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Potential for the Space Solar Energy Sector Development in Compliance with the Sustainable Development Principles

Abstract

The subject of the research is the history and peculiarities of the exploration and use of space by governmental institutions and private and commercial entities, which, with the beginning of the space age, has created several significant threats to the further development of humanity, due to non-compliance with the principles of sustainable development. The research methodology is based on reports, guidelines, statistical databases and forecasts of integration groups, specialised governmental and international institutions and their structural units for the study and control of space debris (Organisation for Economic Co-operation and Development, National Aeronautics and Space Administration, European Space Agency, United Nations), as well as the results of research by private companies in the space solar energy sector. The *purpose* of the paper is to analyse trends in the sustainable development of a globalised society in compliance with the principles of responsible use of outer space and to assess the potential of the space solar energy sector to ensure the sustainability of the competitive position of the world's economies. In today's environment, competitiveness and investment in high-tech industries are the driving forces of development that can lead to a country's transition to a fundamentally new level of development. The issue of efficient use of outer space encourages states to search for new technological opportunities for economic growth and inclusive development. *Conclusion*. The authors have analysed the trends in the use of space, the prospects for sustainable development of the space economy, its impact on the planet's ecosystem, and the main policy directions to help governments take the necessary measures for long-term planning to achieve sustainable and inclusive development. The publication examines space activities related to space debris reduction policies and sustainable solar energy production from space. The authors of the research developed guidelines for space debris mitigation and considered the benefits of using space solar energy.

Keywords

space economy, sustainable space development, rational use of outer space, principles of sustainable development, space debris

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1 Introduction

Countries' leadership in the face of global risks and challenges can only be ensured through accelerated economic growth and the development of high-tech sectors that provide long-term dynamic innovation benefits to all economic actors. Today's sectors include artificial intelligence, the Internet of Things, robotics, bio-, nano- and space technologies. Nowadays, the development of the space economy is a strategic priority for key innovator states, as it encompasses the complete set of resources and activities that generate and deliver value and benefits to humanity in the exploration, understanding, management and sustainable use of space. The space economy ecosystem includes all public and private entities involved in the development, provision and use of space products and services, ranging from research and development, production and use of space infrastructure (ground stations, launchers and satellites) to space products (navigation equipment, satellite phones, meteorological services, etc.), insurance, including the scientific knowledge gained from such activities (OECD Handbook, 2022). Every country in the world is consequently trying to promote the development of the space economy in order to increase its competitive advantages.

Nevertheless, the problem of efficient and rational use of space in terms of compliance with environmental requirements is currently on the agenda of specialised international institutions. The authors' preliminary study of trends in the transformation of the use and exploration of space to achieve sustainable development goals identified relevant initiatives by national and international institutions (in particular, the United Nations, the European Space Agency, NASA, the OECD Space Forum within the OECD Directorate for Science, Technology and Technology and Innovation, the Canadian Space Agency (CSA), the US National Aeronautics and Space Administration (NASA), the United Kingdom Space Agency (UKSA), the French National Centre for Space Research (CNES), the German Aerospace Center (DLR), and national specialised structures), in which companies are also actively involved (Antoniuk, Niameschuk, 2023).

2 Sustainable Development of Countries – Responsible Use of Outer Space

The key areas of national development adopted by the UN Sustainable Development Summit include affordable and clean energy, responsible consumption, production and innovation.To achieve zero carbon emissions, countries are rapidly decarbonising their electricity generation sources and looking for new ways to ensure stable and secure energy supplies (Niameshchuk, Bozhanova, Chala & Hlushchenko, 2021). The International Organisation for Social Progress produces an annual Social Progress Index for 169 countries. It carefully measures a country's performance in many aspects of social and environmental activities relevant to countries at all levels of economic development. According to the organisation's methodology, one of the components of sustainable social development is improving the quality of the environment, reducing emissions and transitioning to low-carbon production. According to the Social Progress Index assessment, the countries that most closely meet the criteria for sustainable development are Norway, Denmark, Finland, Switzerland, Iceland, Sweden, the Netherlands, Germany, Japan and Canada (Green, Harmacek, Htitich & Krylova, 2022). The analysis of Ukraine's Social Progress Index in 2022 and its position in the global ranking showed that Ukraine entered the second cluster of countries in social progress, which includes the countries of Eastern Europe and is characterised by a large gap in social well-being. The country was ranked 59th in the world for environmental quality, 68th for particulate matter and 110th for air pollution (Antoniuk, Anapriuk, 2023).

