HUMAN UTILISATION OF SPACE

Trend Analysis of Opportunities and Risks for the Environment

German Environment Agency

Imprint

Publisher:
German Environment Agency
Section I 1.1: Fundamental Issues, Sustainability
Strategies and Scenarios, Resource Conservation

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Photo credits:
Cover image: Jeremy Thomas/unsplash

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As of June 2024

ISSN 2363-832X

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Abbreviations

5G	5th generation
ACR	Asteroid Capture and Return
AIT	Austrian Institute of Technology
Art.	Article
BDI	Federation of German Industries
BDLI	Federal Association of the German Aerospace Industry
GDP	Gross Domestic Product
BMBF	Federal Ministry of Education and Research
BMDV	Federal Ministry for Digital and Transport Affairs
BMEL	Federal Ministry of Agriculture and Food
BMVg	Federal Ministry of Defence
BMWK	Federal Ministry of Economics and Climate Protection
CalTech	California Institute of Technology
CCDev	Commercial Crew Development programme
CDR	Carbon Dioxide Removal
CDU	Christian Democratic Union of Germany
cm	centimetre
CNES	Centre national d'études spatiales
CNSA	China National Space Administration
Col-CC	Columbus Control Centre
CONFERS	Consortium For Execution Of Rendezvous And Servicing Operations
COPUOS	Committee on the Peaceful Uses of Outer Space
COSPAR	Committee on Space Research
CRI	China Radio International
CSA	Canadian Space Agency
CSCEM	Committee on the Scientific Context for Exploration of the Moon
CST	Crew Space Transportation
CSU	Christian Social Union in Bavaria
i.e.	that is
DLG	German Agricultural Society
DLR G.A.C.	German Aerospace Centre
EAC	European Astronaut Centre
EIB	European Investment Bank
ELDO	European Launcher Development Organisation
ESA	European Space Agency
ESOC	European Space Operations Centre
ESPI	European Space Policy Institute

ESRO	European Space Research Organisation
EU	European Union
FAA	Federal Aviation Agency
FDP	Free Democratic Party
Fraunhofer INT	Fraunhofer Institute for Technological Trend Analyses
CAP	Common Agricultural Policy
GEO	Geostationary orbit
GFZ	German Research Centre for Geosciences
GLONASS	Globalnaja nawigazionnaja sputnikowaja sistema
GNSS	Global Navigation Satellite System
GOSA	German Offshore Spaceport Alliance
GPS	Global Positioning System
HD	High Definition
HPS	High Performance Space Structure Systems
IAEA	International Atomic Energy Agenc
IASS	Institute For Advanced Sustainability Studies
IEA	International Energy Agency
IMF	Institute for Remote Sensing Technology
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
ISECG	International Space Exploration Coordination Group
ISRO	Indian Space Research Organisation
ISRU	In-situ resource utilisation
ISS	International Space Station
IT	Information Technology
ITA	Institute for Technology Assessment
JAXA	Japan Aerospace Exploration Agency
KARI	Korea Aerospace Research Institute
kg	kilogram
AI	Artificial intelligence
LCA	Life Cycle Analysis
LEO	Low Earth Orbit
LIDAR	Light Detection And Ranging
LIST	Luxembourg Institute of Science and Technology
LORRY	Lorry
LOX	Liquid Oxygen
LSA	Luxembourg Space Agency

LTE	Long-Term Evolution
m	metre
Mbit/s	Megabit per second
MEO	Medium Earth Orbit
million	million
MOXIE	Mars Oxygen ISRU Experiment
billion	billion
NASA	National Aeronautics and Space Administration
NEO	Near-Earth-Object
NEPA	National Environmental Policy Act
NTN	Non-Terrestrial Networks
OSIRIS-Rex	Origins Spectral Interpretation Resource Identification Security - Regolith Explorer
PA	Precision Agriculture
PNT	Position, Navigation & Timing
PV	Photovoltaics
RADAR	Radio Detection And Ranging
s.	see
see below	see below
SBSP	Space-Based Solar Power
SDG	Sustainable Development Goal
SETI	Search for Extraterrestrial Intelligence
SIA	Satellite Industry Association
SLS	Space Launch System
SO_2	Sulphur dioxide
SpaceX	Space Exploration Technologies Corporation
S.O.P.o.G.	Social Democratic Party of Germany
SRM	Solar Radiation Management
SSMS	Small Spacecraft Mission Service
SVHC	Substances of Very High Concern
GHG	Greenhouse gas
UBA	Federal Environment Agency
UK	United Kingdom
UN	United Nations
UNODA	United Nations Office for Disarmament Affairs
UNOOSA	United Nations Office For Outer Space Affairs
UVPG	Environmental Impact Assessment Act

Abstract:
Human Utilisation of Space - Trend Analysis of Opportunities and Risks for the Environment

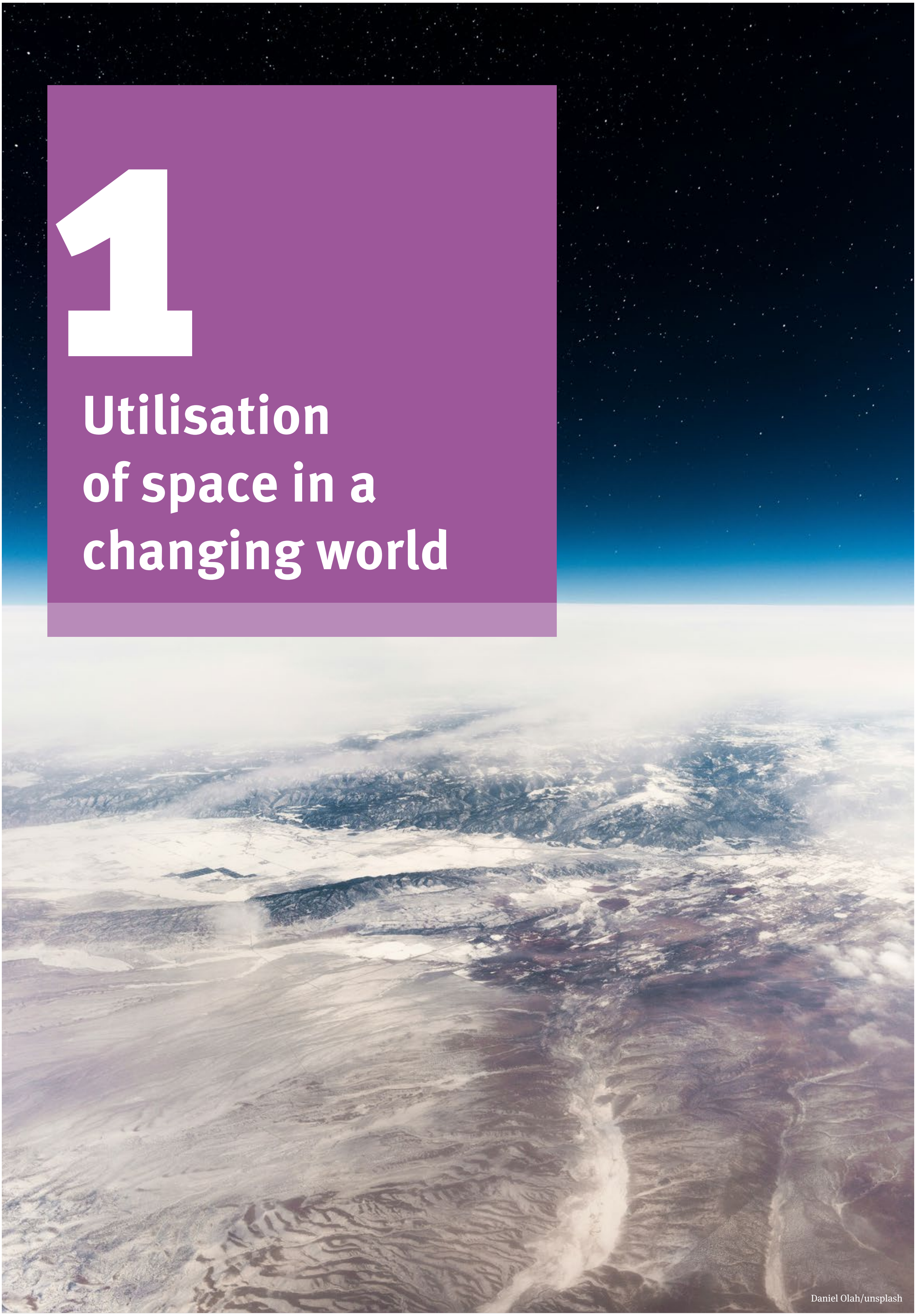
The human use of space has evolved rapidly since its beginnings. The enormous growth in this sector, the shift of space activities to the private sector, and the environmental impact that has already occurred and is to be expected make the question of sustainability ever more urgent. This trend report, commissioned by the German Federal Environment Agency (UBA), provides an overview of all the trends in space use and examines them in terms of their future potential and possible problems for the environment on Earth and in space.

