Zsolt Hetesi[1] – Zsófia Biró[2]

Bon Voyage: Sources of Energy for Space Exploration and Its Current Regulatory Insights

Except for a brief mention at the beginning, the paper deals with the technical and legal aspects of space exploration and, to a lesser extent, the energy sources used in the conquest of space. The idea of energy from space is not new. As early as 1923, Konstantin Tsiolkovsky envisioned a system based on mirrors placed in space to send amplified sunbeams back to Earth. A bit later, in 1941, the famous science fiction writer Isaac Asimov came up with a similar idea (ESA 2022a), and in 1975, the physicist Gerard K. O'Neill took the idea one step further, bringing it even closer to the present day: he had already written that "manufacturing facilities in high orbit could be used to build satellite solar power stations from lunar materials" (O'Neill 1975: 943). If we look at the 20th century space science fiction literature, we can see that the various ways of producing energy that appeared in novels, which seemed impossible and futuristic at the time, are beginning to materialise, or are already partially operational. It might be worth picking up today's science fiction literature to get a more accurate picture of our own future. This paper has a similar goal: to show what kind of energy production and supply opportunities will exist during the exploration and eventual colonisation of space at different locations and distances.

1 University of Pécs, Faculty of Natural Sciences; Ludovika University of Public Service, Faculty of Water Science; ORCID: https://orcid.org/0000-0002-4250-4050; e-mail: hetesi.zsolt@uni-nke.hu
2 University of Pécs, Faculty of Law; ORCID: https://orcid.org/0000-0001-8372-4896; e-mail: dr.biro.zsofia@gmail.com

DOI: https://doi.org/10.36250/01209_06

POSSIBLE ENERGY SOURCES IN AND FROM OUTER SPACE AND PHYSICAL BACKGROUND

The energy sources that have been and may be used in the future to explore space are characterised by diversity, the complexity of the challenges and the evolution of technology. Among the challenges, the energy density of the propellant, the long distances and the need to overcome large potential fields are all tasks that have only just begun in the little more than six decades of space exploration. Future space missions, whether human or automated, will go much further, faster and more efficiently than ever before, but they will require several technical leaps that, for the present, exist more in science fiction literature than on the drawing board. The next two sections define the basic concepts needed to understand the rest, in terms of distance and speed scales, and the following ones the ways and means of using energy.

Distance and velocity basics

Space is characterised by distances that are simply too great for human experience, since for most of us, journeys of a few hundred or a few thousand kilometres are not an everyday occurrence, the current human record being the Moon, with an average distance of 384,000 km from Earth. However, this distance is also small compared to one of the most expressive units of measurement in the solar system, namely the AU, the average Earth–Sun distance, or 149,600,000 km. While the Moon is 0.002 AU from the Earth, the Kuiper Belt, for example, which follows the planets of the Solar System, is about 50 AU away, while the Oort cloud, which lies at the boundary[3] of the Solar System, is between 2,000 and 200,000 AU away. The distance to the nearest star, Proxima Centauri, is so large that it is not practical to express it in AU, about 268,770 AU. Therefore, light years are used for distance measurements in interstellar space, even though

[3] In a strict sense, the boundary of the Solar System can be defined in several ways. One of the most commonly accepted is the heliopause, the boundary where the interstellar medium stops the solar wind.

the light year is small at intergalactic distances, it is still common and has not evolved into a larger unit, unless *parsec* counts as one.

Table 1
Average distances to some celestial bodies

Celestial body	Km	AU	Light year
Moon	384,000	0.002	1.3 light seconds
Sun	150,000,000	1	8 light minutes
Jupiter	602,890,000	4.1	33.5 light minutes
Proxima Centauri	40×10^{12}	268,770	4.3 light years

Source: Compiled by the authors

Of all the man-made objects, the Voyager 1 spacecraft has gone the furthest, currently travelling at a distance of 160 AU, and 4 other man-made objects have exceeded the third cosmic velocity, Pioneer 10 and 11, Voyager 2 and New Horizon.

The spacecraft can be divided into Earth orbiting, interplanetary and interstellar groups based on the location of the mission. This is essentially the same if the objective is not only a mission but also the establishment of a base around the Earth (e.g. the International Space Station), on the Moon (which is not yet considered interplanetary space) or on other planets. The exploration of interstellar space can be regarded as purely theoretical for the time being.

Addendum. Speeds required to explore space: The escape velocities

The force that organises the cosmos on a macroscopic scale is gravity. Therefore, getting into space means, first of all, investing the energy to accelerate the spacecraft to the first cosmic velocity for orbital insertion, the second for interplanetary missions and the third for interstellar missions – although the latter is not entirely true, see later.

Table 2
Cosmic velocities

Cosmic velocity	Velocity [km/s]	Note
First	7.9	Orbit
Second	11.2	Earth leaving orbit
Third	42.1	Orbit out of the solar system

Source: Compiled by the authors

The first cosmic velocity, or escape velocity, means that at least this speed is required to leave the surface of the Earth (interpreted as a cannon shot with a velocity at least equal to the fall towards the surface of the Earth's curvature). At the second cosmic velocity, the speed of the device would decrease to 0 at an infinite distance from the Earth, and at the third cosmic velocity, at an infinite distance from the Sun. The latter two mean that the device would escape from the potential of the Earth or the Sun, because its velocity would decrease to zero at the infinitely distant point from the centre of attraction, i.e. its kinetic energy would be "consumed". It follows from this interpretation that all three velocities are different from planet to planet.

To calculate the velocity required for an orbital path, the centripetal force and the force of gravity must be equated because this path can be formed if the only force acting is gravity, and that is the force that keeps the object in orbit:

$$\frac{mv^2}{R} = G\frac{Mm}{R^2} \rightarrow v_{c1} = \sqrt{\frac{GM}{R}} \quad ,$$

where M is the mass of the planet and *R* is its radius. The way to calculate the second and third cosmic velocities is the same, one has to write down the mechanical energy at an infinite distance from the centre of gravity (second cosmic velocity: Earth, third: Sun). Assume that the kinetic energy resulting from the minimum escape velocity at infinity will be 0, the minimum velocity at which you can travel infinitely far:

$$\frac{1}{2}mv^2 = G\frac{Mm}{R} \rightarrow v_{c2} = \sqrt{\frac{2GM}{R}} \quad .$$

For the second cosmic velocity, M is the mass of the Earth, for the third cosmic velocity, the mass of the Sun and R is the radius of the corresponding celestial body's orbit (NASA 2000).

