograms will be launched into low Earth orbit (LEO). The SBSP satellite will transmit the energy collected via a 2-square-meter solar panel to ground-based receiving antennas in microwave form. This technology aims to reduce reliance on fossil fuels and combat climate change by enabling continuous energy generation unaffected by atmospheric conditions (Brahambhatt, 2025).

From ESA's perspective, within the next 15 to 20 years a significant portion of the European power plants will reach their definitive end-of-life and will have to be replaced. Consequently, they conduct discussions about the most appropriate energy systems for this 21st century which includes the space based solar panels as well (Summerer, Vasile, Biesbroeck and Ongaro, 2003). The first phase of their programme plan has been concluded successfully, with several spin-off projects as a bonus. The renewed interest for solar power from space in the US makes this the right time to start off the second phase of the ESA SPS Programme Plan (European Space Agency, 2008). After these programs, to prepare Europe for future decision making on Space-Based Solar Power, ESA has kicked-off a preparatory initiative, called SOLARIS, for which funding was approved at the ESA Council at Ministerial Level in November 2022. ESA aims to make an informed decision by the end of 2025 on whether to proceed with a development program for SBSP technology.

A notable recent milestone in wireless power transmission was achieved by the Defense Advanced Research Projects Agency (DARPA) in the United States. On May 16, 2025, as part of the Persistent Optical Wireless Energy Relay (POWER) program, DARPA successfully transmitted over 800 watts of power during a 30-second laser-based transfer across a distance of 8.6 kilometers (5.3 miles) in New Mexico. Throughout the broader test campaign, more than a megajoule of energy was transferred — marking a significant leap forward in free-space laser power delivery. Prior to this, the furthest known laser transmission of appreciable power was limited to 230 watts at 1.7 kilometers. This breakthrough sets new benchmarks for long-range optical energy transfer and directly supports the viability of space-based solar power (SBSP) constellations, which depend on efficient, high-capacity energy beaming technologies. If scalable, such achievements could accelerate the deployment of SBSP systems which are currently use microwaves frequencies by addressing one of the most critical technical problems.

In the private industry, companies such as Solaren Corporation, SolAero Technologies, and Azur Space are pioneering the commercialization of SBSP technologies. Solaren was among the first serious initiatives with its 2009 agreement with Pacific Gas & Electric to commercialize SBSP. Azur Space and SolAero supply essential components by developing highly efficient and radiation-resistant solar cells. These companies aim to reduce technology costs through private investment and establish a competitive advantage in the long-term energy market (Emergen Research, 2025). UK-based Space Solar aims to transmit energy to Earth via high-frequency radio waves using a satellite which is planned to launch into orbit by 2029. This initiative represents one of the most concrete European steps toward SBSP commercialization (Space Solar, 2024).

These companies' activities demonstrate that SBSP is not just a technical innovation, but a potential economic paradigm shift capable of reshaping global energy markets. Through public-private partnerships, the initial high-cost phases of SBSP could be overcome, allowing price stabilization through economies of scale. This development could offer new opportunities for countries facing difficulties in energy access while also reducing geographical dependence in energy production.

Finally, SBSP systems can be evaluated within the context of market integration of technological innovations through the "learning curve" effect. This perspective assumes that although systems may initially be costly, increased experience in production and application will reduce costs over time. Therefore, early investments in this technology carry not only economic but also strategic significance. One critical issue that is often overlooked in current assumptions is the future volume and impact of space debris. Within the conceptual framework, SBSP can be seen not only as a technical innovation but also as a transformative factor in competition, accessibility, cost, and sustainability within energy markets.

Current Supply and Demand in Global Energy Markets

In the twenty-first century, global energy markets are undergoing profound transformations on both the supply and demand sides. Worldwide energy demand is accelerating, particularly in developing economies, driven by industrialisation and urbanisation. Meanwhile, the environmental costs of energy production and dependency on fossil fuels are highlighting the need for sustainable alternatives. In this context, renewable energy sources—especially solar and wind—are increasingly being integrated into energy portfolios. However, the inherently intermittent and unpredictable nature of these resources creates structural problems in terms of energy supply security.

Traditional energy markets predominantly rely on land-based production and distribution systems. Factors such as geographic location, access to natural resources, and infrastructure investments determine the competitive capacity of market actors. Within this framework, Space-Based Solar Power (SBSP) systems, which theoretically overcome physical limitations and can operate at higher production frequencies, have the potential to create a paradigm shift in current market structures. When equipped with infrastructure that enables 24/7 energy production and transmission, SBSP systems can enhance supply stability and reduce price volatility in energy markets. However, integrating such systems into global energy markets requires a multi-layered transformation that involves not only technical challenges but also economic and legal dimensions.