Technological progress is enabling more and more state and non-state actors to become active in space and is leading to a rapid increase in the number of users. In addition, innovations are opening up new opportunities for Earth observation, satellite navigation and satellite communications. In the future, it will also be possible to mine resources in space. The report analyses these developments in terms of their background, trends and associated risks and opportunities for the environment. On the one hand, there are environmentally relevant applications, such as monitoring international agreements through Earth observation, controlling traffic flows, collecting more data on the effects of climate change and thus supporting environmental policy decisions. On the other hand, these activities pose risks to protected assets on Earth and in space, which are likely to increase as the use of space expands. This report therefore also addresses the environmental risks of space use in terms of chemical (e.g. greenhouse gases and air pollutants) and physical impacts (e.g. noise, resource consumption in production, operation and disposal). Both the ground infrastructure and the technical systems (launchers, spacecraft, satellites and space probes, propulsion systems and fuels) and space debris are analysed in terms of their environmental impact.

Finally, environmental policy options are presented and discussed. In the future use of space, environmental and sustainability policy principles should be applied, policy regulations should be strengthened and extended, technical systems should be made more sustainable, and the issue of space debris should be brought into focus.

1

Utilisation of space in a changing world



Daniel Olah/unsplash

„ [...] most actors in outer space, space agencies and commercial satellite operators, realise today that our use of outer space since 1957 has been rather careless of its long-term sustainability. The situation might be compared to that of the 19th and 20th centuries with respect to maritime shipping and exploiting the oceans' resources where there was a wilful ignorance of the negative impact of pollution and a general blindness to the long-term effects of over-fishing.“

(Gérard Brachet 2016)

Space has always aroused mankind‘s interest and spirit of exploration. From astronomical artefacts such as the Nebra Sky Disc from the early Bronze Age 4000 years ago, to the development of the first telescopes in the 17th century and finally the launch of the James Webb Space Telescope in 2021, human space observation has undergone enormous development. Whereas in the past, travelling to the moon was something only to be found in science fiction novels such as Jules Verne‘s „From the Earth to the Moon“, today's technologies are bringing us ever closer to travelling to other planets.

The technical achievements of the modern age made it possible to conduct space missions and make parts of space accessible to the human race. Mankind's first forays into space were followed with great fascination by the public: the launch of Sputnik 1 at the end of the 1950s, the first flight into space by Yuri Gagarin in 1961, the first spacewalk in 1965 and the Moon landing in 1969. Space technologies have developed considerably since their beginnings. The theoretical and technical foundations can be traced back to scientists from various nations.

The origins of space travel can be found in the military sector. The rocket engineer Wernher von Braun developed the first functional large rocket, the „Aggregat 4“ (better known as the „V2“), as part of the National Socialist rocket programme in 1942. After the end of the Second World War, von Braun then developed launch vehicles for the US National Aeronautics and Space Administration (NASA), see also chapter 3.1.2. Initial successes in space travel during the Cold War were also seen as a demonstration of military power. The end of the 20th century saw a phase of increased international cooperation in space travel, e.g. through the cooperative construction and joint utilisation of the International Space Station (ISS). This opened up the field of space travel to international research projects.

Finally, the 21st century has seen a shift in space travel from government leadership to the private sector. In 2020, the company SpaceX performed the first manned space flight for NASA to the International Space Station ISS. The increasing number of missions by private companies has shifted attention towards the economic benefits of space. Thanks to private space operators such as Elon Musk‘s SpaceX, Jeff Bezos‘ Blue Orbit, Richards Branson‘s Virgin Galactic and Airbus, as well as new space services, it is even financially possible for medium-sized companies to launch new satellites into space (Seidemann 2022).

Various service companies are interested in positioning their communication, navigation or weather satellites in space. Elon Musk and his company SpaceX are planning to make the internet available everywhere on Earth with the help of 40,000 satellites (under the name Starlink) (Seidler 2019). There are already so many satellites orbiting the Earth that space agencies are increasingly having to plan evasive manoeuvres for individual satellites to avoid collisions (Seidemann 2022). Flights into space by private individuals, for example for a holiday in the „Voyager Station“ space hotel, are also planned for the near future. (Above: Space Development Corporation n.d.). In 2021, the first purely tourist space mission „Inspiration4“ laid the foundation for space tourism (Inspiration4 2021).

However, the utilisation of space also has an environmental impact on Earth and in space itself and entails problems and risks, such as the accumulation of space debris or chemical pollution of the Earth‘s atmosphere (Westram 2021). In the past, space missions have often been conducted without taking into account possible environmental impacts and potential overuse of space. As utilisation increases, these problems can initially be expected to worsen. As mentioned at the beginning, this approach is similar to the way humans have dealt with the world‘s oceans in the past. Once again, there is a risk of unforeseeable and massive environmental consequences if the utilisation of space is not regulated with regard to its environmental impact. In addition to the protection of people and the Earth and safety considerations, it must also be fundamentally questioned to what extent the utilisation of outer space by humans is in the interests of people and the environment, and whether outer space itself should be protected from changes caused by humans, i.e. whether it is itself a protected environment.

Even the use of space technologies that can help combat climate change (e.g. Earth observation satellites) is associated with harmful environmental impacts, such as CO_2 emissions, pollution of the Earth‘s atmosphere, the consumption of finite resources and the generation of space debris. Earth observation satellites offer the opportunity to track changes in the Earth‘s climate and identify impacts (Yang et al. 2013). Such data is also incorporated into Earth system models that forecast climate impacts. This combination of opportunities and risks for the environment makes the utilisation of space a double-edged sword.

With Destination Earth, the European Commission has initiated a project which simulates impacts on our planet at various scales in digital twins and prepares these for decision-makers (European Commission 2022). Research is being carried out worldwide into more environmentally friendly fuels as well as retrieval actions and the reuse of technical systems (German Aerospace Centre (DLR) 2023; Klapetz 2023). Overall, space travel and orbital exploration have not yet been widely discussed as an environmental or sustainability issue, but rather from the perspective of innovation and economic development.

Due to the early stage of the commercial utilisation of space, there are only a few regulations on the part of policymakers that are suitable for dealing with the increase in use and players and avoiding overcrowding and collisions of satellite and scrap parts in near-Earth space (Landwehr 2021). The actions of private actors are currently only subject to legally binding limits through national controls. In the USA, a lawsuit was filed against Elon Musk‘s Starlink in 2021, as the company’s satellite constellations could potentially interfere with astronomical observations and thus violate the National Environmental Policy Act (NEPA) (O‘Callaghan 2021). At the political level, the „Guidelines for the Long-Term Sustainability of Outer Space Activities“ of COPUOS (Committee on the Peaceful Uses of Outer Space) of the United Nations represent an attempt to formulate a sustainability principle for the utilisation and exploration of outer space (United Nations Office For Outer Space Affairs (UNOOSA) 2018b). It describes the Earth‘s orbit as a finite resource that must be handled with care in line with the precautionary principle. Other scientists also emphasise that resources in space are limited and that space debris constitutes pollution (Newman and Williamson 2018; Galli and Losch 2019; Kramer 2020).

The exponential increase in interest in space utilisation and the ever-louder discussions about new fields of application such as space tourism or extraterrestrial resource extraction raise questions about possible future paths for space utilisation. The role of sustainability considerations and thus the answer to the question of whether the same mistakes that led to the exploitation and pollution of the oceans will be repeated in space - as the opening quote of this report emphatically warns - or whether it will be possible to take countermeasures in time, is literally written in the stars.

This study aims to close gaps in environmental assessment and identify opportunities for the sustainable use of outer space. As part of the Strategic Foresight, it takes a look at current trends and future developments in order to gain a comprehensive overview of both negative environmental impacts and opportunities for the environment. In view of these developments, it is important to explore the extent to which environmental policy should concentrate solely on the terrestrial environment or whether space should be focussed on as a further protected asset.

2
Aim and method

This trend report takes the following developments as the starting point for a critical review:

- To what extent do the technical systems of space travel have a negative impact on the environment?
- What are the potentials and risks for environmental research and environmental policy due to trends in space travel?
- What role can the Federal Environment Agency play?

The trend report focusses in particular on near-Earth space, but also occasionally describes issues and technologies that go beyond this. It describes global trends and developments, with a particular focus on European and German space travel. The report does not examine the military utilisation of space.

This study used a method from futurology - trend analysis. The primary aim of trend analysis is to provide the environment department with an overview and thus an information base on the latest developments and their environmental relevance, on the basis of which political approaches and measures can be developed as early and proactively as possible. In addition to a detailed description of key developments in how the use of outer space is currently changing and will potentially continue to change in the future, the report contains an overview of existing and potential future environmental impacts, identifies opportunities and risks and formulates further research requirements and initial policy options.

However, the study is not aimed exclusively at the environment department. Rather, it also aims to sensitise and inform specialists and the public about the environmental impacts associated with the increasing use of outer space. The study aims to make a contribution that can be continued in various (specialised) public discourses, further studies and processes.

As a result, the structure of the trend report is as follows:

- **chapter 3** provides important background information. This chapter defines the term „space“ and outlines the historical development of space travel and its social relevance. The economic perspective in this chapter illustrates both the distribution of interests of various states and private actors and the innovative power of space research. The chapter also presents the key developments in the legal and political framework of space utilisation and highlights the need to consider environmental impacts on Earth and in space.
- **chapter 4** takes a look at the technical systems for the exploration and utilisation of space in the present and the near future. An overview of the manufacturing processes and life cycles of the systems illustrates the resulting impact on the environment.
- **chapter 5** looks at four current and future developments in space travel that are particularly relevant to the environment: the decreasing barriers to reaching space, trends in the field of earth observation, developments in satellite navigation and communication, and the possible depletion of resources. The chapter analyses the potential and risks for the environment. Areas with particular potential for change in the future, such as the colonisation of the Moon, are examined for each of these four trends.
- **chapter 6** sets out precise starting points for policy recommendations. In addition, further research questions are formulated and a conclusion is drawn.