The third cosmic velocity does not necessarily have to be reached during the launch, and a device can still leave the Solar System even if it was launched from Earth at a lower velocity. An example is Voyager 1, mentioned earlier, which was able to gain extra speed by taking advantage of the gravity assist effect of the outer gas planets.

Similarly, the Earth's rotation helps launches, where the energy required to launch the device into space as close as possible to the equator is significantly less because the Earth's rotation "helps". The famous launch sites are therefore as close as possible to the equator: Kourou (ESA), Baikonur (Russia–Kazakhstan) and Cape Canaveral (USA).

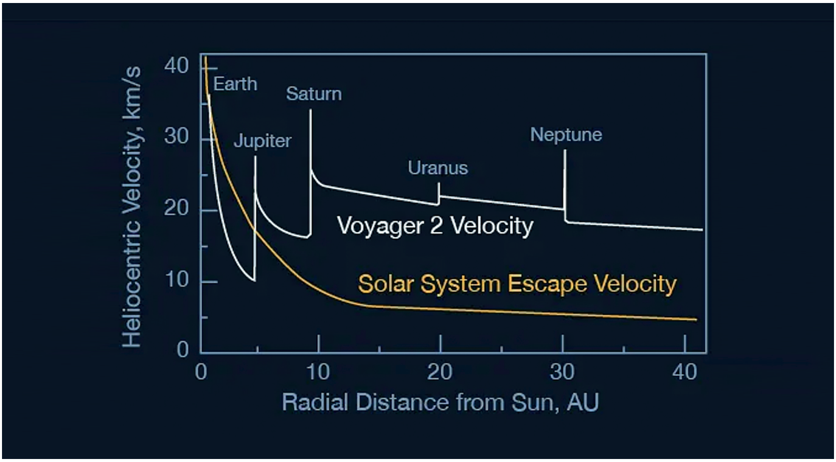

Figure 1

Gravity assist during the Voyager 1 mission

Note: It can be seen that encounters with giant planets increased the probe's speed to well above the third cosmic velocity.

Source: NASA s. a.

Environmental criteria for energy source design

Understanding the space environment and its impact on space devices is fundamental to the successful design and operation of solar cells for various space missions. Moreover, the extreme conditions of space, and the almost total absence of conditions for life, make it difficult to launch instruments or even astronauts. Plans for a permanent human presence on the Moon or a mission to Mars in the not-too-distant future, although technically feasible, are still at the limits of humanity's capabilities.

The development of technology is usually not linear because of the leaps that follow a major discovery, but rather almost stagnant, then bouncing back and so on. At the beginning of the space age, the first space devices (Sputnik 1, early Apollo programme) did not have integrated circuits, and the computer for the moon landing was a very rudimentary device by today's standards. Technological progress in the last period was not so much in launch technology as in the electronics and information technology of the operating system.

Table 3
Challenges of space exploration and technological responses

Challenge	Technological response
Overcoming long distances	New engine types, new propellant, taking into account NASA TMA principles and TLR scale
Long-time flights	Hibernation, dehibernation systems to maintain life functions that can last for centuries
Hostile environment	Life support systems, spacesuits, space stations, colonies

Source: Compiled by the authors

According to a summary from the Johns Hopkins University Applied Physics Laboratory (JHUAPL 2018), in the near future, the speed of smaller devices could be accelerated by a factor of 4, reducing the travel time to 17,500 years, instead of the current technology's travel time of about 75,000 years. More importantly, the material suggests a target of 20 AU/year in the not-too-distant future.

Another important area where progress needs to be made to overcome technological barriers is in reducing the mass ratio. By definition, mass ratio is the ratio of wet mass (rocket + propellant + payload) to dry mass (rocket + payload):

$$\frac{m_{wet}}{m_{dry}}\ .$$

The less propellant required to deliver the same payload (rocket body + payload) to the target, the smaller the number. For multi-stage rockets (see later), this number is between 8 and 20. It is worth noting that this means that between 12.5 and 5% of the mass of the rocket is non-fuel, i.e. the residual mass of the rocket plus the payload.[4]

All the technologies that are classified by NASA Technology Readiness Level (hereinafter TRL) as TRL 1-5 are not yet the subject of a scientific discourse that would make them part of space exploration in the foreseeable future. This includes energy sources and propulsion systems that exist only on paper, not even on a semi-industrial scale or ideas from science fiction literature. Examples include the fusion reactor, travel through wormholes and bending space.

A permanent base on the Moon or Mars, for example, presents a different technological challenge. In both cases, energy supply is probably the least problem, because the solar constant on the Moon is practically the same as on Earth, and there is no atmosphere to limit the radiation, yet on Mars it is 40% of that on Earth (Appelbaum–Flood 1989). The much greater difficulties here are food, clean water and filtering cosmic radiation, among others.

According to the NASA Marshall Space Flight Center, the space environment shall be described with seven main components: neutral thermosphere (atmospheric density, density variations, atmospheric composition), thermal

[4] The definition of the mass ratio is a consequence of the Tsiolkovsky equation, which indicates the maximum velocity that can be achieved by the thrust of the outflowing gas jet.

(solar radiation, radiative transfer, atmospheric transmittance), plasma (ionospheric plasma, auroral plasma, magnetospheric plasma), meteoroids–orbital debris (distribution by size, mass, velocity and directionality), solar (solar physics and dynamics, geomagnetic storms, solar activity predictions, solar–geomagnetic indices, solar constant, solar spectrum), ionising radiation (trapped proton–electron radiation, galactic cosmic rays, solar particle events) and geomagnetic field (natural magnetic field). In addition to this: gravitational field and mesosphere (Bedingfield et al. 1996: 2).

Looking at each environmental factor one by one, it can be concluded that plasma, which is the flow of charged particles ejected from the solar corona, poses a serious threat to the long-term operation of space devices, as it can cause surface charge, electrostatic discharge, energy loss and short circuits in electronic and photovoltaic components. Furthermore, when the solar wind reaches the Earth, it interacts with the magnetic field, so incoming charged particles tend to get trapped in the region called Van Allen radiation belts. It is therefore obvious that space devices orbiting at such altitudes must be able to withstand such conditions, i.e. the effects of radiation. Likewise, the dangers associated with indirect ionising radiation are also problematic for the stability of space assets, as they can release charged particles in materials. The next factor responsible for space-induced degradation is thermal fluctuations. Thermal cycling is very dangerous for the materials and devices of space assets, as it can cause thermal stresses and eventually cracking of some components or detachment of several layers. The factors discussed so far are also seriously influenced by the activity of the Sun. It is also necessary to mention the neutral atmosphere, which affects the service life of space device components primarily due to the presence of atomic oxygen and high vacuum. Finally, meteors and space debris, which pose a threat to space devices due to the disastrous consequences of possible collisions, should be mentioned as a final but important factor (Verduci et al. 2022: 6).