According to the International Energy Agency (IEA), global electricity demand is expected to grow at a faster pace over the next three years, averaging 3.4% annually through 2026. In 2023, electricity consumption in advanced economies declined, which restricted global demand growth. Overall electricity demand rose by 2.2% in 2023, slightly below the 2.4% increase recorded in 2022. While countries such as China, India, and many Southeast Asian nations saw strong growth in electricity demand, slow macroeconomic environment and high inflation in developed economies led to a decrease in manufacturing and industrial output, resulting in notable declines (International Energy Agency, 2024).

Between mid-2025 and 2026, about 85% of additional electricity demand is projected to come from countries outside advanced economies, with China continuing to play a significant role despite structural economic changes. In 2023, China's electricity demand rose by 6.4%, driven by growth in the services and industrial sectors. As China's economic growth slows and its reliance on heavy industry diminishes, its electricity demand growth is projected to decline to 5.1% in 2024, 4.9% in 2025, and 4.7% in 2026. Nonetheless, the cumulative increase in China's electricity demand through 2026 is expected to reach approximately 1,400 terawatt-hours—exceeding more than half the European Union's current annual electricity consumption. Per capita electricity consumption in China surpassed EU levels at the end of 2022, and it is expected to rise further. The rapid expansion of solar photovoltaic (PV) modules and electric vehicle production, along with the associated material processing activities, is likely to continue supporting electricity demand growth in China, despite structural shifts in its economy (International Energy Agency, 2024).

Although energy markets typically operate under free-market principles, energy security, environmental considerations, and the long-term nature of infrastructure investments make them prone to government intervention. Given their space-based nature, SBSP systems require large-scale investments, long return periods, and significant technological development—demands that are difficult for the private sector to meet alone. Consequently, integration into the energy market will necessitate state-supported programmes, public-private partnerships, and the involvement of international consortia. Therefore, the introduction of SBSP into the energy market implies not only a technological innovation but also a need for a new institutional framework.

Comparative Economic Analysis with Solar Power Plants

Comparing space-based solar panel systems (SBSP) with existing terrestrial solar power plants from an economic perspective is essential for evaluating how these technologies might be integrated into energy markets. This comparison can be structured around key economic parameters such as investment costs, energy efficiency, risk profile, payback period, and market integration.

Terrestrial solar energy systems have seen significant cost reductions over the past decade due to technological advancements and increased production scales, which have lowered per-unit investment costs. As of 2024, the installation cost of commercial-scale photovoltaic (PV) systems ranges between USD 850 and 1,200 per megawatt, with a return on investment estimated between 11 and 13 years (Balal, Kantarek, Wilson and Stewart, 2024). In contrast, SBSP systems still require extremely high fixed capital investments, amounting to billions of dollars per system. They also involve complex infrastructure layers such as launch operations, orbital placement, microwave/laser transmission systems, and ground-based receiving stations.

Furthermore, SBSP deployment and orbital operations involve considerable risks and uncertainties. Terrestrial systems generally have a capacity factor of 20–25%, affected by cloud coverage, the day-night cycle, and seasonal variations. However, SBSP systems theoretically have more consistent access to sunlight, making them promising candidates for continuous baseload renewable energy production.

Terrestrial solar power plants are technologically mature, with established maintenance and operational frameworks. Their risk and regulatory uncertainties are relatively low. SBSP systems, on the other hand, involve high technological uncertainty, undefined investment return periods, and evolving regulatory frameworks. While some sources, like Criswell and Waldron (1990), argue that SBSP systems could yield internal rates of return as high as 40%, these projections depend heavily on long-term technical success and massive capital investments. Furthermore, space debris and rising satellite traffic may introduce additional unforeseen risks.

According to Schubert et al. (2018), lunar-sourced geostationary power satellites could produce energy at a cost of around $0.03 per kilowatt-hour, achieve payback in seven years, and meet 22% of global demand for 20 years. Oderinwale and McInnes (2022) report that solar power satellites and orbital reflectors could generate internal rates of return of 2.57% and 3.82%, respectively, assuming launch costs remain at USD 414–543 per kilogram. However, Criswell and Waldron's projections rely on very high capital requirements.

As Balal et al. (2024) show, solar farms currently produce approximately 153.58 gigawatt-hours per year, with payback periods between 11.7 and 13 years. Research indicates that SBSP faces substantial hurdles, including high upfront costs, low technological maturity, and integration challenges, whereas terrestrial systems benefit from compatibility with existing grids and more predictable returns.

While terrestrial solar power plants can be directly connected to existing grid infrastructure, SBSP-generated energy must be collected (via microwave or laser) at ground stations and converted for grid use, requiring the development of new and untested infrastructure. This adds to integration costs and necessitates new regulatory frameworks. For now, terrestrial solar systems—with lower entry costs, predictable ROI, and infrastructure compatibility—remain more appealing in the short to medium term.

Nevertheless, SBSP systems hold long-term potential due to advantages such as high efficiency, operational continuity, and independence from geographic limitations. They could offer geoeconomic leverage and strategic energy security. However, realising this potential will require not only technological progress but also substantial public investment, international cooperation, and regulatory development.