The developments discussed in chapter 5 were seo lected with the aim of reflecting the breadth of the discussion. This includes activities that are already being implemented (such as Earth observation) but are currently in a highly dynamic development phase, as well as those that are still only aspirations for the future (such as resource extraction in space).

In order to answer the questions formulated at the beginning, the current, relevant research literature was comprehensively researched and analysed. In addition to deriving and describing the status quo, a strong focus was placed on predicting future developments and trends in the utilisation of space. These forecasts were underpinned by specialist knowledge on environmental impacts, which was not only compiled and collected in the specialist literature, but also in workshops with external experts and experts from the UBA and BMUV.

It is clear that this report can only be a starting point for the discussion of these issues, especially if the future utilisation of space develops further and perhaps differently than currently assumed. However, it is also clear that a discussion must be held on how opportunities for the environment can be systematically utilised and how the environmental damage resulting from the various developments in the use of space can be countered - even if they serve environmental and climate protection purposes. The report makes it clear how important it is to avoid repeating the mistakes of the past in dealing with the environment, e.g. by ignoring environmental aspects in favour of economic aspects, as in the case of maritime shipping mentioned at the beginning of this report (Brachet 2016). The bottom line is that we need to act now before the problems described in the report, or other, as yet unforeseeable, problems materialise.

3

Space utilisation: understanding the term and framework conditions

3.1 Utilisation of outer space: what does it actually involve?

3.1.1 Definition of terms

Space refers to the three-dimensional space between stars, planets and other astronomical objects (Howell 2022). Space can be divided into near-Earth, interplanetary, interstellar and intergalactic space as well as „voids", the empty spaces between galaxies (Carroll and Ostlie 2017; p. 1038ff.). Where space begins, as seen from Earth, is not clearly defined. A common boundary between airspace and outer space is the Kármán line, which marks the area 100 km above sea level where aviation is no longer possible, as the Earth's atmosphere is no longer sufficient for dynamic lift for aircraft there (Freistetter 2015).

Space is not empty, but an almost perfect vacuum filled with gases, cosmic dust and elementary particles and permeated by electric and magnetic fields, gravitational fields and electromagnetic waves (Hawking 1988; p. 67ff.; Herrmann 2005; p. 168ff.). The average temperature of outer space is -270.3°C. The temperature of matter and radiation in space varies greatly depending on the respective conditions (Moore 2013; p. 109). The force of gravity acts everywhere in space, causing objects to attract each other. Weightlessness occurs when gravity is not hindered by opposing forces and the object is set in accelerated motion (Herrmann 2005; p. 58ff.).

Due to the enormous distances involved, both manned and unmanned exploration of interstellar and intergalactic space have been virtually impossible to date. Interstellar and intergalactic space is explored with radio or optical telescopes from Earth, or with space telescopes such as the Hubble Space Telescope or the James Webb Space Telescope (Space Telescope Science Institute (STScI) 2023a; Space Telescope Science Institute (STScI) 2023b).

Space travel has so far been limited to interplanetary space within our solar system. Only the two space probes „Voyager 1" and „Voyager 2", launched in 1977, have left the solar system as man-made objects and reached interstellar space (Voyager 1 in 2012 and Voyager 2 in 2018; NASA Jet Propulsion Laboratory n.d.).

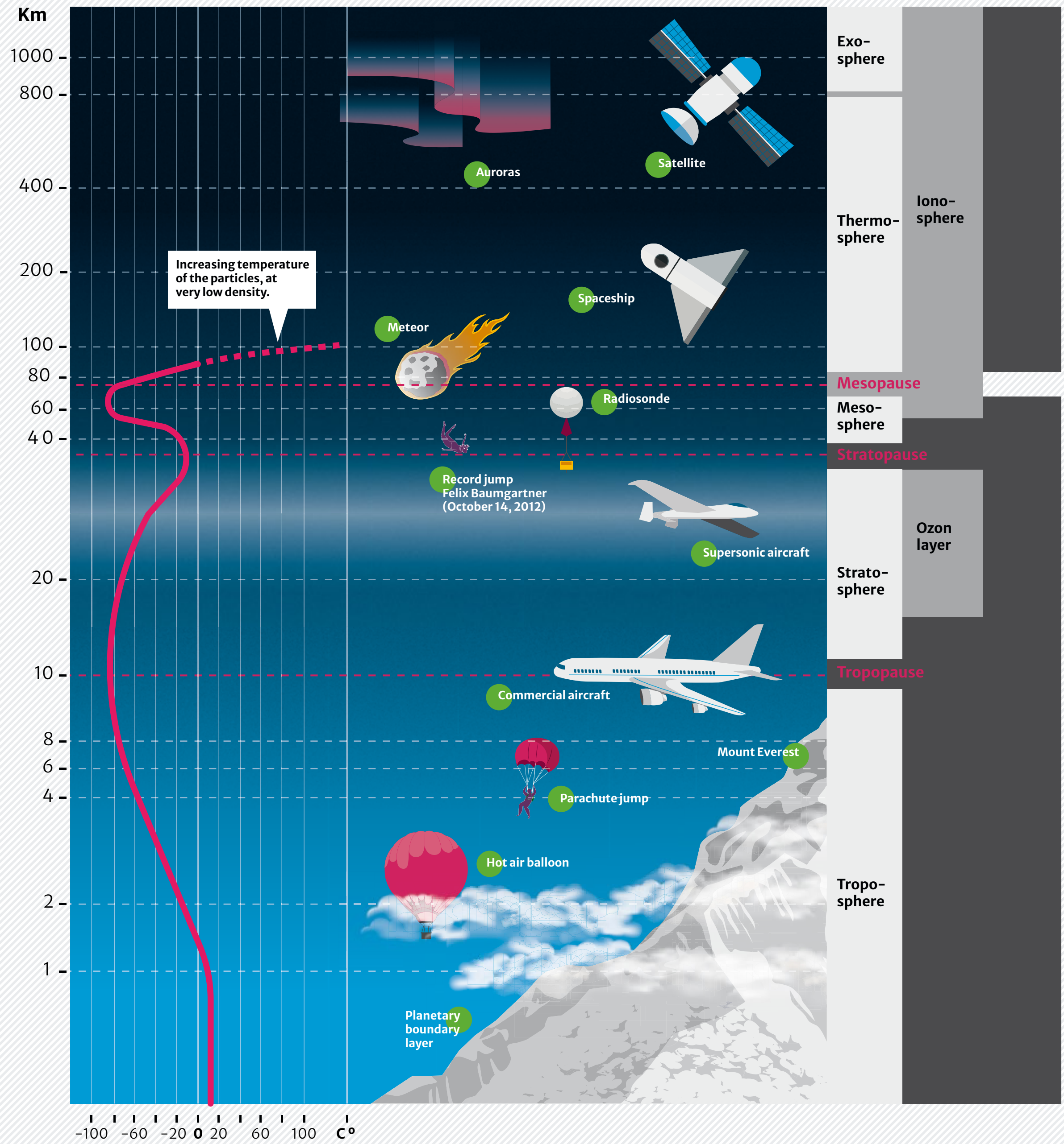
Within our solar system, unmanned missions have reached the dwarf planet, Pluto, explored the moons of Jupiter, explored Venus and, in particular, performed numerous journeys to Mars, the planet closest to Earth. We should also remember the six manned Moon landings by the USA as part of the Apollo programme between 1969 and 1972. Predominantly, space travel - especially manned space travel - takes place in near-Earth space.

Near-Earth space covers the area up to approximately 36,000 kilometres above sea level. In this area, spacecraft and humans are exposed to special conditions in an almost perfect vacuum (Wittmann 2011; p. 57):

- Microgravity prevails, i.e. near-weightlessness.
- Residual atmosphere in which rockets, spacecraft and satellites are slowed down by flow resistance and which can cause space objects in Low Earth Orbit to crash slowly but surely if the orbit is not corrected with thrusters.
- Particle radiation and high-energy electromagnetic radiation, which pose a risk to electronic components and human health in the radiation belt around the Earth. This is why radiation protection is of particular importance in space travel.
- Temperature conditions that, depending on the location of a spacecraft or satellite, e.g. in sunlight, require temperature equalisation, which is achieved by means of technical subsystems (see chapter 4.1.4).

Figure 1

Structure of the atmosphere and transition to space with temperature curve in logarithmic representation along the height above sea level



Source: Own illustration based on BR 2023

3.1.2 Historical classification and current developments

Space travel during the Cold War

The origins of space travel date back to the early twentieth century, when the theoretical and technical foundations for rocket technology were successively developed by Konstantin Tsiolkovsky (Russia), Robert Goddard (USA), Herman Oberth (Austria/Germany) and Wernher von Braun (Germany), among others (Osterhage 2021; p. 34ff.). The first airworthy rockets („V2") were developed in Germany during the Second World War (Fischer et al. 2019).

German space research was initially prohibited by the four occupying powers between the end of the war in 1945 and the entry into force of the Paris Agreement in 1955. It then quickly gained momentum, as West Germany helped found the European Space Research Organisation (ESRO) and the European Launcher Development Organisation (ELDO) to develop a European launcher (Reinke and Müller 2010; Fischer et al. 2019). The first German research satellite Azur was sent into orbit in 1969 using an American rocket (Fischer et al. 2019).

