

Types of space-based energy harvesting technologies: applications, economic approach, advantages, and disadvantages

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ABSTRACT

With the increasing global demand for energy and the environmental challenges posed by fossil fuels, space-based energy harvesting technologies have emerged as a potential solution for sustainable energy supply. This article reviews various types of space-based energy harvesting technologies, including space-based photovoltaic systems, solar dynamic systems, wireless energy transmission via microwave and laser beams, and solar wind energy harvesting. The economic approach of these technologies is evaluated through analysis of capital investment costs, launch and maintenance costs, and comparison with terrestrial energy sources. Results indicate that although these technologies currently face significant technical and economic challenges, recent advances in space technologies and reductions in launch costs have increased the feasibility of their commercialization in the coming decades.

Keywords: Space-based solar power, wireless power transmission, microwave, laser, solar wind, life cycle cost analysis, baseload power generation

1. INTRODUCTION

Sustainable and clean energy supply is one of the greatest challenges of the twenty-first century. With the growing global population and industrialization, energy demand is increasing exponentially. Terrestrial renewable energy sources such as solar and wind, despite significant advances, face limitations including the day-night cycle, weather conditions, and the need for energy storage [1].

Space-based energy harvesting technology is a concept first proposed by Peter Glaser in 1968, involving the collection of solar energy in Earth orbit and transmitting it to the Earth's surface

via electromagnetic waves [2]. The main advantage of this approach is continuous access to solar radiation without atmospheric interference and the day-night cycle. Recent studies show that space-based solar power systems can reduce power system costs by 7 to 15 percent and replace up to 80 percent of terrestrial wind and solar capacity [3].

This article aims to provide a comprehensive review of space-based energy harvesting technologies, their potential applications, economic analysis, and examination of the advantages and disadvantages of each.

2. MAIN BODY OF THE ARTICLE

2.1 Types of Space-Based Energy Harvesting Technologies

2.1.1 Space-Based Photovoltaic Systems

Space-based photovoltaic systems are the most common approach for harvesting solar energy from space. In these systems, large arrays of solar cells are placed in Earth orbit and convert solar energy into electricity. These systems are typically deployed in geostationary orbit (GEO) at an approximate altitude of 36,000 km to ensure continuous access to sunlight and a fixed position relative to ground stations [4].

Space solar cells utilize advanced technologies such as III-V multi-junction cells, which offer higher efficiency than conventional silicon cells. Studies indicate that perovskite cells and transition metal dichalcogenides (TMDs) are being investigated as alternative ultrathin materials for space applications [5].

