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THE DEVELOPMENT POTENTIAL OF THE SPACE-BASED SOLAR POWER SECTOR IN THE CONTEXT OF SUSTAINABLE DEVELOPMENT PRINCIPLES IMPLEMENTATION

The global energy crisis represents one of the major challenges of the 21st century, posing a threat to all spheres of human activity and endangering not only sustainable economic growth but also potentially leading to humanitarian and environmental crises. The roots of this issue can be traced back to the 20th century, during the era of industrialization, when economic growth was prioritized and accompanied by the increasing exploitation of non-renewable energy sources.

At the present stage, the transition toward renewable energy contributes to addressing this problem to some extent; however, modern sources of green energy remain insufficient to fully meet global energy demands. Scientific and practical developments in this area have led to the emergence of the concept of Space-Based Solar Power (SBSP), which justifies the feasibility of continuously collecting solar energy in outer space using satellites and transmitting it to Earth [2; 6].

The utilization of space-based solar power is particularly relevant due to its potential to provide clean solar energy, thereby contributing to the achievement of Sustainable Development Goal (SDG) 7, which focuses on ensuring access to affordable, reliable, and clean energy sources. Furthermore, the adoption of this energy source positively correlates with the realization of SDGs 13, 14, and 15, aimed at climate action, the preservation of marine ecosystems, and the protection of terrestrial ecosystems.

Given the growing importance of developing activities related to ensuring access to space-based solar power, the selected research topic is highly relevant within the current stage of modern scientific inquiry.

The purpose of this study is to identify and conceptualize the geopolitical potential of the space-based solar power sector within the framework of sustainable development principles.

Methodology. The research is based on a comprehensive approach to examining the structure of actors within the space-based solar power (SBSP) sector in the global dimension. A comparative analysis will also be employed to assess and contrast the potential and capacity for geopolitical influence of the leading players in this sector on the global energy balance. The application of content analysis methods enables the evaluation of the main strategic foundations for the development of the SBSP sector at the level of key global actors.

The process of generating space-based solar power possesses a number of specific features and technical challenges, which determine that its implementation can be carried out only within the framework of large-scale projects – both at the level of major national powers and supranational entities (in particular, the European Union). The analysis of scientific and analytical sources [1; 9] demonstrates that the formation of the SBSP concept began in the 1970s and continues to develop throughout the 21st century (Table 1).

The analysis of the range of power plant models developed within the SBSP concept (Table 1) indicates that by 2020, five major global players had emerged in this sector, which, in the medium and long term, are expected to reshape the structure of the global energy system. It is also worth highlighting the significant efforts of India, which, due to its rapid economic growth, increasing demand for clean energy, and the development of its R&D sector, is actively advancing in the domain of space-based solar energy.

When considering the global advantages that have emerged at the current stage in the development and implementation of the space-based solar power (SBSP) concept as a prerequisite for decarbonization and the transformation of the global energy geopolitical landscape, several key directions can be identified [9; 11]:

1. Development of applied innovations aimed at improving technologies and equipment for solar power plants. India is implementing the SBSP 2030 Mission under the leadership of the Indian Space Research Organisation (ISRO). Within the framework of this mission, a low-cost, scalable model is being developed, building upon the experience of Aditya-L1 – India's first spacecraft for solar observation launched in 2023.

Table 1

List of power plant models within the space-based solar power (SBSP) concept

No.	Model Name	Characteristics			
		Frequency	Frequency	Frequency	Frequency
I	**United States**				
1.1	Developer: National Aeronautics and Space Administration (NASA)				
1.1.1	Reference Model (1979)	2,45 GHz	30–50 thousand MT	Geostationary Earth Orbit (GEO)	5 GW
1.1.2	Sun tower (1995 p.)	5,8 GHz	2–7 thousand MT	Medium Earth Orbit (MEO)	От 100 до 300 MW
1.1.3	SOLAR DISC (1997 p.)	5,8 GHz	8–70 thousand MT	GEO	От 1 до 10 GW
1.1.4	ISC (1998 p.)	2,45 GHz	22,4 thousand MT	GEO	1,2 GW
1.2	ALPHA (2012) (Developer: Artemis Innovation Management Solutions LLC)	2,45 GHz	25,3 thousand MT	GEO	2 GW
1.3	SPS-ALPHA Mk-II (2017) (Developer: Mankins Space Technology, Inc.)	2,45–5,8 GHz	9,2 thousand MT	GEO	1–2 GW
II	**Japan**				
2.1	SPS 2000 (1993) (Developer: ISAS)	2,45 GHz	n/a	Low Earth Orbit (LEO)	10 GW
2.2	Tethered (2001) (Developer: USEF / METI)	5,8 GHz	3,8 thousand MT	GEO	750 MW
III	**European Union**				
3.1	Sail Tower (1999) (Developer: ESA)	2,45 GHz	2,1 thousand MT	GEO	450 MW
IV	**China**				
4.1	OMEGA (2015) (Developer: Xidian University)	5,8 GHz	22,9 thousand MT	GEO	2 GW
4.2	MR-SPS (2015) (Developer: CAST)	5,8 GHz	10 thousand MT	GEO	2 GW
V	**United Kingdom**				
5.1	CASSIOPeiA (2017) (Developer: IECL – Institute for Civil Control)	2,45 GHz	2 thousand MT	GEO	2 GW

Source: compiled based on [1; 10]

2. In this context, Japan, considering the characteristics of SBSP power plant models (Table 1), is developing a joint JAXA–Mitsubishi SBSP satellite, planned for deployment by the end of 2025. One of its major technological achievements is the successful transmission of 1.8 kW of power over a distance of 55 meters using microwaves, which will be utilized for energy transmission from space to Earth.