After the end of the Second World War, a large number of the scientists involved in the National Socialist rocket research programme were brought to the USA by the Allies to help shape the research programme there. The Soviet Union also endeavoured to push ahead with its own rocket research after the end of the war, which ultimately resulted in the first artificial satellite, Sputnik (October 1957) (Richers 2019). During the Cold War, a race for access to and exploration of outer space began, which culminated in the first manned Moon landing by the US American „Apollo 11" mission on 20 July 1969. The competition for supremacy in space was not only a technological one, but a political one, too. This was also reflected in the history of German manned space travel: on 26 August 1978, Sigmund Jähn, a citizen of the GDR, became the first German in space. His flight took him to the Soviet space station Salut 6 (European Space Agency (ESA) n.d. b). Ulf Merbold later became the first West German in space, on 28 November 1983. He took part in the maiden flight of the European space laboratory Spacelab and was part of the first ESA astronaut group (European Space Agency (ESA) n.d. c).

Cooperation in space

While the early days of space travel were characterised by competition and rivalry between the USA and the Soviet Union and a battle for supremacy in space (Spillmann 1988; p. 24), the willingness for international cooperation crystallised in Europe as early as the beginning of the 1960s. The Western European states quickly realised that they could neither compete nor keep up with the two superpowers through national projects alone (Weyer 1993). As a result, the organisations ELDO (European Launch Development Organisation) and ESRO (European Space Research Organisation) were created, which eventually merged to form ESA in 1975 (European Space Agency (ESA) n.d. k). In 1998, the European astronaut groups, some of which were still organised nationally, were merged with the ESA astronaut team to form the ESA Astronaut Corps in order to improve coordination among astronauts and make optimum use of limited resources (European Space Agency (ESA) n.d.).

Over time, the USA and the Soviet Union also moved closer together in matters of space travel and began to cooperate more closely. The turning point in the relationship was the Apollo-Soyuz Test Project (ASTP) in 1975, which is considered a milestone for the cooperation between the two nations and marked a shift from the competitive nature of their space programmes (Kilian 2019). The motivation for this project was to provide mutual assistance to the spacecraft of both nations by means of docking manoeuvres, similar to sea rescue (Kowalski 2015). The flight of Apollo 13 in 1970, which almost ended catastrophically, clearly demonstrated how risky space flights can be. The spacecraft was severely damaged by an explosion and the astronauts were only narrowly rescued (Lorenzen 2020). The image of Soviet and American astronauts shaking hands in space was intended to symbolise cooperation in space travel, despite the tense political situation (Logar 1976).

From a global perspective, the ISS is the most remarkable example of ongoing international cooperation in the field of space travel. the Americans came up with the idea of the ISS in the 1980s. The first modules were sent into space to build the space station in 1998 (Banner 2021). At present, 15 nations are involved in the ISS as part of five space programmes (Hall n.d.) and 269 people from 21 countries have visited the ISS[1] (Garcia n.d.).

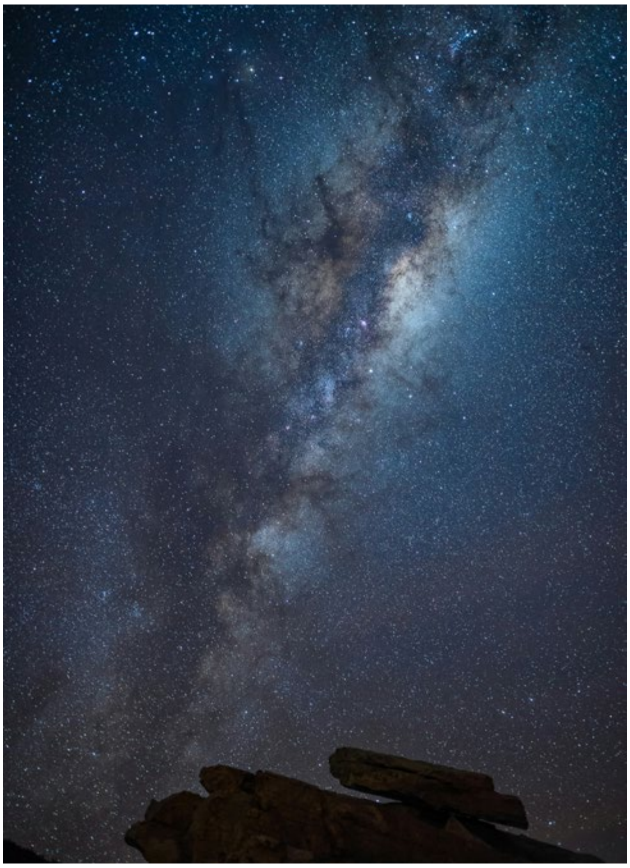
The Russian war of aggression against Ukraine since February 2022 interrupted this trend of international co-operation. The outbreak of the war led to the suspension of cooperation between the ESA and Roskosmos, the space organisation of the Russian Federation, in the ExoMars project (European Space Agency (ESA) 2023). The DLR (German Aerospace Centre) has stopped all cooperation with Russian institutions (German Aerospace Centre (DLR) 2022). The use of Russian SOJUZ rockets by international partners has also been significantly reduced as a result of the sanctions imposed on Russia (Jones 2023b). The ISS is the only area where cooperation between Russia and the Western spacefaring nations is ongoing: In April 2023, following interim reports of Russia‘s intention to withdraw from the programme after 2024 (tagesschau.de 2022), the partnership was extended until 2028 (Liverpool 2023).

The potential for the civilian use of space was recognised at an international level early on. In 1965, the commercial communications satellite „Intelsat I“ was put into geostationary orbit (Fischer et al. 2019). Since then, satellite communication has, almost without being noticed, become interwoven with everyday life, so much so that it is now impossible to imagine modern society without it. In addition to telecommunications, the transmission of television signals was first realised in the late 1960s and early 1970s, initially in the former Soviet Union (Whalen 2010). In April 1960, the USA also put the world‘s first weather satellite into operation (TIROS I). It enabled researchers to observe large-scale weather phenomena from space for the first time (National Air and Space Museum (NASM) n.d.).

Space travel after the Cold War: intensification and phase of cooperation

The end of the Cold War saw a phase of intensified international co-operation, particularly between the USA and Russia. Although tensions did arise, the construction and ongoing operation of the International Space Station (ISS), which began in 1998, can be seen as a significant milestone. Today, space travel is a global endeavour in which more and more countries are participating or striving to participate.

In 2018, as many as five countries founded their own space agencies: Luxembourg, Saudi Arabia, Greece, Australia and Zimbabwe (Moranta et al. 2020; p. 129). Four more countries followed suit in 2019 (Egypt, Portugal, Turkey and the Philippines). The year 2020 saw the creation of a space agency in El Salvador and the formation of the supranational Latin America and Caribbean Space Agency, whose member states include Mexico, Argentina, Bolivia, Ecuador and Paraguay, with Colombia and Peru as observers. As a result, 88 nations worldwide are now conducting or planning to conduct space activities (Moranta et al. 2021; p. 140). The goals and programmes of state space travel are correspondingly diverse.



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[1] The number includes both trained astronauts and private „space flight participants“.

Table 1

Space Agencies

Name	Acronym	Founding year	Country
National Aeronautics and Space Administration	NASA	1958	USA
Indian Space Research Organisation	ISRO	1969	Indien
European Space Agency	ESA	1975	Europe[2]
Korea Aerospace Research Institute	KARI	1989	South Korea
China National Space Administration	CNSA	1993	China
Japan Aerospace Exploration Agency	AXA	2003	Japan
New Zealand Space Agency		2016	New Zealand
Roskosmos		2016 (predecessor of the same name founded in 1992)	Russia