Conceptual Scenarios and Economic Implications for the Future

As expected, the small satellite industry continued to grow in 2023, with Novaspace (2023) projecting a total of 26,104 small satellite launches between 2023 and 2032. While this expansion reflects a broader trend of miniaturization and commercial democratization in space access, it has also been accompanied by significant challenges. The year 2023 saw worsening macroeconomic conditions globally, a series of high-profile mission failures, and increasing financial difficulties for start-up ventures attempting to remain solvent. The anticipated surge in small satellite deployments, while essential for communication, observation, and navigation purposes, also raises serious concerns about orbital congestion and the proliferation of space debris. This is especially critical for systems like SBSP, which require large, stable, and uninterrupted infrastructure in geostationary or low-Earth orbit. The accumulation of inactive or malfunctioning satellites may dramatically increase the risk of collision, electromagnetic interference, and cascading debris events (could ultimately lead to Kessler Syndrome), thereby threatening the long-term safety and viability of orbital energy infrastructures and other satellites. For SBSP to be a reliable component of the global energy future, such externalities must be accounted for in early-stage design and policy frameworks.

There are also some developments in technological innovation process. Traditional single-junction photovoltaic (SPV) systems, commonly based on crystalline silicon (c-Si), are known for their high efficiency but present limitations in weight and rigidity for space applications. In contrast, organic photovoltaics (OPVs), though still largely theoretical and offering lower efficiency, promise advantages such as lightweight, flexibility, and potential cost reductions—making them particularly suitable for reducing launch and deployment costs in space-based systems.

A study conducted at the University of Oxford's Department of Physics using laboratory tests that simulate geostationary orbit conditions and Monte Carlo economic modelling suggests that while OPVs still face technical durability limitations, their cost-lowering potential could improve the financial sustainability of SBSP projects (Niebla del Campo, 2024). In this context, practical verification tests using small-scale missions such as CubeSats are expected to play a crucial role in the maturation of OPV technologies. Additionally, the development of OPVs could support not only SBSP systems but also next-generation solutions for terrestrial solar energy, thereby making such material innovations strategically valuable for both energy production and climate action.

Recent projections indicate that the space economy is rapidly expanding beyond its traditional focus on defence and telecommunications into civil sectors such as energy, mining, and data services. According to report by McKinsey, the global space economy will be worth $1.8 trillion by 2035 (accounting for inflation), up from $630 billion in 2023 (McKinsey & Company, 2023). Key drivers of this growth include reduced launch costs, increased private-sector participation, and the diversification of orbital services. In this context, capital-intensive yet high-return technologies like SBSP are regarded as foundational pillars of the expanding economic domain. SBSP is expected to influence not only the energy sector but also space-based infrastructure, data transmission, and strategic autonomy.

If broadly adopted in the marketplace, three main economic outcomes can be projected for SBSP systems: (1) Long-term price stabilisation in energy markets, (2) Reduced geopolitical risks in supply security, and (3) The emergence of new actors in international energy trade. The continuous generation capacity of SBSP could help mitigate volatility in energy prices, fostering a more stable price structure in spot markets and offering a redefinition of energy sovereignty, especially for energy-importing nations. However, these outcomes depend on the international collaboration for peace and security for the space constellations and solutions for the space debris problem.

While these future projections are promising, they also entail increasing associated risks. The expected rise in satellite launches and orbital infrastructure will likely lead to higher volumes of space debris. This, in turn, increases the vulnerability of large-scale and expensive SBSP arrays. Given the high cost and inherent risks of such ventures, investments by companies or states may appear irrational under current conditions. Therefore, positive long-term expectations must be balanced with the growing risks they may entail.

Conclusion and Policy Recommendations

This study has demonstrated that space-based solar power (SBSP) systems represent not only a technical innovation but also an economic paradigm shift with the potential to reshape global energy markets structurally. SBSP systems offer strategic advantages such as continuous energy generation, supply security, and geographic independence only if there is international collaboration and concrete solutions for space debris problem. There are also significant limitations, including high capital requirements, technical uncertainties and regulatory deficiencies.

In contrast, terrestrial solar energy systems are more feasible in the short to medium term due to their easier integration into existing infrastructure, lower investment risk, and predictable returns. Nevertheless, in the long-term perspective, the economic viability of SBSP systems could be enhanced through international cooperation and publicly funded financial models. This necessitates the development of national strategic roadmaps, international legal and licensing frameworks, and transparent property rights regimes for space-based energy.

The advancement of lightweight and flexible solar cell technologies such as OPVs, and the proliferation of low-cost test platforms like CubeSats, could reduce technological uncertainties and increase investor confidence. For policymakers, the key takeaway is that SBSP should not be seen merely as an alternative energy technology but as a critical domain intersecting strategic energy sovereignty, technological transformation, and integration into the space economy. Therefore, supporting this technology should be considered not only from a technical standpoint but also as a strategic priority with economic, environmental, and diplomatic benefits.

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