ENERGY SOURCES BY TYPE

Rocket propulsion, and motion in space in general, is facilitated by propulsion based on Newton's third axiom of action–reaction, where the motion of the device is caused by matter flowing out of the device at high speed, and thus the device is subject to thrust due to the action–reaction principle.

In the earliest phase of the space age, the challenge was to get spacecraft out of the atmosphere, initially using only chemical propellants. Even the earliest rocket propellants were based on a chemical reaction, using Chinese gunpowder propelled firecrackers.

For chemical propellants, the exhaust velocity out of the rocket can be between 3,000 and 5,000 m/s,[5] for a single stage the top speed at which the rocket can run out of fuel is high if a significant part of the launch mass is fuel, but it is obvious that the mass ratio (m_{wet}–$m_{dry)}$ is limited, so the top speed is limited. If a single stage rocket is to reach interplanetary space (where a velocity of $v = 11.2$ km/s is required, see earlier), the mass ratio should be around 13 for an exhaust velocity of 4,500 m/s. To give an example, for a hen's egg the mass ratio of the shell to the yolk and protein of the egg is 10, and for a bag of cereal 100, so it can be seen that it is almost impossible to reach interplanetary space with a single stage rocket, leaving a meaningful mass to be placed. To add to the rocket's velocity ratios, the Tsiolkovsky equation must be supplemented by the velocity-reducing effect of the Earth's gravity field, which makes the situation even worse.

Multi-stage rockets were invented to solve this problem, where the first stage and later the second stage are ejected from the launcher during the launch and fall back into the Earth's atmosphere (or to the surface of the Earth), where they burn up. This can increase the relative size of the payload that can be delivered by up to a factor of ten, compared to the single stage rocket.

[5] German A4 rocket's outflow speed was 2,100 m/s.

Chemical propellants

Chemical propellants are generally two components in their operating principle, i.e. they burn a fuel and an oxidising agent together. In the first rockets, because they operated in the atmosphere, the propellant was gunpowder (one component), but later a mixture of ammonium perchlorate (oxidiser) + aluminium powder (fuel) was developed, but solid propellants were not widely used in space exploration because of their low specific burning rate.

For chemical propellants, the following are important considerations: specific thrust, fuel density, combustion temperature, combustion stability and fuel toxicity. While thrust is important for the maximum achievable speed, density affects the design of the rocket, exhaust velocity and heat of combustion affect the design of the engine and nozzle.

Liquid propellants have a higher outflow rate and have been used in practice from the first space rockets until today. One of the most common is hydrazine (N_2H_4). Stable at room temperature, it decomposes almost explosively at higher temperatures and can exhaust at 4.5 km/s with a properly designed nozzle. Both hydrogen peroxide and kerosene + liquid oxygen are used. Kerosene was mainly used in Soviet rockets and its environmental impact is less severe than that of hydrazine. Hydrazine is a very dangerous and toxic compound. It is a carcinogenic and irritating substance, highly toxic when released into the environment, and its replacement has become a major issue of our time. Several attempts have been made to make the propellant "green", one of the most promising being the liquid methane + liquid oxygen two-component propellant. Efforts are being made to ensure that methane does not come from fossil sources but is renewable in origin.

Electromagnetic reactive propulsion

In case of electric propulsion, there are several types of ionised propellants that work on several principles: electrostatic, electrothermal and electromagnetic.

In the case where the reactive force is based on the Coulomb repulsion, we speak of electrostatic propulsion. In this case, the mechanism can be, for example, an ion engine (one of the most common). In the engine, gas is ionised and the ions are accelerated by an electric field parallel to the direction of travel. Electrons stored in the spacecraft are injected into the outgoing ion stream so that the outgoing cloud is neutral. While the engine uses only Coulomb separation, it is purely electrostatic. The ion engine of Deep Space has achieved an exhaust speed of 4.5 km/s. However, the typical thrust is less than that of chemical propulsion, and this type of propulsion works in space.

In electromagnetic, or plasma, propulsion, the acceleration of the ions is done by the Lorentz force, so that the electric field is perpendicular to the outflow. In these devices, the exit velocity is high, 20–50 km/s, but the thrust is relatively small. Devices of this type are typically used in a vacuum.

In summary, ion and plasma thrusters are not suitable for enabling lift-off from a planet, but they can operate efficiently in space because little material needs to be transported to generate thrust (the mass ratio is small). *Figure 2* shows the specific impulse as a function of thrust for different engines and propellants. Specific impulse measures how efficiently a reactive engine uses propellant: in effect, it measures how many seconds it would take for a given propellant to accelerate the initial mass of a given engine to 1 g.

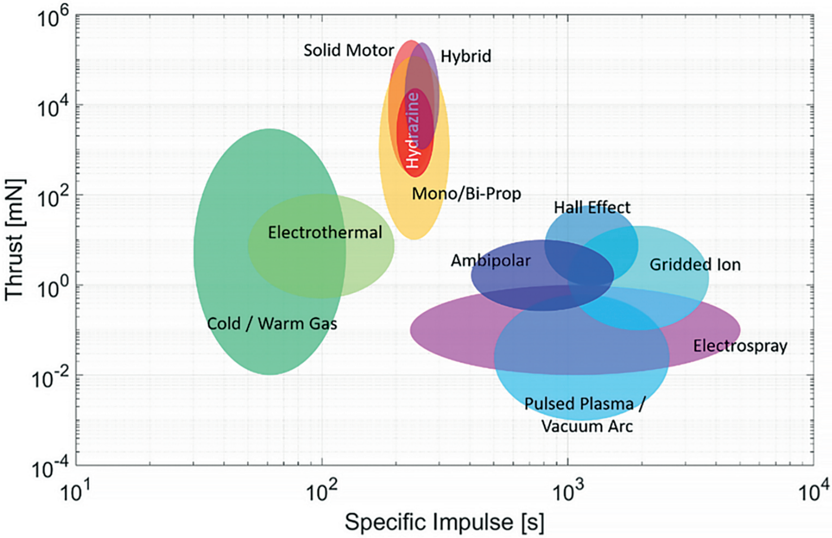

Figure 2

Current chemical propellants (left and top centre) and electricity-based propulsion (ion and plasma)

Source: NASA 2023

Nuclear energy

Radioisotope Thermoelectric Generator (hereinafter RTG) has been the main power source for the U.S. space programme practically since the beginning. The high decay heat of plutonium-238 (0.56 W/g) enables its use as an electricity source in the RTGs of spacecraft and satellites. Because of the mainly intense alpha decay process with negligible gamma radiation, no significant shielding is required because the alpha radiation is practically absorbed by a sheet of paper. Americium-241, with 0.15 W/g is another source of energy used by the European Space Agency, though it has high levels of relatively low-energy gamma radiation, so requires more shielding.