Increased government spending on space exploration worldwide, an increase in the share of defence spending in national budgets to 45% in 2022 compared to 41% in 2021, increased spending on military space programmes amid rising tensions due to Russia's invasion of Ukraine and growing rivalry with China in the Western Pacific underscore that in the context of globalisation and economic challenges, high-tech industries, including space, play a strategic role in the competitiveness of states. The European Space Agency (ESA) publishes an annual Space Environment Report (ESA's Space Environment Report, 2021), which provides a transparent overview of global space activities, assesses the environmental impact of the industry, and identifies how international debris reduction measures are improving the long-term sustainability of space (European Space Agency, 2023).

For more than 20 years, the Inter-Agency Space Debris Coordination Committee (IADC) has been working effectively, bringing together 13 specialised government agencies that set trends in the development of the global space economy: Canada, China, India, Italy, Japan, the United Kingdom, the United States, Spain, Italy, Canada, NASA, Germany, South Korea, Russia and Ukraine (Inter-Agency Space Debris Coordination Committee, 2023). The IADC is an international forum for intergovernmental coordination of space activities on debris reduction policies (Inter-Agency Space Debris Coordination Committee, 2023). Today, the Inter-Agency Space Debris Coordination Committee organises the leading countries within the forum into a Steering Group and four working sub-groups, which are responsible for measuring the amount of debris (WG1), monitoring the environment and maintaining a specialised database (WG2), protecting against the formation of debris (WG3) and mitigating the consequences for space and its users (WG4).

According to the approach of the Inter-Agency Space Debris Coordination Committee, any activity carried out in space must comply with the norms for protecting the unique nature of LEO (Low Earth Orbit up to 2 thousand kilometres from the Earth's surface) and GEO (Geostationary Orbit up to 35.8 thousand kilometres from the Earth's surface) orbits (Inter-Agency Space Debris Coordination Committee, 2023). These standards are based on the results of previous studies: since 2005, the environment in LEO orbit has been characterised as unstable due to a large amount of space or orbital debris (IADC Space Debris Mitigation Guidelines, 2021).

It is estimated by the Organisation for Economic Co-operation and Development that the amount of orbital debris has increased significantly over the past 15 years, and the social and economic impact of potential collisions with space debris could be dramatic due to cascading effects. A major concern is that the density of orbital debris is reaching levels that could cause the so-called Kessler Syndrome, a catastrophic and irreversible chain reaction of in-orbit collisions between debris and operational satellites, which could render some orbits unusable, and the concentration of debris could even block access to some of them. The results of a study by the Environmental Monitoring Working Group of the Intergovernmental Space Debris Coordination Committee show that as of January 2023, the most important problems of environmental compliance in outer space were as follows:

– An increase in space debris. While in May 2021, NASA tracked 27 thousand objects (NASA, 2021), by the end of 2022, according to ESA, this number had already increased to 30 thousand (European Space Agency, 2023). In January 2023, according to the IADC, more than 30 thousand objects larger than 10 cm, 900 thousand larger than 1 cm and 128 million objects between 1 mm and 1 cm will be floating in space. The presence of many objects in LEO orbit causes a significant density of the debris layer, making it difficult for solar radiation to penetrate the Earth's atmosphere.
– A significant increase in the number of launches, in particular of vehicles into LEO orbit. The current number of launches is ten times higher than in 2000. Correspondingly, the number of launch vehicles and their parts returning to the Earth's atmosphere has increased significantly.
– Increase in the number of on-orbit manoeuvres. The deployment of large constellations of satellites requires rapid response and motion control mechanisms;
– an increase in the number of object fragmentation events. The average annual rate of uncontrolled orbital fragmentation over the last 20 years has been 12 events; in 2021 there will be 6 such events;
– insufficient rate of objects being removed from protected regions at the end of their missions. The proportion of spacecraft that successfully apply space debris mitigation measures is 60-90%. However, the success of these measures is largely due to the favourable effects of natural physical processes in orbit. For other orbits, the success rate is much lower – 10-40 % (by 2017) (IADC Report, 2023: 5-6).