Current developments: US presidency and China's engagement

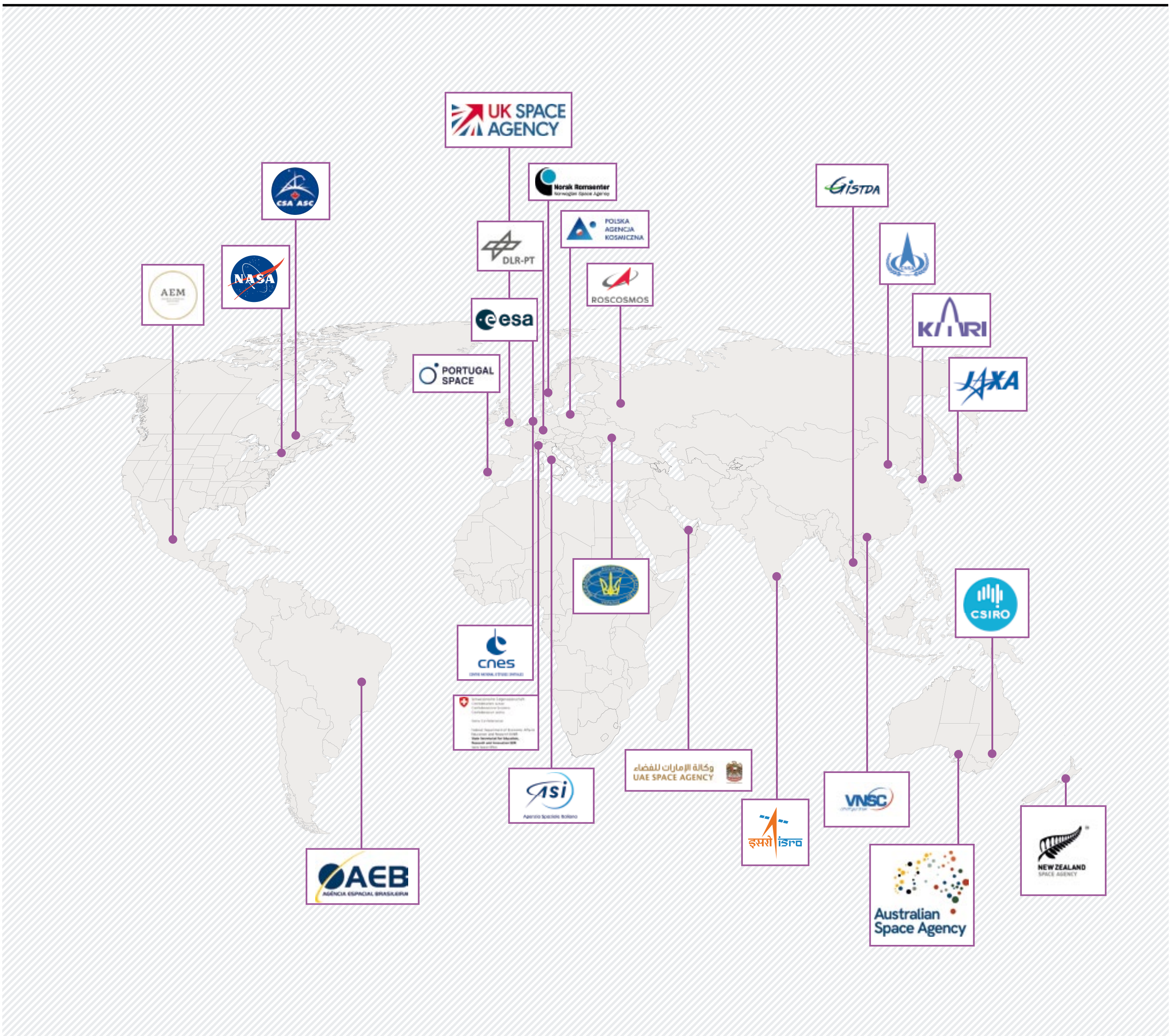
The years 2020 and 2021 were characterised by numerous changes. The change of presidency in the USA had direct consequences for NASA's budgets and programmatic priorities (Foust 2020; Roulette 2021; Space.com 2021; Davenport 2021). It became clear that the Biden administration would continue to pursue Donald Trump's goal of sending a man and a woman to the Moon in 2024, albeit with a delayed target of 2025 (Foust 2021).

China also has developed into an important player in recent years. Its capabilities not only include manned space travel; it also put its own space station, the Tiangong Space Station, into Earth's orbit in November 2022 (Jones 2023c). Since the adoption of the manned space programme in 1992, Chinese space travel has been developing at a rapid pace (Wu 2016). For example, the number of successful rocket launches has risen from 6 launches in 2010 to 64 in 2022, and over 200 spacecraft and satellites are expected to be transported into space in 2023 (Jones 2023a). The Chinese government publishes a white paper on the current situation in space travel and its goals for the next five years. After completing its own space station, China intends to pursue ambitious goals, such as further exploration of the Moon, a mission to return samples from Mars and the exploration of the Jupiter system (Jones 2021a).

[2] Member states: Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, Netherlands, Norway, Poland, Portugal, Romania, Spain, Sweden, Switzerland, United Kingdom. Associate members: Canada, Bulgaria, Latvia, Lithuania, Malta, Slovak Republic and Slovenia.

Figure 2

Overview of space agencies



Source: Own illustration based on International Space Exploration Coordination Group (ISECG 2022)

India is another ambitious player on the international stage, with plans to send Indian astronauts into space and unmanned missions to Venus and Mars in the coming years (Goswami 2021). On 24 August 2023, India became the fourth nation in the world to successfully land an unmanned space probe on the Moon. The Chandrayaan-3 space probe landed in a little-explored region at the south pole of the Earth's satellite (Schwerin 2023). On board is a rover that will analyse the composition of the lunar surface and provide important findings for science (Indian Space Research Organisation (ISRO) n.d.).

Space travel in the future: private companies commercialise space activities

Private companies have worked closely with government space agencies since the beginning of the space age. In the course of increased innovative capacity and cost reductions, space agencies such as NASA and ESA no longer only work with long-established companies such as Lockheed Martin or Boeing, but also support young companies such as Space Exploration Technologies Corporation (SpaceX), founded by Elon Musk in 2002, by changing procurement processes and promoting development (Kind et al. 2020; p. 25ff.). Thanks to financial support from NASA, SpaceX has become one of the leading providers of launch services over the past 20 years; the company carried out 31 successful rocket launches in 2021, followed by 61 launches by the beginning of December 2022 (Statista GmbH 2023b).

Another area in which space activities are increasingly being performed by private companies and thus commercialised is satellite communications. Three companies - SpaceX with its operational Starlink project, Amazon with its planned Kuiper project (Berger 2022) and OneWeb with the project of the same name - are endeavouring to set up so-called „mega constellations", i.e. swarms of thousands of small satellites, providing global broadband Internet coverage in Earth's orbit (see chapter 5.2.2).

Business models based on the processing of data collected in space are also becoming increasingly important. This involves processing data from earth observation and navigation satellites, which is of particular interest to companies in application areas beyond the space industry, such as agriculture, logistics or risk and crisis management (see chapter 5.3.2).

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3.2 A topic of growing relevance

3.2.1 Social aspects

Space plays an influential part in everyday life, even if this is frequently not obvious. Satellite-based technologies such as positioning services, weather observation and telecommunications enable us to navigate to unknown places, access accurate local weather forecasts and communicate almost instantaneously with people on the other side of the world. Against this backdrop, it is hardly surprising that space is increasingly becoming the focus of public attention.

The social debate on space travel is primarily characterised by media coverage. A number of themes are at the forefront. Firstly, the discourse on the benefits of space travel for Earth and society and the closely related question of costs and benefits. In addition, debates about the benefits of manned space travel versus unmanned space travel (satellites, remote sensing) crop up at irregular intervals. Ultimately, the media-effective dissemination of visions of the future, such as the colonisation of Mars or the extraction of resources in space, as well as the public appearances of astronauts, briefly attract the attention of society and generate excitement and a sense of adventure.

Space travel - especially manned space travel - can inspire and motivate us, for example, to change individual behaviour towards fellow human beings and the environment (e.g. Sagan 2011, see box below). Space exploration also generates knowledge that improves our underAs ofing of planet Earth and its formation as well as the solar system, the Milky Way and the universe. Scientific findings from space exploration frequently form the basis of innovations on Earth; NASA alone lists over 2,000 commercial products that have emerged from its work since 1976 on its „NASA Spinoff" website[3] (National Aeronautics and Space Administration (NASA) n.d. b). Technologies created or advanced by space exploration include smartphone cameras, indoor air purification and the food safety assurance processes in the USA (National Aeronautics and Space Administration (NASA) n.d. a). In the medical field in particular, there are many areas of overlap between research for human spaceflight and ap-

[3] https://spinoff.nasa.gov/

plications on Earth, for example in the development of new tools for health monitoring and with regard to a deeper understanding of physiological and psychological processes, which can improve diagnostics and treatments (European Space Agency (ESA) n.d. i).

The fascination of space - how the view from "above" can influence life "below"

The view of Earth from space can show humanity how unique and worthy of protection its planet is. In the past, looking back at Earth has evoked feelings of awe, self-transcendence and a strong sense of connection with all of humanity and nature on Earth in astronauts (Yaden et al. 2016; Voski 2020). The perceived fragility of the Earth as a whole has been repeatedly emphasised and played a role in the emergence of the environmental movement (Banner 2020).

This effect of viewing the earth "from the outside" is known as the Overview Effect (White 1987). It can also be observed when viewing images of the Earth taken from space (Yaden et al. 2016). Among the most famous of these photographs are the "Earthrise" images from 1968 (image of the Earth from the surface of the Moon; Yaden et al. 2016) and "Pale Blue Dot" from 1990 (image of the Earth from the Voyager 1 probe; National Aeronautics and Space Administration (NASA) 2019d). NASA scientist Carl Sagan famously said the following about the "Pale Blue Dot" photo he advocated: "Look again at the dot. This is here. This is home. This is us. Everyone you love, everyone you know, everyone you've ever heard of, every person who has ever existed has lived their life on it" (Sagan 2011, translation by Banner (2020).

Against this background, it is not surprising that many astronauts are particularly concerned about environmental issues (Voski 2020). Some specifically use their public profile to draw attention to environmental concerns, such as the French astronaut Thomas Pesquet, who became an FAO Goodwill Ambassador after his stay on the ISS out of concern for the environment (Blendis 2022). German astronaut Alexander Gerst also posted highly publicised photos of natural disasters from space during his stay on the ISS (Tagesspiegel 2018). After his return, Gerst broadcast a video appeal for the opening of the 2018 UN World Climate Conference (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) 2018) and warned of the consequences of climate change in a speech to the Bundestag's Economic Affairs Committee (Tagesspiegel 2019).

The debate about manned and unmanned space travel has continued with varying intensity since the beginning of the space age. There have been several disasters in manned spaceflight that have cost human lives. Two space shuttle disasters, involving the „Challenger" in 1986 and „Columbia" in 2003 took the lives of all those on board (14 in total) (Uri 2021; Uri 2023).