The next step is the reactor-powered propulsion system, which so far only exists in concrete design, is based on the fact that the heat provided by the reactor heats up a working gas, typically hydrogen, which flows through a nozzle into space, creating thrust. Since reactors are compact devices, the mass ratio can be as low as 7, compared to 10–20:1 for chemical rockets. Because the energy source is efficient, the outflow rate is high, partly because the gas medium is hydrogen and the molecular weight of hydrogen is small.

Both Soviet and American technology have been at the forefront of compact reactor construction since the beginning, and such reactors have powered nuclear submarines. Developed by Los Alamos National Laboratory, Heat Pipe Power System (hereinafter HPS) fast reactors operate at 400 kW(t) of power, coupled with 100 kW(e) of electricity generation, using a Stirling or Brayton power cycle. Here (e) stands for electric and (t) for thermal power. These reactors can be used not only to power rockets or interplanetary spacecraft but also to power colonies. This latter use is obvious because photovoltaic power generation alone will not be sufficient for the Moon or Mars, and geothermal (not in the strict sense of "geo") power is not available either, for lack of planetary volcanism. The Moon has 14 days of night due to its tidal locking, and at Mars's distance, the solar constant is 40% of that on Earth.

Small modular reactor (hereinafter SMR) technology, which refers to reactors that are smaller than conventional reactors, can be assembled from parts and easily scaled up, allowing for rapid replacement, easy repair and reliable operation for decades. Progress in the management of nuclear waste is also encouraging, as Russian technology has come close to completing the fuel cycle for the Beloyarsk BN-600 reactors, which means that there is essentially no or much less spent fuel.

The question of the fusion energy of the He-3 isotope will be discussed later. In the following, we will look at the regulation of nuclear energy in space law, and then return to the analysis of other energy sources.

Energy-related regulations in international space-related treaties

If we take an interdisciplinary approach, the Outer Space Treaty and the Moon Agreement, as well as the Artemis Accords are inescapable. Article IV of the 1967 Outer Space Treaty already states that nuclear weapons must not be placed in orbit around the Earth, placed on celestial bodies or otherwise kept in outer space. (By the way, this is also stipulated in Article 3 of the Moon Agreement concerning the Moon, orbits around the Moon and orbits leading to it.) This, of course, does not exclude the use of nuclear energy as a resource in space, since this type of energy (RTG) has also been used on deep space missions, such as Voyager 1–2 (Petrocelli et al. 2023: 9).

Principles Relevant to the Use of Nuclear Power Sources in Outer Space and the Safety Framework for Nuclear Power Source Applications in Outer Space

The United Nations Office for Outer Space Affairs (hereinafter UNOOSA) implemented the decisions of the Committee on the Peaceful Uses of Outer Space (hereinafter UN COPUOS). UNOOSA recognises "that for some missions in outer space nuclear power sources are particularly suited or even essential owing to their compactness, long life and other attributes" and "that the use of nuclear power sources in outer space should focus on those applications which take advantage of the particular properties of nuclear power sources". It has adopted a set of principles (see in next paragraph) applicable "to nuclear power sources in outer space devoted to the generation of electric power on board space objects for non-propulsive purposes", for radioisotope systems and fission reactors as well (World Nuclear Association 2021).

Session 47/68 of 1992 Principles Relevant to the Use of Nuclear Power Sources in Outer Space acknowledged the essential importance of nuclear energy in space missions, which should always be based on a thorough safety assessment. Furthermore, in the preamble, the document provides its own revision for the future, since the number of solutions based on nuclear energy will increase. As this study demonstrates, that time has come, because of the possibilities outlined in Principle 3, point 2 about where nuclear reactors can operate (such as in interplanetary missions, sufficiently high orbits and in low Earth orbits if they are stored in sufficiently high[6] orbits after the operational part of their mission). The regulations also state that nuclear reactors shall use only highly enriched Uranium-235 as fuel.

In 2009 the UN COPUOS Scientific and Technical Subcommittee and the International Atomic Energy Agency (hereinafter IAEA) jointly published a document on the Safety Framework for Nuclear Power Source Applications in Outer Space, having regard to the fact that "nuclear power sources (hereinafter NPS) for use in outer space have been developed and used in space applications where unique mission requirements and constraints on electrical power and thermal management precluded the use of non-nuclear power sources. Such missions have included interplanetary missions to the outer limits of the Solar System, for which solar panels were not suitable as a source of electrical power because of the long duration of these missions at great distances from the Sun" (UN COPUOS – IAEA 2009: 1).

The Safety Framework for Nuclear Power Source Applications in Outer Space focuses on the safety for relevant launch, operation and end-of-service phases of space applications using NPS. It provides high-level guidance on programming and technical aspects of security, including the design and application of NPS in space. However, the detailed implementation of these guidelines depends on the specific design and application. The implementation of guidance in the safety framework would complement existing standards that address other aspects of space NPS applications (UN COPUOS – IAEA 2009: 2).

As space exploration has gained momentum since 2009 and human missions could take us beyond Mars by the end of the century, the wider use of nuclear energy sources has become indispensable. Therefore, on 15 February 2023, in

[6] The definition of "sufficiently high" is rather vague, and it would be a desirable solution if this concept were clarified in a legal source or an international treaty, and to make the legal definition meet the practical criteria of astronautics.

Vienna, U.S. Representative Kevin Conole at the U.S. Mission to International Organizations in Vienna highlighted the significance of the 2009 document and presented that the United States calls on Member States and international intergovernmental organisations that are considering the use of space NPS to implement the joint Safety Framework developed in 2009. The need for this is clear: "Use of NPS for in-space propulsion of spacecraft is a potential technology for crew and cargo missions to Mars, and scientific missions to the outer solar system, enabling faster and more robust human and robotic missions. Expanding into a new era for space exploration depends on mass-efficient, high-energy solutions[7] to power deep space vehicles, operate in harsh environments, and increase mission flexibility" (Conole 2023).