According to the IADC methodology: "Space debris are all man made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non functional." ("Space debris are all man made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non functional.") (IADC Statement, 2022: 6). Space debris consists of both natural and man-made objects. Natural objects include parts of meteorites orbiting the Sun, while artificial objects are those built by humans or formed as a result of human exploration and use of space and orbit the Earth (NASA, 2021). Orbital debris consists of satellites that have outlived their usefulness (about 2.85 thousand units in December 2020), parts of launch vehicles that did not burn up in the Earth's atmosphere (1.95 thousand units), and other objects of various origins (The United Nations Office for Outer Space Affairs, 2023). Orbital debris poses a particular threat because, due to their small and very small size, they drift in orbit at high speeds (about 17,000 miles per hour) and cannot be detected and tracked by Earth-based monitoring tools. The collision of these elements with each other and with satellites, launch vehicles, etc., results in further fragmentation of debris, an increase in the number of debris fragments from damaged useful objects, and thus further contamination of LEO orbits. Low Earth orbits are a unique but limited natural resource. The compaction of the orbital debris layer threatens both the natural processes of sunlight distribution on the surface of the planet and further effective space activities. To ensure the success of monitoring and remote sensing projects, it is essential to adhere to the principles of rational use of natural resources. Neglecting these principles can lead to complications and impede progress, ultimately jeopardising the sustainability of the environment. The cleanliness of Earth's orbits is key to the sustainable operation of satellites for various purposes and to the safety of manned spacecraft.

The main objective of the measures recommended by the international community is to slow down and reduce the effects of space pollution. In particular, the Space Debris Elimination Guidelines provide for actions at the planning stages of space missions, design, manufacture and operational use of spacecraft and launch vehicle stages in orbit (Table 1).

The Intergovernmental Space Debris Coordination Committee calls on space agencies to passivate, i.e., to utilise all the energy stored on a spacecraft to prevent its destruction. Typical passivation methods include removing or burning excess fuel, discharging battery coolers and venting pressure vessels (IADC Space Debris Mitigation Guidelines, 2021). The possibility of using passivation technology is one of the most promising areas of innovative spacecraft design.

TABLE 1 Space debris mitigation guidelines

Principle	Essence	Threat
Reduce waste generation during regular missions	Strengthening facility design	Fragile launch vehicle designs in the first decades of the space age
Minimising the destruction of assets during operation	Prevention of accidental destruction of equipment during emergency modes	Lack of recycling and passivation mechanisms
Reduce the likelihood of accidental collisions in orbit	Careful design and monitoring of the launch trajectory and in-orbit stay	Increase in the amount and mass of untracked space debris
Avoid intentional destruction or damage to equipment	Performing the necessary destruction operations in low orbits to burn fragments	Lack of destruction phase in the mission plan, premature failure of the launch vehicle
Preventing equipment damage due to accumulated energy	Use of passivation technology for launch vehicles after completion of missions; licensing of launches	Explosions of upper stages and upper stages of launch vehicles
Limit the presence of objects in LEO after the completion of missions	Controlled removal of vehicles from LEO orbit	Fall of the remaining parts to the Earth
Limit the presence of objects in GEO after the completion of missions	Removal of assets from GEO	Probability of collisions

Source: compiled by the authors on the basis of (IADC Space Debris Mitigation Guidelines, 2021; The United Nations Office for Outer Space Affairs, 2023)

3 Sustainable Development of Countries – the Potential of the Space Solar Energy Sector

The identified trends in the pollution of near-Earth orbits raise the issue of finding additional ways to collect and use solar energy in the interests of the global economy. Rapid population growth and the trend towards industrialisation are factors in the development of global electricity consumption. Decarbonisation and investment in renewable energy research are becoming key issues for the growth of highly developed countries.

In early 2022, the European Space Agency commissioned two independent studies from Frazer-Nash and Roland Berger on the cost-effectiveness of solar power in space. Roland Berger's experts define space solar power as the collection of solar energy by a spacecraft in Earth orbit and its return to Earth (Hader, Hoyer, 2022). The technological advantage is round-the-clock energy collection and transmission due to the absence of day/night cycles, and a high solar energy collection factor, since with ground-based systems more than half of the solar energy is lost on its way from the Sun to the Earth due to the scattering effect of the Earth's atmosphere. The mechanism of operation of solar energy collection devices from orbit is to convert sunlight into electricity, which is transmitted to Earth wirelessly, most likely using radio frequency waves. Thus, the system can supply "green" electricity to the grid 24 hours a day, seven days a week (Hader, Hoyer, 2022). Analysts at Grand View Research, a research and consulting company, have estimated the global space solar market at 519.1 million USD in 2022. They forecast its growth by 9.1% over the next eight years. North America (the United States, Canada and Mexico) dominates the space solar energy production market, accounting for 41% of the industry's global revenue.