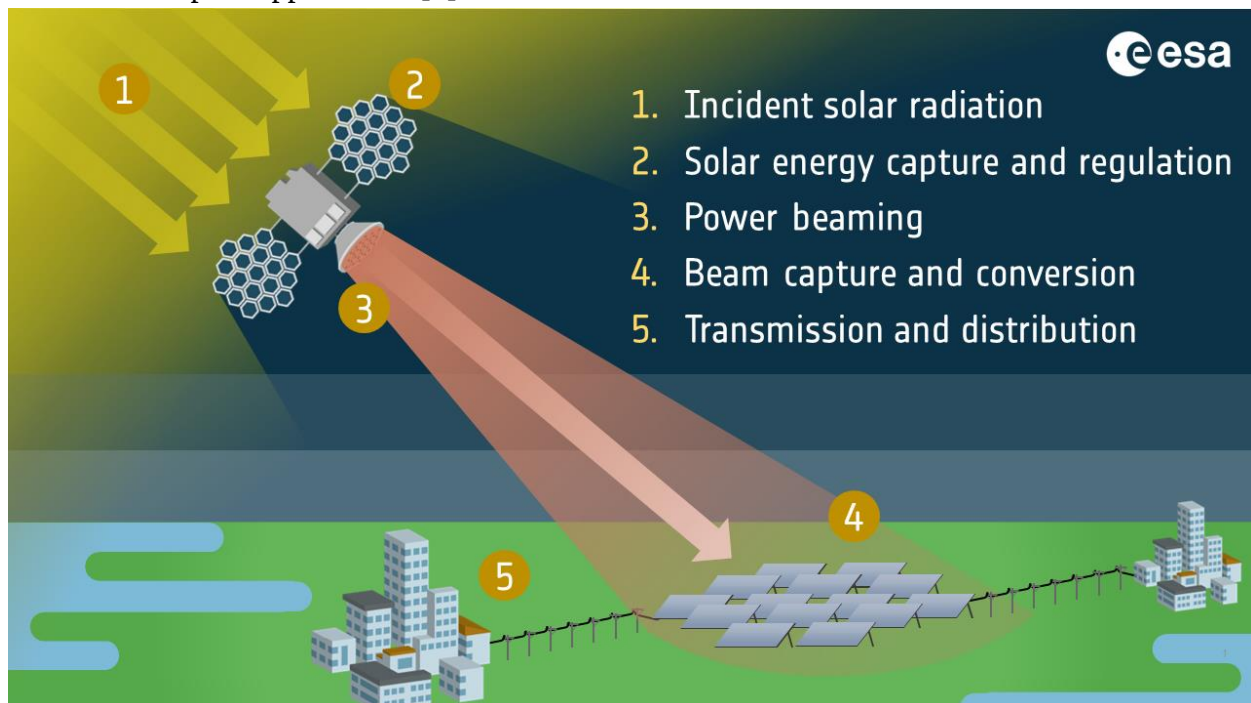


Figure 1. Operational stages of the space-based solar power system: (1) Incident solar radiation, (2) Solar energy capture and regulation, (3) Power beaming, (4) Beam capture and conversion, (5) Transmission and distribution. (Source: ESA [6])

2.1.2 Solar Dynamic Systems

Solar dynamic systems offer an alternative approach for converting solar energy, where sunlight is directed by concentrating mirrors to a receiver that heats a working fluid. This heated fluid is then converted to electricity through a heat engine (typically a Brayton cycle) [7].

The main advantages of these systems include higher efficiency (up to 47% under ideal conditions), greater resistance to space radiation, and the ability to generate high-voltage AC power. Studies show that a 10-megawatt SD module can achieve a specific power exceeding 700 W/kg under advanced technology conditions [7].

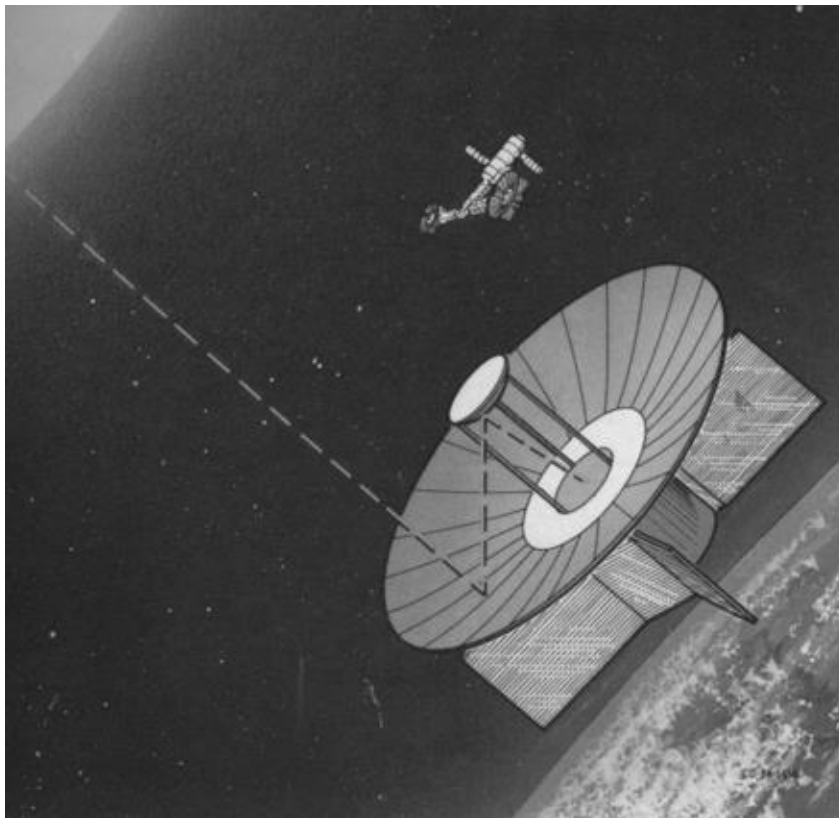


Figure 2. Conceptual design of a solar dynamic power system with Cassegrain concentrator and heat engine. (Source: NASA [7])

2.1.3 Wireless Power Transmission

Wireless power transmission is one of the key technologies for space-based energy harvesting systems. Two main approaches exist for this purpose:

a) Microwave Power Transmission (MPT)

This more mature technology involves converting electrical energy into microwave waves at frequencies of 2.45 or 5.8 GHz and transmitting them to ground stations. Ground stations use rectenna (rectifying antenna) arrays to receive and convert the waves to DC [8]. The main advantage of this method is its ability to penetrate clouds and atmosphere with minimal loss.