The above-mentioned Principles from 1992 and the Document from 2009 were also cited by the UN COPUOS in 2018 in the Guidelines for the Long-term Sustainability of Outer Space Activities. According to Guideline A.2 2. (e) in developing, revising or amending, as necessary, national regulatory frameworks, States and international intergovernmental organisations should implement the guidance contained in the Safety Framework for Nuclear Power Source Applications in Outer Space and satisfy the intent of the Principles Relevant to the Use of Nuclear Power Sources in Outer Space through applicable mechanisms that provide a regulatory, legal and technical framework that sets out responsibilities and assistance mechanisms, prior to using nuclear power sources in outer space.

Solar energy

Solar power has always been an important element in the operation of satellites and space probes, and this will not change in the future for planetary missions, but solar power is typically enough to power or contribute to the operation of the probe's instruments. In the outer parts of the solar system, the solar constant

7 From a physical point of view, the correct wording would actually be "of high energy output", i.e. there is a huge difference between high-energy physics and an energy source with high energy output.

is so reduced that it can only be used as an auxiliary power source. The table shows that the outer part of the solar system receives less than a thousandth of the irradiance of the Earth.

If solar cells are to be used to some extent to power planetary colonies, it is important to bear in mind that the already low power density of solar cells will only allow them to be used if they can be manufactured on the planet, or at least the largest possible parts can be produced. In this respect, the use of photovoltaic films and surface materials such as paints is a good step forward.

Table 4
Solar irradiance at the distance of the planets (mean value for Mercury, Mars and Pluto)

Planet	Distance (in 10^9 m)	Mean solar irradiance (W/m^2)	Irradiation compared to the Earth's
Mercury	57	9116.4	6.673
Venus	108	2611	1.911
Earth	150	1366.1	1.000
Mars	227	588.6	0.431
Jupiter	778	50.5	0.037
Saturn	1,426	15.04	0.011
Uranus	2,868	3.72	0.003
Neptune	4,497	1.51	0.001
Pluto	5,806	0.878	0.001

Source: Compiled by the authors

An alternative use of solar energy is the solar sail, which uses the radiation pressure of the solar radiation. The first successful solar sail probe was the Japanese IKAROS.

In the following, we will look at the energy sources according to where they are used.

ENERGY SOURCES BY PLACE

Energy in orbit around the Earth

In general, the type of energy source and energy production method used depends on the distance from Earth and the Sun and the type of mission: its energy intensity and length (Datas–Martí 2017: 285; Miller et al. 2016: 197). In orbit around the Earth, we find mostly solar-based solutions: its great advantage in space is that the solar radiation performance at the top of the atmosphere is more than ten times stronger than on the Earth's surface, there are no clouds and there is no change of time of day (ESA 2022c; Nagy 2018: 67). For short missions, chemical energy production is usually used in the form of non-rechargeable batteries or fuel cells (Verduci et al. 2022: 2).

Chemical energy production can also be a feature of the very small CubeSats that have become fashionable (and cost-effective) today: since very little energy is produced by the solar cells on them, their propulsion and thrust must consume as little energy as possible. A joint development by MIT and NASA could be a solution to this, for which the idea was taken from plants, whose water absorption is based on porous and capillary effects. Plants absorb water through capillary pores at the root level, which travels through smaller and smaller capillaries through their trunks to branches and then to leaves, where it evaporates. The invention consists of a porous layer of tiny peaks through which ionic liquid is sucked all the way to the outer surface of the peaks, where the liquid can be expelled as a spray under the influence of electrical voltage between two electrodes. The ionic liquid spray flows out of the pores like a propeller, moving the nanosatellite in the opposite direction to the flow. According to measurements, for example, 500 porous tips can produce 50 micronewtons of thrust, which is capable of moving a device weighing up to 1.5 kg in space. The voltage value applied to these peaked inserts can also be used to change the driving force of the outflowing ion spray, allowing precise control. The invention was called the Ion Electrospray Propulsion System (Braun 2018: 97).

For longer missions, photovoltaic rechargeable batteries are the most common choice. A possible alternative to solar panels is solar heat generation through generators that allow heat storage at very high energy densities, but these systems have only been experimentally studied and flight experiments have not yet been conducted. Nuclear power generation is used for deep space and interplanetary missions because there the intensity of solar power is already too low (Datas–Martí 2017: 285).

Thanks to technological advances, in the late 2010s there were efforts to radiate solar energy produced in space to Earth (Nagy 2018: 68). One of the unresolved problems is how to put such a huge structure into Earth orbit. To be effective, the size of the space solar power plant could reach ten square kilometres (1,400 football fields), so it is necessary to work with extremely light materials since the most expensive part of the whole project would be to launch the device into orbit itself. One proposal, widely supported, is to build a solar power plant out of thousands of smaller satellites equipped with solar panels that would assemble in space into one large structure. What is certain, is that such solar power plants orbiting the Earth could be realised in the coming decades. So far, only China has a concrete plan for this, which in 2016 presented plans for a solar power plant that could produce 2 gigawatts of energy. The SSPS-OMEGA (Space Solar Power Station via Orb-shape Membrane Energy Gathering Array) is planned to be operational in 2050 and could replace the full capacity of more than six million terrestrial solar panels at maximum capacity (Hughes–Soldini 2020). OMEGA can be thought of as a modular, spherical system concept in which sunlight is collected by the main reflector and energy is produced in a series of PV cell arrays. Electricity is supplied to microwave devices using electrical cables and conductive joints (Yang 2016: 53).

One such attempt is CASSIOPeiA (Constant Aperture, Solid-State, Integrated, Orbital Phased Array), which is a new format microwave antenna. According to its creators, when combined with a space-based solar system, it will serve as the basis for a satellite that will be able to partially meet the growing terrestrial energy demand at high specific power. By using an appropriate orbit (the best would be geosynchronous – in this case, there is no need for several ground stations, one is enough), the technology would be in sunlight 24 hours a day, and if several ground receiving stations were in its field of view at the same time, the generated energy could be continuously radiated to the ground station with minimal atmospheric loss at frequencies below 10 GHz (Cash 2019: 170–171; Zhang et al. 2021: 2). The same Space-Based Solar Power (hereinafter SBSP) solution will be offered by ESA's SOLARIS project: "The goal of SOLARIS is to prepare the ground for a possible decision in 2025 on a full development programme by establishing the technical, political and programmatic viability of SBSP for terrestrial clean energy needs" (ESA 2022b). True, even though almost all the equipment and techniques required for a Space Solar Power Station (hereinafter SSPS) or SBSP are already well developed, both the launch infrastructure and the huge costs of ground stations are not affordable, which is why it remains a significant obstacle to achieving viable economic performance. (Solar panels currently designed for use in space have a very high price of around \$500/W; taking efficiency into account, a power plant providing 1 GW of electricity on the surface would require 11.2 GW of solar panels. A price of \$250/W seems achievable in the foreseeable future, but it would still cost \$2,800 billion for solar panels alone) (Zhang et al. 2021: 3; Nagy 2018: 70). But this does not deter innovators, in 2021 ESA finally highlighted 16 ideas out of 85 received on the topic "Solar Power from Space" that could be put on the path to implementation (ESA 2021).