In view of the loss of human life, various arguments and counter-arguments are put forward: from a benefits perspective, the question is asked as to what added value human space travellers bring compared to technical systems such as satellites, space probes and robotic systems. From a financial perspective, the costs of manned spaceflight are compared to unmanned spaceflight. From a technical perspective, it is discussed which technologies are required for manned spaceflight and which technical innovations can be produced by manned vs. unmanned spaceflight, e.g. in the field of robotics. From a scientific perspective, the focus is on what research is possible in the context of unmanned or manned spaceflight and what benefits these findings can have for scientific progress, e.g. for medical therapies or robotic systems. There is also the philosophical perspective, which deals with the question of how the manned exploration of space influences the perception of the universe and the self-image of the individual (see box on p. 27).

However, it is just as conceivable that the importance of individual arguments will diminish in periods during which manned spaceflight proceeds without any significant incidents or setbacks. Due to the various possible perspectives, the weighting of individual arguments and the different objectives of spacefaring nations, it is not possible at this point to formulate a conclusive result of this ongoing discussion. Ultimately, from an environmental perspective, it can be stated that space flights have a negative impact on the environment, regardless of whether they are manned or unmanned. Manned space flights has led to a rising number of launches for space tourism, while unmanned spaceflight is predominantly responsible for an increase in space debris in Earth's orbit.

The benefits of space travel for technological, scientific or social progress - be it manned or unmanned space travel - are constantly questioned when the benefits are set in relation to the costs.

The public perception of the costs of space travel is subject to significant distortion. A representative survey[4] (Harris Interactive 2019) in Europe has shown that the annual tax expenditure for space travel is greatly overestimated. While the actual costs are around 10 euros per capita per year (in relation to the population of the countries surveyed), respondents in Germany estimated costs of around 284 euros per capita per year. The average estimate was around 245 euros. However, the same survey also showed that there is nevertheless a high level of approval for space travel among the population as a whole and that space activities are considered important (Harris Interactive 2019). Despite developments such as the significant increase in the ESA budget in 2022 by 17% to 7.15 billion euros (European Space Agency (ESA) 2022a; European Space Agency (ESA) 2022c), the per capita costs of space travel have by no means risen to the level estimated in the study: the estimated budget for 2024 for the entire aerospace sector is 2.4 billion euros (Federal Ministry of Economics and Climate Protection (BMWK) 2023), representing an average of € 28.81 per citizen (population data: Statista GmbH 2023c). Nevertheless, this represents a significant increase in taxpayer money spent on space travel.

Public interest in space travel in Germany is not only due to its economic importance (see chapter 3.2), but above all due to the publicity surrounding German astronauts and successes in unmanned space travel. The two missions of the German astronaut Alexander Gerst (European Space Agency (ESA) n.d. a) on the International Space Station ISS (2014 and 2018) attracted a great deal of media attention. Matthias Maurer was the fourth German astronaut to work on the ISS from 11 November 2021 to 5 May 2022 (European Space Agency (ESA) n.d. h). The „Astronaut" initiative, launched by entrepreneur Claudia Kessler, also attracted public interest. The initiative aims to train a German female astronaut for the first time and enable her to work on the ISS (Foundation for the first female German astronaut in 2022).

Unmanned space travel with significant German involvement have also achieved success in the recent past. These include the successful landing of the „Philae" space probe on comet 67P/Churyumov-Gerasimenko in 2014 (European Space Agency (ESA) n.d. e).

3.2.2 Economic aspects

The global space market, i.e. the industrial sector whose value creation is related to space activities, is a growth market that encompasses various segments. In addition to national space budgets, it includes satellite launches/services, ground stations/services and space-related products and services. When quoting figures for the individual market segments below, it should be noted that two different sources (BRYCE Space and Technology 2022; Space Foundation 2022) arrive at different estimates regarding the size of the market segments due to their different methodological approaches (Rencelj et al. 2023; p. 126).

1. With regard to the first market segment, the national space budgets, Figure 4 shows an increase in cumulative global government spending on space since 2016 (Rencelj et al. 2023; p. 139). The range is between USD 62.2 billion and USD 82.9 billion in 2016 and USD 92.4 billion and USD 107.3 billion in 2021. The US budget accounts for the largest share of this: at USD 51.8 billion to USD 54.59 billion, it is more than all other space-faring nations combined (Rencelj et al. 2023; p. 141). The consolidated budget for European space travel in 2021 totalled 14.1 billion euros (Rencelj et al. 2023; p. 141). Of this budget, approx. 6.49 billion, almost half. went to the ESA (European Space Agency (ESA) 2021a). In absolute figures, German spending on space in 2021 totalled around 2.38 billion euros, i.e. only around 2.5% of global government spending (Rencelj et al. 2023; p. 141). In terms of expenditure in relation to GDP, Germany was the sixth largest space nation in the world in 2021 (USA: 0.23% of GDP, Germany: 0.06% of GDP; Rencelj et al. 2023; p. 142).

[4] 5,227 participating residents from Germany, France, Italy, Spain and the United Kingdom.

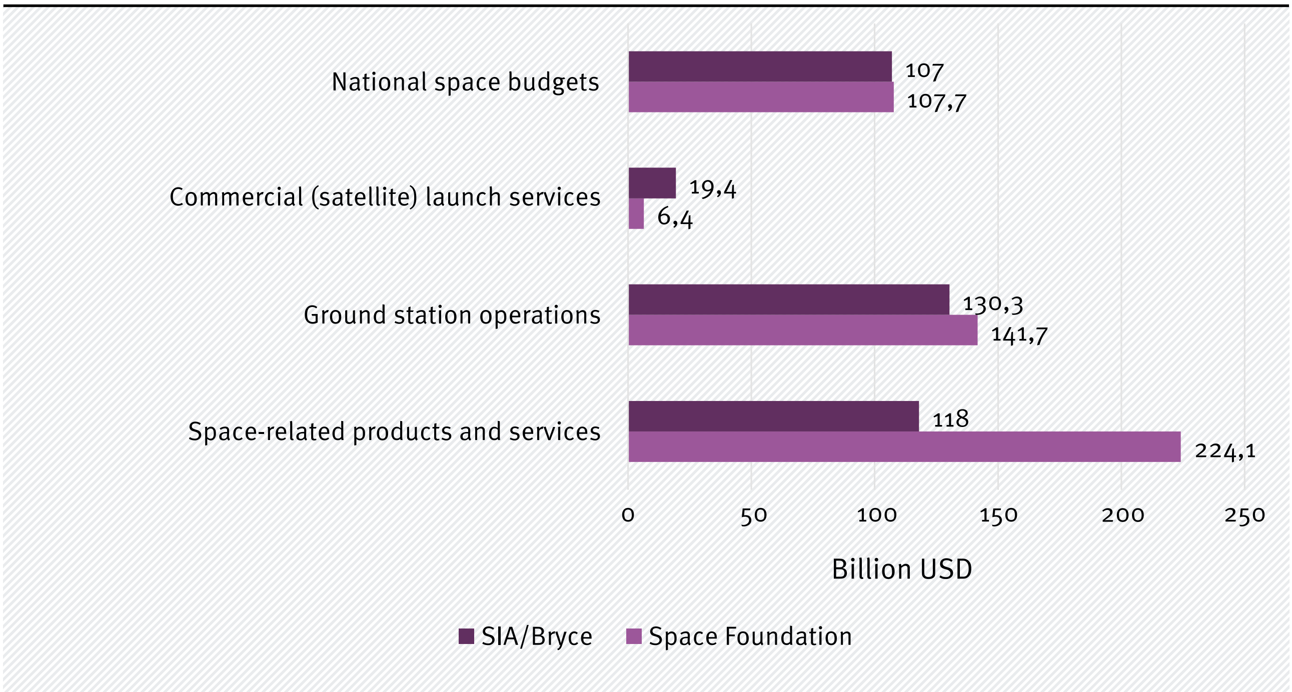
2. The second market segment of the global space market is commercial (satellite) launch services (see Figure 5). Depending on the structure of this market segment, its volume totalled between USD 6.4 billion and USD 19.4 billion in 2021 and is now trending upwards again after a decline in 2019 (Rencelj et al. 2023; p. 129ff.). At this point, it should be mentioned that there is a close link between the commercial market segment and the area supported by public funds. For example, the US company SpaceX sells a large proportion of its launch services to NASA and has also been partially subsidised with public funds (Kind et al. 2020).

3. A third market segment is formed by services associated with the operation of ground stations (e.g. control centres, data processing centres, receiving and observation stations and communications infrastructure) (see Figure 5). With a turnover of between USD 130.3 billion and USD 141.7 billion, it is one of the largest market segments and is increasing in size (Rencelj et al. 2023; p. 132).

4. The fourth market segment is space-related products and services (see Figure 5). These include end customer services in the form of consumer services, e.g. TV and radio (between 42 % and 83 %), communication services (between 8 % and 15 %) and remote sensing (between 1 % and 2 %). Depending on whether PNT services (Position, Navigation & Timing ; 42 %) are included (Space Foundation 2022 does include them, while BRYCE Space and Technology 2022 does not), the market volume for 2021 was between USD 118.3 billion and USD 224.1 billion (Rencelj et al. 2023; p. 133f.).