Table 1. Comparison of microwave transmission parameters in proposed JAXA and NASA/DOE models. (Source: Heliyon [8])

Parameter	JAXA Model	NASA/DOE Model
Frequency	5.8 GHz	2.45 GHz
Transmitter Antenna Diameter	1.93 km	1 km
Output Power	1.3 GW	6.72 GW
Central Power Density	114 mW/cm ²	2.2 W/cm ²
Collection Efficiency	87%	89%

b) Laser Power Beaming

In this method, solar energy is converted into laser light and directed toward ground receivers. The main advantage of lasers is the ability to use smaller receivers and higher targeting accuracy. However, this method is more affected by atmospheric conditions and clouds, and raises greater safety concerns [4].

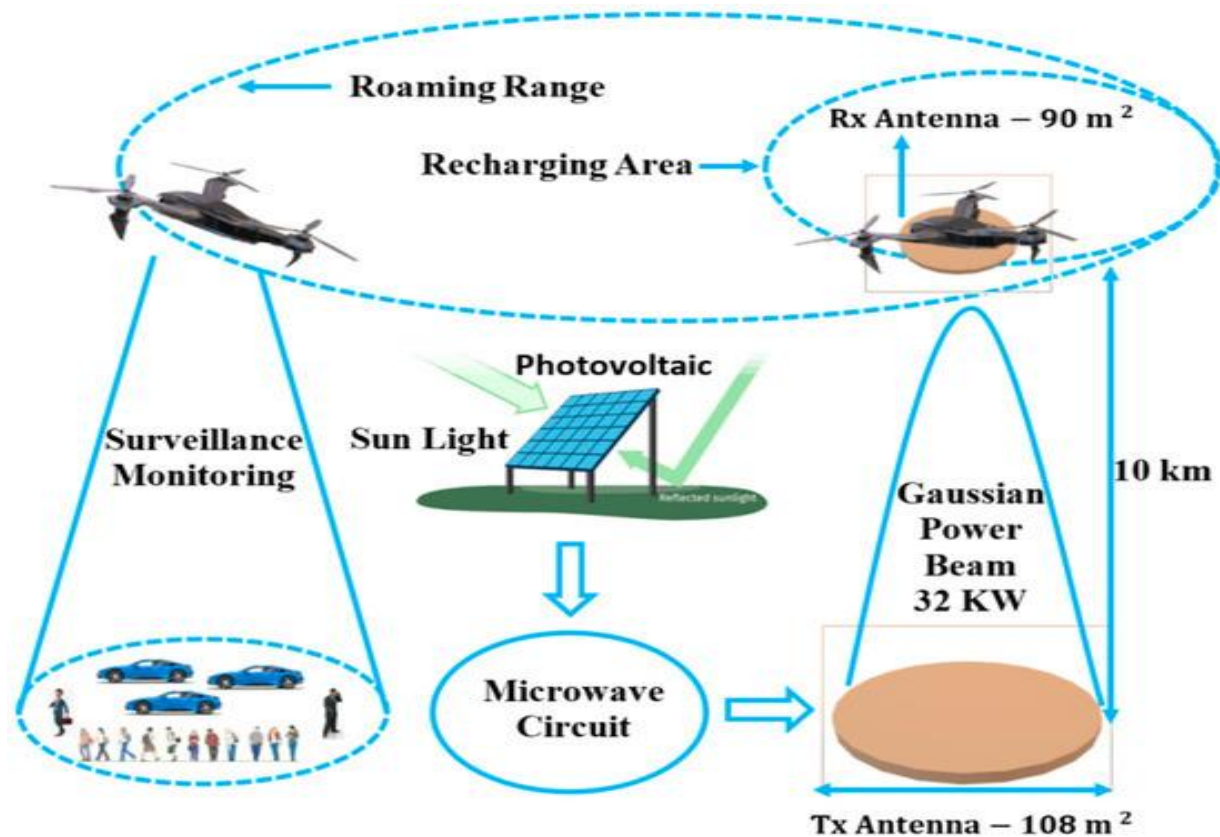


Figure 3. Example of a microwave wireless power transmission system for UAV applications. (Source: MDPI [9])

2.1.4 Solar Wind Energy Harvesting

Solar wind is a continuous stream of protons and electrons emitted by the Sun. Dyson-Harrop satellites and solar wind power satellites utilize this stream to generate electrical energy [10].