By the way, successful attempts have already been made: the electrical energy generated in space with solar panels was converted into microwaves and beamed down to Earth, where it was converted back into electric energy (Perkins 2023). So, science fiction of the 20th century is actually starting to become a reality.

Possible power supply of the future lunar base

Future lunar bases could not only offer the possibility of energy sharing between lunar-based energy communities, but the Moon could also be a possible point from which the solar energy generated there, but not used locally, could be beamed to Earth in the future. Not only with the help of satellites but also with the help of the Moon – taking advantage of the correspondence between its rotation period around its axis and its orbital period around the Earth – the base load of electricity worldwide could be complemented by the beamed energy from there. What is more, the isotope ^{3}He is located on the Moon, which, together with deuterium, provides fuel for fusion energy. According to some calculations, if fusion power plants could operate on the moon, only 20 tons of isotope ^{3}He would be needed to meet the entire annual electricity demand of the United States. It is another matter, of course, that although the Moon consists of 30% machinable metals, 20% silicon and 40% oxygen, which can help build a power plant locally with the help of robots (Lior 2001: 1772–1773), the question arises whether this is the more economical solution or transporting isotope ^{3}He to Earth.[8]

Fleith and co-workers offer a solution for storing energy produced on the Moon and then used locally: One of the biggest challenges of exploring the Moon is storing the energy needed for missions. Due to the prohibitive costs of transporting materials from Earth, In-Situ Resources Utilization (hereinafter ISRU) is necessary for energy production and storage. If batteries were used for energy storage, their number would be at least two orders of magnitude larger than that used on the International Space Station, leading to a dramatic increase in the mass to be launched from Earth. Fortunately, lunar poles are regions that receive prolonged exposure to sunlight due to the low inclination of the Sun and local topography. Therefore, photovoltaic panels could be used over long periods of time, which would reduce the amount of energy to be stored during dark periods. Regarding energy storage, ISRU's approach as a means

8 Other useful materials are also "by-products" of the mining of isotope ^{3}He, which can contribute to sustaining local life.

of energy supply is to use lunar regolith to store thermal energy, similar to the concept of underground thermal energy storage used on Earth. On the Moon, a cold working fluid would pass through the heat mass and absorb heat, which could be used as a source for a heating system. Heat masses could be produced using sintered regolith on the Moon (Fleith et al. 2020: 1–3).

Energy to Mars

The average distance between the Sun and Earth is about 150 million kilometres, while the average distance between the Sun and Mars is 228 million kilometres (ELTE s. a.) and the irradiation of the Sun between the Sun and Mars is 40% of the terrestrial value (as it was mentioned before), therefore, especially at the beginning of colonisation and infrastructure construction, nuclear energy will be needed due to the high energy demand.

NASA's Kilopower fission surface power project – initially planned for 10 kilowatts – could offer a solution in the late 2020s. The project has developed preliminary concepts and technologies for an affordable nuclear fission power system enabling long-term stays on the planetary surface. Following the successful completion of The Kilopower Reactor Using Stirling Technology (KRUSTY) experiment in March 2018, the Kilopower project team has started to develop the mission concepts for the lunar demonstration. The lunar demonstration, part of the current fission surface power project, will pave the way for future fission surface power systems. The technology could enable the establishment of human outposts on the Moon and Mars, including mission operations in harsh environments (Mohon 2017).

For those who think even bigger, Saturn's largest moon, Titan, is one of the most interesting places in the Solar System, with a dense atmosphere, surface and subsurface oceans and complex topography. Paluszek and co-workers present a conceptual design for a fusion-powered system to explore Titan and enable the use of powerful instruments. The plan includes a fusion-powered orbital transfer vehicle and an electrically powered aircraft. The Direct Fusion Drive (hereinafter DFD) could put the spacecraft into orbit around Titan in less than two years. A second fusion reactor would be used to power the electric aircraft. Both reactors are based on the Princeton Field-Reversed Configuration concept, a technical solution that uses a novel radio-frequency plasma heating system and deuterium-helium-3 fuel. The electric aircraft would be propelled into Titan and then be able to fly at subsonic speeds anywhere on Titan. The DFD-powered transfer vehicle would allow the transfer stage in orbit to change inclination as needed to cover different areas of the surface (Paluszek et al. 2023: 82–93). The exploration of Mars, and especially further afield, also raises the need for settlements and colonies in space. Let us now examine the energy aspects of these communities from the point of view of energy communities.

The future opportunity of shared energy production in space

Returning to the Outer Space Treaty, Articles 9 to 12 regulate cooperation between States Parties to the Treaty on the Moon and other celestial bodies, but it is Article 12 that actually states: "All stations, installations, equipment and space vehicles on the Moon and other celestial bodies shall be open to representatives of other States Parties to the Treaty on a basis of reciprocity." This cooperation may already raises the possibility of sharing energy sources, energy production and use, and consuming jointly produced energy locally if the individual bases are sufficiently close since locally produced and consumed energy is the most economical solution. Furthermore, Article 4 of the 1979 Moon Agreement states that "due regard shall be paid to the interests of present and future generations" – this statement may be familiar concerning sustainable development in terrestrial terms, and indirectly about energy use. Also, Article 4 point 2 states that "States Parties shall be guided by the principle of co-operation and mutual assistance in all their activities concerning the exploration and use of the moon", which reciprocity could also be valid and economical for energy production and use, especially considering that Article 9 could soon become a reality and lunar base(s) could be established. When these are established, they will be able to generate energy and feed themselves even with the help of natural resources found on the Moon, i.e. it will be necessary to establish the international regime referred to in Article 11, points 5–7 of the Moon Agreement, which according to the agreement will regulate a) the orderly and safe development of the natural resources of the moon that will be based on b) the rational management of those resources and c) the expansion of opportunities in the use of those resources. Last but not least, d) an equitable sharing by all States Parties in the benefits derived from those resources, whereby the interests and needs of the developing countries, as well as the efforts of those countries which have contributed either directly or indirectly to the exploration of the Moon, shall be given special consideration.