Figure 3

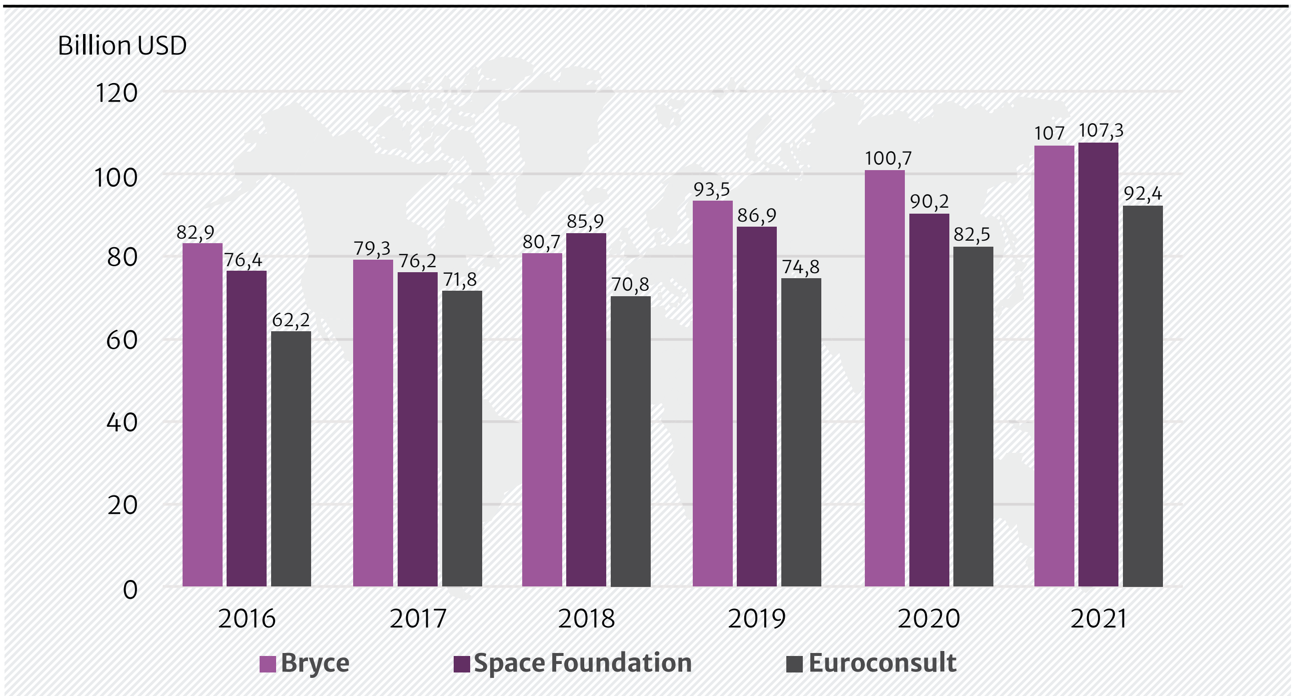
Volumes of the four market segments in USD billions for 2021



Source: Own illustration based on data from Rencelj et al. 2023, P. 125

Figure 4

Development of the global institutional space budget between 2016 and 2021 (in USD billion)



Source: Own illustration based on data from Rencelj et al. 2023; P. 139

The economic benefits of public spending on space are often questioned (see chapter 3.2.1), but an analysis by NASA for the year 2019 (National Aeronautics and Space Administration (NASA) 2022) shows that a high economic benefit can be achieved. For example, NASA's budget in 2019 (USD 21.5 billion) generated an economic output of USD 64 billion. More than 312,000 jobs were directly dependent on NASA projects in 2019. In addition to these effects within the USA, NASA also cooperates with public and private sector players worldwide, which means there are additional economic effects not included in the above-mentioned figure.

In Germany, the aerospace industry generated sales of €31.4 billion in 2021, 72% of which was attributable to exports; 8% of the industry's sales were invested in research and development (Federal Ministry of Economics and Climate Protection (BMWK) 2022).

3.2.3 Legal and political aspects

Fundamental aspects of access to space and its utilisation and exploration have been regulated under international law since 1967 in the Outer Space Treaty (United Nations (UN) n.d.). By August 2023, the Outer Space Treaty had been ratified by 114 states, including all leading spacefaring nations, and signed by a further 22 (United Nations Office for Disarmament Affairs (UNODA) n.d.). It states that activities in outer space should be carried out for the benefit and in the interest of humanity (Art. 1), that outer space and celestial bodies are equally usable by all states and cannot become part of the territory of individual states (Art. 2 and 3). All states are responsible for their activities in outer space, as well as for the non-state activities of their nationals. Non-governmental activities must be authorised by the states and monitored for compliance with the Outer Space Treaty (Art. 6). All states are liable for any damage caused by objects they launch into outer space (Art. 7). All activities should be carried out with the interests of all states on Earth in mind. States are required to perform activities in order to avoid contamination of outer space (Art. 9).

Additional international treaties and conventions, such as the Outer Space Convention (1968), the Outer Space Liability Convention (1972), the Outer Space Registration Convention (1976) and the Moon Treaty (Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, 1979) specify the points set out in the Outer Space Treaty. The Outer Space Rescue Convention is derived from Art. 5 of the Outer Space Treaty, the Outer Space Liability Convention from Art. 7, the Outer Space Registration Convention from Art. 8, and the Moon Treaty from the entire Outer Space Treaty, in which the Moon is specifically and repeatedly mentioned as a celestial body. However, only 18 nations worldwide have ratified the Moon Treaty and a further 4 nations have signed it, including none of the leading spacefaring nations - making the Moon Treaty largely meaningless in practice (Schladebach 2019).

Overall, there are major gaps in the international treaties in view of the dynamic - especially commercial - developments of recent decades. There is, therefore, a need for additional regulation (Federal Government 2018; Federal Government 2019b). The following three aspects in particular illustrate this need:

1. The increasing number of artificial objects in space exacerbates the problem of space debris (see chapter 4.2.4). In order to be able to identify the objects sent into space, the Space Registration Convention was adopted in 1975 as a supplementary treaty to the Outer Space Treaty (United Nations Office For Outer Space Affairs (UNOOSA) 1974; Federal Foreign Office 2023). This international agreement obliges all contracting parties to record the objects they launch in a national register. In addition, this must be made available in the international, freely accessible register administered by the United Nations Office for Outer Space Affairs (UNOOSA). Over 14,800 objects have been registered since 1957 (as of 03/09/2023; United Nations Office For Outer Space Affairs (UNOOSA) 2023). In addition, it is estimated that there are over 100,000 pieces of space debris larger than one centimetre (36,500 larger than ten centimetres; ESA Space Debris Office 2021). The main criticism of the Space Registration Convention relates to the fact that registration is sometimes delayed by months or even years, meaning that there are de facto gaps in which unregistered objects are active in space whose position, lifespan and type remain unknown to other spacefaring nations.

2. Closely linked to the problem of the increasing number of objects in space and the resulting problem of space debris is the legal question of liability in the event of damage, for example due to the collision of two satellites. So-called space liability is regulated in the 1972 Outer Space Liability Convention (United Nations Office For Outer Space Affairs (UNOOSA) 1972). Together with the Space Registration Convention, it should be possible to identify the space objects concerned in the event of damage. The Outer Space Liability Convention primarily regulates the provision of appropriate compensation in the event of damage (Federal Foreign Office 2023). On the one hand, the state that is considered the launching state or to which the object causing the damage can be assigned can be held liable. The operator of the space object, e.g. a company, is also subject to potential liability (Richter and Schwenke 2021; 59:00). Space objects are all man-made objects that are intended for use in space. There have also been other cases that fall within the scope of the Outer Space Liability Convention, in which the issues were resolved in other ways (Richter and Schwenke 2021; 59:00). For example, the crash of the Soviet nuclear-powered satellite „Kosmos 954“ over uninhabited territory in Canada in 1978 triggered a dispute over compensation. Although this was eventually settled (Cohen 1984; Parks 2009), it also highlighted the fact that environmental damage was not directly regulated by the Liability Convention at that time. This led to the adoption of a UN resolution in 1992 and an updated and more ambitious version of the Outer Space Liability Convention in 2009 in the form of the so-called „Safety Framework“ (United Nations Committee on the Peaceful Uses of Outer Space Scientific and Technical Subcommittee (COPUOS) and International Atomic Energy Agency (IAEA) 2009).

National legislation that follows the provisions of the Outer Space Treaty can partially exempt states from their unlimited liability towards private space companies. This serves to protect states from the actions of unreliable space companies (Schladebach 2019). This has not yet been regulated in Germany, while countries such as France, for example, have set upper liability limits for companies, up to which the companies are liable for damages before the state steps in (Sürig 2021c).