The rest of the market is covered by Europe (UK, Germany, France) and the Pacific Rim (China, Japan, India, South Korea, Australia) (GVR, 2020). At present, the production of solar energy in space involves several risks: the need to develop and build the structural elements of large modular structures in orbit, research into the methods and risks of using wireless networks to ensure the functioning of the technology in space, and the study of ways of transferring the solar energy produced to Earth (Hader, Hoyer, 2022). However, along with the risks, the use of solar energy in space promises many benefits (Table 2).

Experts from the US firm Frazer-Nash Consultancy predict that the cost of the first space-based solar power plant to come online in 2022 will be 9.8 billion EUR, with operating costs of 3.5 billion EUR over a 30-year lifetime. Due to economies of scale, subsequent systems to be launched will be cheaper. The cost of launching the tenth space power plant is estimated at 7.6 billion EUR, with operating costs of 1.3 billion EUR.

By contrast, the cost of electricity is estimated to be 206 EUR/MWh for the first launch and 156 EUR/MWh for the tenth launch, making space solar power technology competitive with all leading low-carbon energy sources (Frazer-Nash Consultancy, 2021). Once the technical risks of space solar power generation are reduced, investors will be able to set a financial threshold; at a 10% threshold, the levelized cost of electricity from the first space solar power plant can be compared to the cost of building a new nuclear power plant (109 EUR/MWh vs.

TABLE 2 Advantages of using space solar energy

Economic	Environmental	Strategic
Stability of electricity prices: by reducing dependence on imported energy, it is possible to create a more resilient economy that is less sensitive to price increases caused by global risks beyond our control. This will not only benefit people in the short term, but will also strengthen long-term economic stability and security.	Reducing carbon and other pollutant emissions: space solar power will reduce dependence on fossil fuels for electricity generation and significantly reduce emissions of harmful substances into the atmosphere.	Intensification of R&D and technological progress: research into space solar energy production methods will contribute to the development of technologies and knowledge that will help create new products and markets to improve the living conditions of mankind.
New export opportunities: energy production using space technologies can significantly increase export potential. Space energy can be exported outside the country of origin.	Diversification of energy sources: space technologies make it possible to generate electricity for daily power supply, which will allow to abandon oil and gas power plants and accelerate the transition to stable renewable energy sources, creating a diversified and reliable energy complex.	Grid integration: the technology can provide a continuous supply of energy that is not sensitive to weather conditions, making it a useful tool for maintaining grid stability in the future energy system.
Independence and security of the national energy complex: space energy will reduce the dependence of countries on imports of gas and other energy carriers, which will guarantee energy security and can be used as a strategic tool.	Avoidance of land use for terrestrial technologies: space energy is a land-saving electricity generation technology that uses only 5 m^2 of land per MWh, which is much less than most alternatives.	International cooperation: space energy research will strengthen innovative cooperation between states and the exchange of technologies and developments.

Source: compiled by the authors on the basis of (Hader, Hoyer, 2022)

108 EUR/MWh). At a 5% threshold levelized cost of electricity, the first system will cost 69 EUR/MWh, making it more cost competitive than any other alternative (Frazer-Nash Consultancy, 2021). The company also suggests that space-based solar energy production can replace the use of oil, coal and natural gas, and predicts a doubling of demand for space stations between 2040 and 2070, based on an estimate of the cost of building and launching a space power plant. Experts also emphasise the reduction in the amount of land required to site space solar power repeaters, which will be 5.9 m^2/MWh, significantly less than that required for solar photovoltaic power plants (13-22 m^2/MWh) or wind power plants (99 m^2/MWh).

4 Conclusions

The space economy plays an important role in sustainable competition among states and is a strategic aspect that ensures high competitive advantages of global leadership. The development of high-tech sectors can not only contribute to a rapid increase in the competitive position of states, but can also become a key to achieving the UN Sustainable Development Goals, increasing sustainable competitiveness and improving the Social Progress Index. The implementation of measures for the efficient and rational use of space and the launch of a large-scale space energy production programme will encourage states to master space technologies and help increase their competitiveness on the global stage. The international use of space solar energy can become a tool to compensate for the consumption of unstable renewable energy sources, provide an alternative to nuclear power and reduce energy dependence on fossil fuels. Investment in research, development and implementation of renewable solar energy production and distribution technologies can significantly increase the economic benefits of space energy and accelerate the achievement of net-zero in the coming decades.

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