Of course, all these need to be adapted to today's prospects, which the Artemis Accords partially did, and also the number of its signatories should be higher than in the case of the Moon Agreement, with special attention to those States who have an interest in establishing a lunar base. Point 2 of Section 10 on space resources states that "the Signatories affirm that the extraction of space resources does not inherently constitute national appropriation under Article II of the Outer Space Treaty" – nothing could demonstrate this better in practice than sharing the resources extracted and used locally for energy production or sharing the energy produced. At the same time, Section 11 on deconfliction of space activities: point 7 refers to the so-called "safety zone", which refers to an "area wherein this notification and coordination will be implemented to avoid harmful interference". In other words, the Signatories will likely want to establish safety zones around their own facilities, so isolation from each other may make distributed energy production and use more difficult.

As it is recently recognised, (e.g. MacKay 2008: 231–255) the most economical and nature-friendly method of energy production and use on Earth is always locally produced and used, even optimally shared with smart devices. Presumably, this will be no different in space for bases established on individual celestial bodies. In other words, community energy production and use serve not only sustainability, which is considered important in space contracts and treaties but also economic operation, which is one of the primary considerations for an extremely expensive industry.

Possible parallels between energy communities on Earth and future energy communities in space

In terrestrial environments, community energy production and use are currently implemented by energy communities, which are still in their infancy but are developing rapidly, with several pilot projects underway throughout the European Union and around the globe. As regards the EU regulation, Directive 2019/944/EU (about the internal electricity market) already deals extensively with energy communities, paragraph (44) of the Preamble states that any legal entity may be a member of energy communities, but that the decision-making power of the Community can only be exercised by members who do not engage in extensive commercial activities or who do not carry out their main economic activities in the energy industry.

It can be seen that the regulation was designed for terrestrial relations, i.e. about natural and legal persons, and there is no international legal basis on which the individual cooperating nations could build when establishing a space base, and later a space and planetary colony. That is why bilateral international treaties may be the simplest solution initially.

One thing is for sure, under Article 2 (11) point b) of Directive 2019/944/EU, the energy community is a legal entity whose primary objective is not to make financial gains, but to provide environmental, economic and social community benefits to its members or shareholders or local areas under its operation – has some echoes with the provisions of the Outer Space Treaty on the shared use of outer space.

Point c) of the same article defines the concept of energy community as a legal entity which may participate in energy production, including renewable sources, energy distribution, energy supply, energy consumption, aggregation, energy storage or energy efficiency services, or provide services for the recharging of electric vehicles, or provide other energy services to its members or shareholders. In addition, Article 16 highlights that participation in energy communities should be based on a voluntary decision, which should be an open opportunity for all, also members should subsequently be entitled to leave the community (Biró 2022: 21), which also parallels the Outer Space Treaty, as it is an opportunity open to all.

However, while regulatory sandbox has been the possible solution for energy communities and related innovations on Earth, this is unlikely to be feasible in a highly regulated environment such as space. The essence of the regulatory sandbox, as stated by the Council of the European Union, is that it is increasingly used in a range of sectors, for example in finance, health, legal services, aviation, transport and logistics as well as energy, often including the use of new, emerging technologies or the innovative use of existing technologies (Council of the European Union 2020). In other words, the operation of energy communities that may be created in space in the future will not be characterised by free development, but their operation will be limited by strict regulations, which should be based on the application of the most serious and secure technological developments, and not on the subsequent regulation of freely emerging, experimental developments.

CONCLUSIONS

Overall, the paper reviewed what kind of conclusions could be drawn from the current legal regulation on energy use in space and examined the possible energy sources belonging to missions planned at different distances that are the most likely to be applicable at the moment. Based on the discussed international space-related treaties, legal documents and recommendations, it can be concluded that the legitimacy of NPS applications is recognised, as they are essential, given that the opportunities for interplanetary missions are about to open up for humanity. Moreover, as soon as technological solutions not only theoretically but also practically enable long-distance missions, NPS applications and other possible solutions outlined in this paper that may seem futuristic today, such as HPS and SMR and nuclear fusion, will need to be regulated in detail as well. On the other hand, it is also conceivable that there will be technological breakthroughs in the energy production methods currently used in orbit, in which case new regulations will be needed, where the mentioned SSPS and SBSP technologies are expected to be among the first. Space exploration and technological progress have been on a mutually reinforcing path in the past, we can assume the same in the future, and it is likely that if we can rise above our challenges on Earth, science fiction can become a reality.

REFERENCES

Appelbaum, J. – Flood, D. J. (1989): *Solar Radiation on Mars.* NASA Technical Memorandum 102299. Online: https://ntrs.nasa.gov/api/citations/19890018252/downloads/19890018252.pdf

Bedingfield, K. L. – Leach, R. D. – Alexander, M. B. (1996): *Spacecraft System Failures and Anomalies Attributed to the Natural Space Environment.* NASA Reference Publication 1390. Alabama: Marshall Space Flight Center. Online: https://ntrs.nasa.gov/api/citations/19960050463/downloads/19960050463.pdf

Biró, Zs. (2022): The Current EU and Hungarian Legislation of Energy Communities and Possible Future Directions. In Garayová, L. (ed.): *Budúcnosť práva – Právo budúcnosti II. Zborník príspevkov z online vedeckej konferencie – The Law of the Future – The Future of Law II. Conference Proceedings.* Bratislava: Paneurópska vysoká škola, Fakulta práva. 165–185.

Braun, T. (2018): Rubik-kockával a világűrkutatásban. Ionos folyadékokkal hajtott nanoműholdak. *Magyar Kémikusok Lapja,* 73(3), 96–99. Online: https://doi.org/10.24364/MKL.2018.03

Cash, I. (2019): CASSIOPeiA – A New Paradigm for Space Solar Power. *Acta Astronautica,* 159, 170–178. Online: https://doi.org/10.1016/j.actaastro.2019.03.063

Conole, K. (2023): *U.S. Statement as Prepared for U.S. Representative Kevin Conole.* U.S. Mission to International Organizations in Vienna. Online: https://vienna.usmission.gov/u-s-statement-agenda-item-15-use-of-nuclear-power-in-outer-space-60th-session-of-the-stsc-of-copuos/

Council of the European Union (2020): Council Conclusions on Regulatory sandboxes and experimentation clauses as tools for an innovation-friendly, future-proof and resilient regulatory framework that masters disruptive challenges in the digital age. 12683/1/20 REV 1. Brussels, 16 November 2020, 13026/20.