These systems require positioning at distances far from Earth orbit and face challenges in transmitting energy back to Earth.

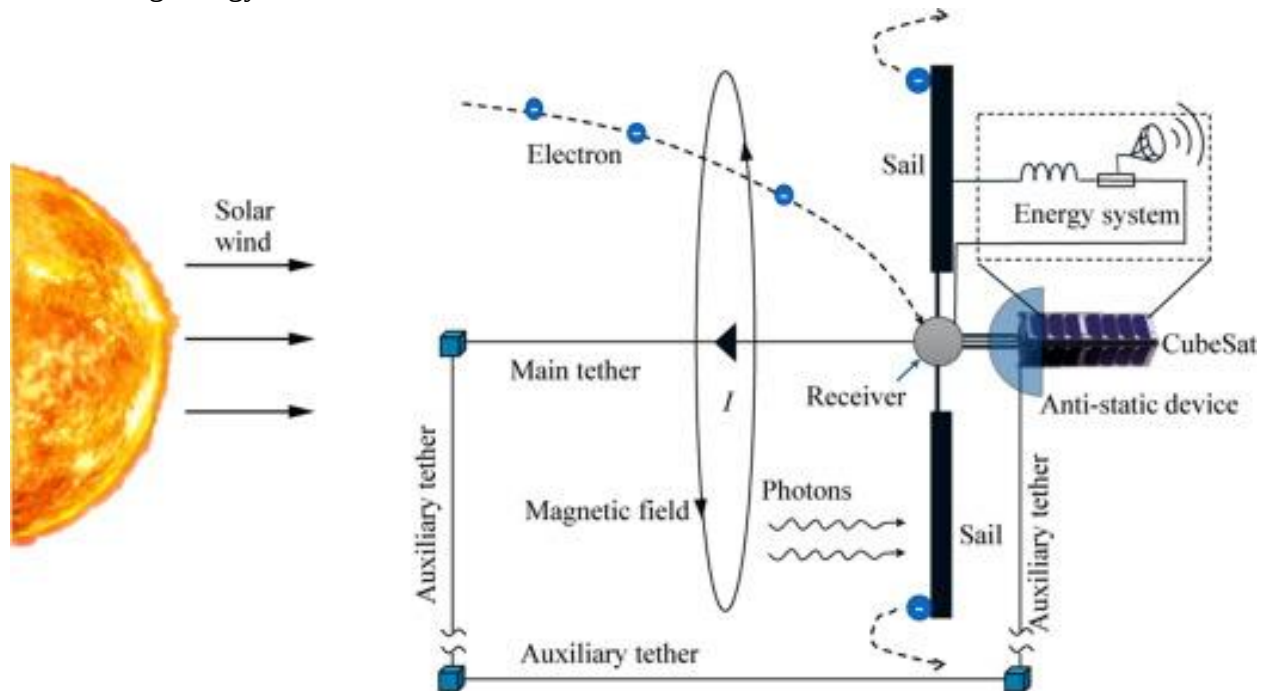


Figure 4. Conceptual design of a Dyson-Harrop satellite for harvesting solar wind energy using conductive wires and magnetic fields. (Source: ScienceDirect [10])

2.2. Applications of Space-Based Energy Harvesting Technolog

2.2.1 Stable Power Supply for Terrestrial Grids

The primary application of space-based solar power systems is providing stable and uninterrupted electricity for terrestrial power grids. Studies show that a 2-gigawatt system in geostationary orbit can produce electricity equivalent to the output of a nuclear power plant [3]. These systems are capable of providing baseload power and can replace fossil fuel sources or even complement terrestrial renewable sources.

2.2.2 Energy Supply for Space and Lunar Missions

Space-based energy harvesting systems can be used to power lunar exploration missions and other space systems. Recent studies show that a constellation of small space solar satellites can provide 36 to 40 kilowatts of stable power for Artemis stations on the Moon [11].