3. Creation and testing of comprehensive technological infrastructure for the implementation of large-scale projects focused on the collection and transmission of space-based solar energy.

4. China has demonstrated significant progress in developing a mega-constellation system of SBSP satellites, consisting of high-precision SPS solar modules designed to collect solar energy in space and transmit it to Earth. The solar arrays used in China's project are engineered with an optimized angular trajectory, ensuring high average energy transmission efficiency. The technological design of these solar panels also incorporates the use of high-frequency radiation techniques [11]. This project – The Spacesail Constellation – is being implemented by the state-owned corporation Shanghai Spacecom Satellite Technology (SSST). Its key objectives include both securing access to space-based solar power and competing with the United States in this strategic energy domain.

5. The United States, guided by the outcomes of its own satellite launches, is conducting a testing program for solar power satellites under the leadership of NASA and the Defense Advanced Research Projects Agency (DARPA). This program aims to enhance microwave transmission systems for use in SBSP collection and transmission operations, with the implementation period projected to extend until 2032.

The fundamental principles of the development of the space-based solar power (SBSP) concept among leading actors in the global space sector are outlined in a series of strategic and programmatic documents, as follows:

1. NASA has not issued specific directives exclusively dedicated to SBSP; however, the agency has conducted detailed studies assessing the potential and challenges of this technology. NASA also contributes to the formulation of regulatory pathways for emerging technologies such as SBSP, which could serve as a future source of clean and stable energy. Certain studies project that the cost of SBSP-generated electricity could range from 30 to 80 USD per MWh by 2050 [3].

2. The European Space Agency (ESA) launched the Solaris Programme (2022), which focuses on fundamental and applied research regarding the feasibility of using SBSP to supply the Earth with clean and continuous energy. Within this programme, various satellite-based solar

energy concepts are being developed, with potential launches projected for the 2030s. The ultimate goal of the Solaris initiative is to contribute to achieving net-zero emissions in Europe [8].

3. Under the Space Solar Power Initiative (SBSP), China has approved plans to construct a massive solar power station approximately one kilometer in width, positioned in geostationary orbit at about 36,000 kilometers above Earth. This initiative aims to harness solar energy more efficiently than terrestrial methods, potentially marking a new era of clean and uninterrupted power generation. According to projections, a 1-kilometer-wide solar array in orbit could collect as much energy annually as the total amount of oil extractable from the Earth's surface [6].

4. At the current stage, India's strategy is primarily focused on commercial participation in the development of SBSP technologies. However, upon confirmation of viable opportunities and effective risk mitigation mechanisms, the state may engage in public–private partnerships (PPPs) in this field.

5. Japan's SBSP strategy is formalized in its Basic Plan for Space Policy, which has included SBSP since 2009. This plan is aimed at conducting key experiments on wireless power transmission from space to Earth. The initiative is supported by other national strategic programs and envisions active public–private collaboration in space research and technology development [5].

It can be observed that the space-based solar power (SBSP) segment is gradually demonstrating steady growth trends. Specifically, the market volume was estimated at USD 2.9 billion in 2023, increased to USD 3.1 billion in 2024, and is projected to reach approximately USD 6.6 billion by 2034, with an average annual growth rate (CAGR) of 7.9%.

This expansion is driven by the broader development of the space economy, both globally and among leading participants in this sector. According to forecast data, by 2034, the United States is expected to account for about 38% of the total global SBSP market, while the remaining 62% will be distributed among other players [4].

Conclusions. The world stands at a crossroads, facing a dual challenge: meeting the growing energy needs of an expanding global population while simultaneously combating climate change. The rising demand for energy – driven by accelerating electrification, the development of big data, and artificial intelligence – renders current energy systems increasingly unsustainable.

Although terrestrial renewable sources such as wind and solar play a crucial role, they remain intermittent and require vast land resources. One of the potential frontiers for ensuring a truly clean and abundant energy future lies in space-based solar power (SBSP).

The analysis of the potential and activities of the major global players in this sector indicates that, in the medium term, the geopolitical landscape of global energy will undergo significant transformation, enabling positive climate outcomes – specifically, a transition to clean energy that will contribute to reducing CO_2 emissions in the energy industry. Such transformations entail both environmental benefits and risks – affecting not only fossil fuel–based energy sectors but also terrestrial renewable energy systems. These emerging challenges will confront individual states as well as entire regions, emphasizing the need to identify optimal pathways for the green energy transition.

In this context, to prevent the monopolization of outer space, avoid interstate conflicts, and address the issue of space debris, it is essential to establish global partnerships at the level of international organizations and supranational alliances. The leading experience of key participants in the global SBSP market, combined with the applied results and competencies of Ukraine's space economy actors, can serve as a foundation for strengthening Ukraine's position in this field.

The development and implementation of national technologies for the collection and transmission of space-based solar energy will enable Ukraine to establish promising international partnerships in this area – fostering GDP growth, enhancing energy independence, and advancing progress toward the goal of climate neutrality.

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