Datas, A. – Martí, A. (2017): Thermophotovoltaic Energy in Space Applications: Review and Future Potential. *Solar Energy Materials and Solar Cells,* 161, 285–296. Online: https://doi.org/10.1016/j.solmat.2016.12.007

ELTE (s. a.): *A Naprendszer adatai.* Online: http://sterni.web.elte.hu/anyag/ora2.html

ESA (2021): *Clean Energy – New Ideas for Solar Power from Space.* Online: https://ideas.esa.int/servlet/hype/IMT?documentTableId=45087625530300097&userAction=Browse&templateName=&documentId=514a8db636ea637f6e27069183966350

ESA (2022a): *SBSP History.* Online: www.esa.int/Enabling_Support/Space_Engineering_Technology/SOLARIS/SBSP_history

ESA (2022b): *SOLARIS.* Online: www.esa.int/Enabling_Support/Space_Engineering_Technology/SOLARIS

ESA (2022c): *Space-Based Solar Power Overview.* Online: www.esa.int/Enabling_Support/Space_Engineering_Technology/SOLARIS/Space-Based_Solar_Power_overview

Fleith, P. – Cowley, A. – Canals Pou, A. – Valle Lozano, A. – Frank, R. – López Cordóba, P. – González-Cinca, R. (2020): In-situ Approach for Thermal Energy Storage and Thermoelectricity Generation on the Moon: Modelling and Simulation. *Planetary and Space Science,* 181, 1–12. Online: https://doi.org/10.1016/j.pss.2019.104789

Hughes, A. J. – Soldini, S. (2020): Solar Power Stations in Space Could Be the Answer to our Energy Needs. *The Conversation,* 19 November 2020. Online: https://theconversation.com/solar-power-stations-in-space-could-be-the-answer-to-our-energy-needs-150007

JHUAPL (2018): *Interstellar Probe: Study for Upcoming Heliophysics Decadal Survey.* Presentation. Online: https://interstellarprobe.jhuapl.edu/

Lior, N. (2001): Power from Space. *Energy Conversation and Management,* 42(15–17), 1769–1805. Online: https://doi.org/10.1016/S0196-8904(01)00040-1

MacKay, D. J. C. (2008): Sustainable Energy – Without the Hot Air. Cambridge: UIT Cambridge. Online: www.withouthotair.com

Miller, T. F. – Paul, M. V. – Oleson, S. R. (2016): Combustion-based Power Source for Venus Surface Missions. *Acta Astronautica,* 127, 197–208. Online: https://doi.org/10.1016/j.actaastro.2016.05.006

Mohon, L. (2017): *Kilopower.* Online: www.nasa.gov/directorates/stmd/tech-demo-missions-program/kilopower-hmqzw/

Nagy, I. (2018): Naperőművek föld körüli pályán. *Repüléstudományi Közlemények,* 30(2), 67–74.

NASA (2000): *Explanatory Supplement. Chapter 7: Fundamentals of Orbital Mechanics.* Online: https://spsweb.fltops.jpl.nasa.gov/portaldataops/mpg/MPG_Docs/MPG%20Book/Release/Chapter7-OrbitalMechanics.pdf

NASA (2023): *In-Space Propulsion.* Online: www.nasa.gov/smallsat-institute/sst-soa/in-space_propulsion/

NASA [s. a.]: *Basics of Space Flight. Chapter 4: Trajectories.* Online: https://science.nasa.gov/learn/basics-of-space-flight/chapter4-1/

O'Neill, G. K. (1975): Space Colonies and Energy Supply to the Earth. *Science,* 190(4218), 943–947. Online: https://doi.org/10.1126/science.190.4218.943

Paluszek, M. – Price, A. – Koniaris, Z. – Galea, C. – Thomas, S. – Cohen, S. – Stutz, R. (2023): Nuclear Fusion Powered Titan Aircraft. *Acta Astronautica,* 210, 82–94. Online: https://doi.org/10.1016/j.actaastro.2023.04.029

Perkins, R. (2023): *In a First, Caltech's Space Solar Power Demonstrator Wirelessly Transmits Power in Space.* Online: www.caltech.edu/about/news/in-a-first-caltechs-space-solar-power-demonstrator-wirelessly-transmits-power-in-space

Petrocelli, A. – Bettinger, R. A. – Kutz, N. C. – Hartsfield, C. (2023): Atlas of Historical and Proposed Nuclear Devices and Power Systems in the Earth–Moon System and Wider Solar System. *Progress in Nuclear Energy,* 164, 1–19. Online: https://doi.org/10.1016/j.pnucene.2023.104857

UN COPUOS – IAEA (2009): *Safety Framework for Nuclear Power Source Applications in Outer Space.* United Nations Committee on the Peaceful Uses of Outer Space – International Atomic Energy Agency.

Verduci, R. – Romano, V. – Brunetti, G. – Yaghoobi Nia, N. – Di Carlo, A. – D'Angelo, G. – Ciminelli, C. (2022): Solar Energy in Space Applications: Review and Technology Perspectives. *Advanced Energy Materials,* 12(29), 1–24. Online: https://doi.org/10.1002/aenm.202200125

World Nuclear Association (2021): *Nuclear Reactors and Radioisotopes for Space.* Online: https://world-nuclear.org/information-library/non-power-nuclear-applications/transport/nuclear-reactors-for-space.aspx

Yang, Y. – Zhang, Y. – Duan, B. – Wang, D. – Li, X. (2016): A Novel Design Project for Space Solar Power Station (SSPS-OMEGA). *Acta Astronautica,* 121, 51–58. Online: https://doi.org/10.1016/j.actaastro.2015.12.029

Zhang, T. – Li, Y. – Chen, Y. – Feng, X. – Zhu, X. – Chen, Z. – Yao, J. – Zheng, Y. – Cai, J. – Song, H. – Sun, S. (2021): Review on Space Energy. *Applied Energy,* 292, 2–23. Online: https://doi.org/10.1016/j.apenergy.2021.116896

Further legal documents

The Artemis Accords. Principles for Cooperation in the Civil Exploration and Use of the Moon, Mars, Comets, and Asteroids for Peaceful Purposes

Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on Common Rules for the Internal Market for Electricity and Amending Directive 2012/27/EU

Guidelines for the Long-term Sustainability of Outer Space Activities A/AC.105/2018/CRP.20

Moon Agreement. 34/68 Agreement Governing the Activities of States on the Moon and Other Celestial Bodies

Outer Space Treaty. 2222 (XXI). Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies

Resolution 47/68 of 1992. Principles Relevant to the Use of Nuclear Power Sources in Outer Space