2.2.3 Military and Defense Applications

Armed forces are seeking to use this technology to power remote bases and field operations. The U.S. Air Force Research Laboratory (AFRL) is advancing the SSPIDR project to develop space-to-ground power transmission technologies for military applications [12].

2.3 Economic Approach

2.3.1 Life Cycle Cost (LCC) and Levelized Cost of Energy (LCOE) Analysis

Economic analyses indicate that current costs of space-based solar power systems are significantly higher than terrestrial energy sources. NASA's 2024 report shows that LCOE for reference SBSP designs ranges from \$0.61 to \$1.59 per kWh, which is 12 to 80 times higher than terrestrial renewable sources [13].

LCOE Comparison

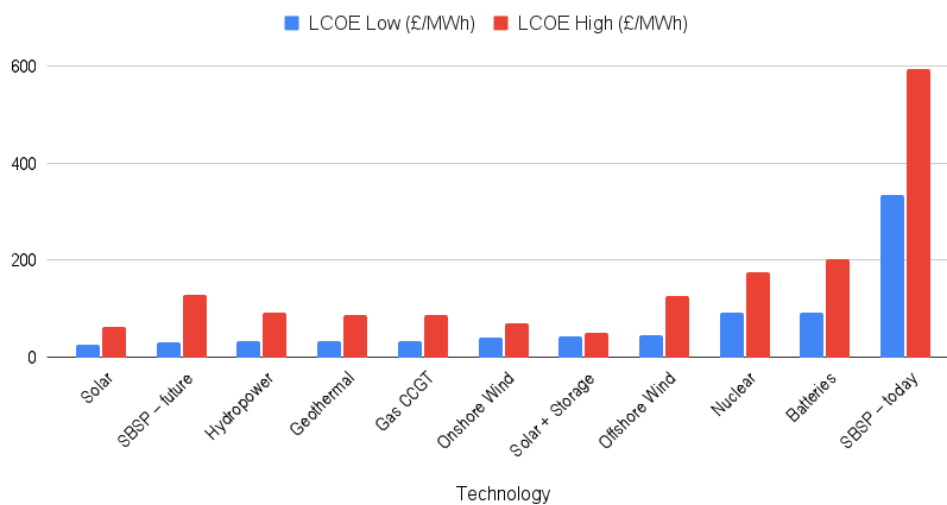


Figure 5. LCOE comparison for various energy technologies. Current SBSP has significantly higher costs compared to other sources. (Source: Impakter [14])

2.3.2 Factors Affecting Launch and In-Orbit Assembly Costs

The largest cost factor in SBSP systems is launch and in-orbit assembly costs. NASA's report indicates that reducing launch costs from \$100 million to \$50 million per launch decreases LCOE by approximately 36 to 39 percent. If reduced to \$10 million, this decrease reaches 64 to 70 percent [13].

Table 2. Impact of launch cost reduction and technology improvement on SBSP system LCOE. (Source: NASA OTPS [13])

Scenario	RD1 LCOE (\$/kWh)	RD2 LCOE (\$/kWh)
Baseline (100M\$)	0.61	1.59
Launch 50M\$	0.40	1.00
Launch 10M\$	0.20	0.50
Electric Transfer to GEO	0.20	0.50
Competitive Scenario	0.03	0.08

2.3.3. Economic Comparison with Terrestrial Renewable Energy Sources

A recent Elsevier study shows that if the heliostat swarm design can produce electricity at 6 to 9 times the projected cost of terrestrial PV in 2050, total European power system costs would decrease by 7 to 15 percent. Under these conditions, SBSP could replace up to 80% of terrestrial wind and solar capacity and reduce battery needs by more than 70% [3].

2.4 Advantages and Disadvantages of Space-Based Energy Harvesting Technologies

2.4.1 Advantages

- **Continuous access to solar energy:** Space systems can access sunlight 99% of the time [4].
- **Independence from weather conditions:** Solar radiation in space is uninterrupted by clouds, rain, or dust [4].
- **Higher collection efficiency:** Solar radiation intensity in space is approximately 30% higher than on Earth's surface.
- **Stable power generation:** Ability to provide baseload power unlike intermittent terrestrial sources [3].
- **Environmental benefits:** Much lower greenhouse gas emissions compared to fossil fuels [13].

2.4.2 Disadvantages and Challenges

- **Extremely high initial capital investment:** Requires multi-billion dollar investments [13].
- **Technical challenges:** Assembly and maintenance of kilometer-scale structures in orbit, precise beam control [15].
- **Safety risks:** Concerns about the effects of microwave and laser beams on human health and the environment [8].
- **Space debris:** Increased risk of collision with space debris and need for orbital cleanup strategies [16].
- **Social resistance:** Public concerns about safety and technology ownership [16].

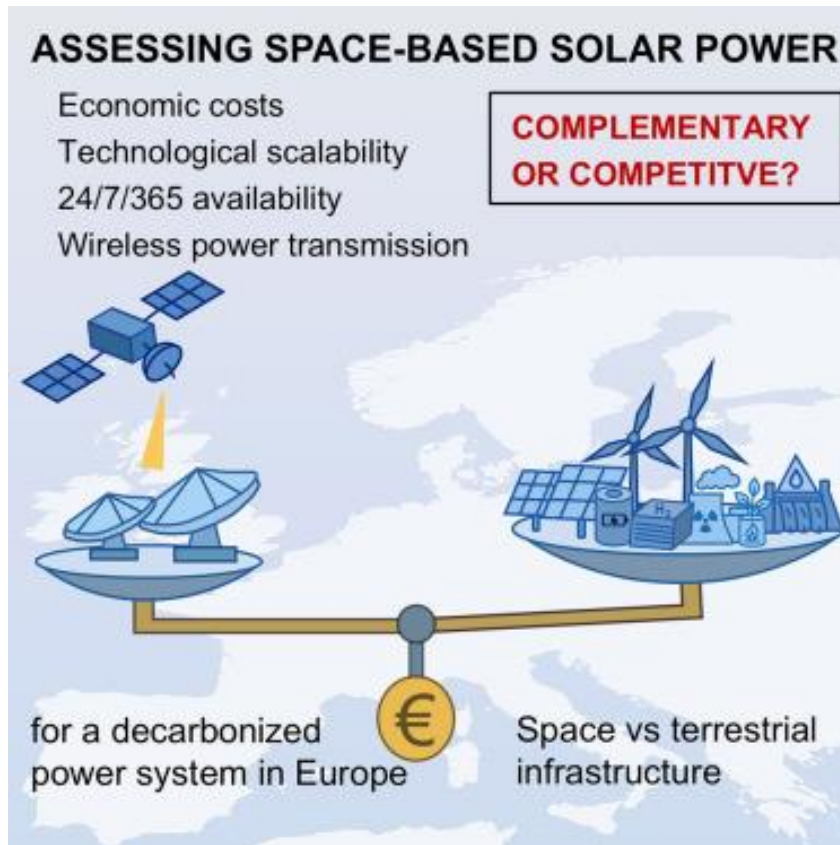


Figure 6. Assessment of space-based solar power in terms of economic costs, technological scalability, 24/7/365 availability, and wireless power transmission compared to terrestrial infrastructure. (Source: Elsevier [3])

3. RESULTS

The analyses conducted in this article indicate that:

1. Space-based energy harvesting technologies, particularly space-based solar power (SBSP) systems, have significant potential for sustainable and clean energy supply.
2. Microwave wireless power transmission technology is currently more mature and reliable than laser transmission, although both methods have their own technical and safety challenges.
3. Economically, SBSP is currently not competitive with terrestrial energy sources. Current LCOE ranges from \$0.6 to \$1.6 per kWh, which is much higher than terrestrial solar energy (approximately \$0.03 to \$0.06).
4. Reduction in space launch costs and advances in in-orbit assembly technologies are the most critical factors for improving SBSP economics. If launch costs are reduced to \$10 million and other parameters are improved, LCOE could reach \$0.03 to \$0.08 per kWh.

5. Space-based solar power systems can play a complementary role to terrestrial renewable sources and help decarbonize power systems by filling gaps caused by the intermittent nature of terrestrial wind and solar.

4. CONCLUSION

Space-based energy harvesting technologies, despite significant technical and economic challenges, are emerging as a long-term solution for sustainable and low-carbon global energy supply. Recent advances in space technologies, reductions in launch costs, and increases in solar cell efficiency have enhanced the feasibility of commercializing this technology by 2050.

To realize this potential, long-term investments in research and development, international collaborations, and the establishment of appropriate legal and safety frameworks are needed. Space-based solar power systems can not only contribute to energy security but also play a significant role in achieving net-zero goals and mitigating climate change.

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