3. A third aspect in which national legislation complements international regulations is the regulation of private-sector activities, using the example of resource extraction in outer space. Both the Outer Space Treaty and the Moon Treaty stipulate in principle that territories in outer space cannot be appropriated by individual nations. Nevertheless, the question of resource extraction is legally controversial, as it has not been conclusively clarified whether it is carried out for the benefit of humanity or for specific commercial interests. This has led to individual nations, so far the USA, Luxembourg, the United Arab Emirates and Japan (Gradoni 2018; German Federal Government 2019b; Emirates News Agency (WAM) 2020; JapanWelt 2021; Luxembourg Space Agency (LSA) 2021) creating national laws on this aspect. These laws intend to create a legally secure framework for companies seeking to mine resources in space. To date, there has been no practical application of resource extraction (see chapter 5.4), but legal regulations should be seen as an incentive for companies to establish their business activities in these countries. It is therefore to be expected that other countries will also introduce national legislation. This will also increase the need for multilateral and bilateral coordination that is already evident, because, as already mentioned, the technical, economic and political complexity of space travel means that it is difficult for countries to pursue it on their own. In 2019, for example, the USA and Luxembourg issued a declaration of intent on future cooperation in the mining of resources (The Luxembourg government 2019; Zeit Online 2019). New agreements, on the other hand, harbour the risk of coming into conflict with existing regulations under international law: The „Artemis Accords - Principles for Cooperation in the Civil Exploration and Use of the Moon, Mars, Comets, and Asteroids for Peaceful Purposes“ initiated by the USA (National Aeronautics and Space Administration (NASA) 2020b) have been criticised because, among other things, they provide for the establishment of safety zones in Section 11, in which the designating actor can declare a right of first refusal to carry out its activities undisturbed (Stirn 2020). However, the Outer Space Treaty prohibits such appropriation of areas in outer space and the associated restriction of the activities of other actors (see above; Art. 2, 3, 6). Although the Artemis Accords are merely guidelines without legally binding force, critics fear that this will lead to the establishment of customary law in outer space, which is intended to weaken the existing regulations under international law in the long term (Stirn 2020).

President Lyndon B. Johnson and the USSR Ambassador, Anatoly Dobrynin, shake hands at the signing of the Outer Space Treaty, January 27, 1967 / © Digital Public Library of America

In Germany, commercial space activities are gaining momentum (see chapter 3.2) and therefore the need for legally binding regulations within which companies can develop their business activities is also increasing. As mentioned, there is no legal framework for companies in the area of liability. Companies, especially start-ups, are confronted with business risks if they are required to bear unlimited liability. German space companies also want the aspect of resource depletion to become part of a national space law (Wachter et al. 2018; p. 14). In November 2021, the Federation of German Industries created a New Space Initiative, which is to be active in individual working groups on various aspects, including a national space law (Sürig 2021b; Wachter 2021). The German government has been discussing a national space law since 2017. It has not yet been implemented (Sürig 2019; Sürig 2021c), even though the coalition agreement between the CDU/CSU and SPD of 2018 mentioned this as a goal (Federal Government 2019a; p. 58). However, the 2021 coalition agreement between the SPD, FDP and Bündnis 90/Die Grünen makes no further reference to this, even though space travel and New Space are recognised as technologies of the future (Social Democratic Party of Germany (SPD) et al. 2021; p. 27). As described in chapa ter 3.2, the drafting of a Space Act is planned after the Federal Government‘s space strategy, which is currently being developed, has been completed (as of 2 September 2023).

3.2.4 Space nation Germany

Today, Germany plays an important role in international space travel and space exploration. Germany makes the second-highest financial contribution to the ESA budget after France (see chapter 3.2.2). Important ESA sites are located in Germany, including the Satellite Control Centre (ESOC) in Darmstadt, the European Astronaut Centre (EAC) in Cologne and the Columbus Control Centre (Col-CC) in Oberpfaffenhofen, from where the European Columbus module of the International Space Station (ISS) is controlled.

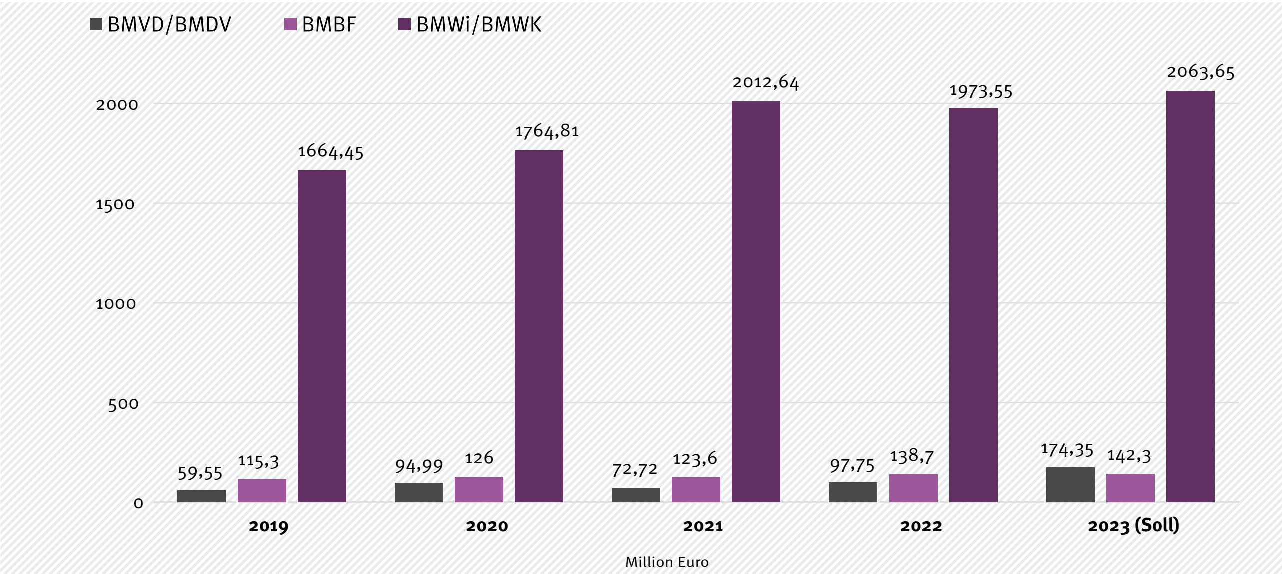
The first German space strategy was published in 2010 (Federal Ministry of Economics and Technology (BMWi) 2012; p. 2). Although an update was planned for the last legislative period (2017 - 2021), it was not implemented. In the coalition agreement of the current federal government, the updating of the German space strategy was once again set as a goal (Social Democratic Party of Germany (SPD) et al. 2021; p. 27). The Federation of German Industries (BDI) and the German Aerospace Industries Association (BDLI) also considered it necessary to update the strategy in order to strengthen the position of German aerospace (Thalhofer 2021; Wachter et al. 2021). The public strategy consultation process was finalised in April 2023 with the involvement of representatives from science, industry, public authorities and ministries (Federal Government 2023; p. 3). It was adopted by the Federal Cabinet in September 2023 (Federal Ministry of Economics and Climate Protection (BMWK) 2022). The drafting of a German Space Act is planned once the space strategy is finalised (Federal Government 2023; p. 13).

As an additional funding programme, the German Space Agency‘s INNOspace initiative is intended to provide targeted support to companies from the new space sector and enter into close dialogue with them, such as the developers of smaller launch systems (Federal Government 2023; p. 8).

The planned public expenditure on aerospace for 2024 amounts to around EUR 2.4 billion, an increase of EUR 1.75 billion compared to 2009 (Federal Ministry of Economics and Climate Protection (BMWK) 2023). A large part of this is the responsibility of the Federal Ministry of Economic Affairs and Climate Protection (BMWK), which is also responsible for the German contribution to ESA (Federal Ministry of Education and Research (BMBF) n.d.), finances the National Programme for Space and Innovation and supports the operation of the German Aerospace Centre (DLR) (Federal Ministry of Finance (BMF) 2021a; Federal Ministry of Finance (BMF) 2021b). The Federal Ministry of Education and Research (BMBF), the Federal Ministry of Digital and Transport (BMDV) and the Federal Ministry of Defence (BMVg) are involved in the development and operation of space technologies and space research (Federal Ministry of Education and Research (BMBF) 2021a; Federal Ministry of Finance (BMF) 2020).

Figure 5

Expenditure of the federal ministries[5] on space from 2019 to 2023



Source: Own illustration based on data from bundeshaushalt.de

There are currently more than 600 German companies in science, research and industry which are directly involved in space travel (Zeitler et al. 2019). One of the best-known players is DLR, which is responsible for space operations, conducts space research and now maintains 55 institutes at 30 locations in Germany (German Aerospace Centre (DLR) 2021). Within the DLR, two institutes focus on space issues. The German Space Agency represents the Federal Government in international committees and plans and implements German space activities (German Aerospace Centre (DLR) 2021). The German Remote Sensing Data Centre (DFD) and the Institute of Remote Sensing Technology (IMF) form DLR‘s Earth Observation Center (EOC), which deals with Earth observation and its application (German Aerospace Centre (DLR) n.d.).

German companies are cooperation partners in the development of space technologies, e.g. the Airbus Defence and Space division of the Airbus Group in Bremen is constructing the European Service Module, which is expected to be part of the Orion lunar module on its return to the Moon in 2025 (Amos 2020).

Another important economic player is OHB SE, also based in Bremen, which manufactures satellites and components for space probes, such as all 34 satellites for the European GALILEO system (OHB SE 2023). The „new space“ scene also includes start-ups such as ExoLaunch GmbH, which offers ride sharing (the joint use of a rocket to transport satellites from several companies into space) (Exolaunch 2022).

Economic players active in the aerospace sector are represented by the German Aerospace Industries Association (BDLI)[6] and the Federation of German Industries (BDI); Wiskow 2019), through which they lobby politicians. In 2022, German companies in the aerospace sector generated sales totalling around 2.6 billion euros and employed around 9,000 people (Statista GmbH 2023d; Statista GmbH 2023e).

Space players from industry, science and space management (ESA and DLR facilities for space operations) are primarily located in Bavaria, Bremen, Baden-Württemberg, Hesse, Berlin and North Rhine-Westphalia. For young companies and start-ups, the geographical

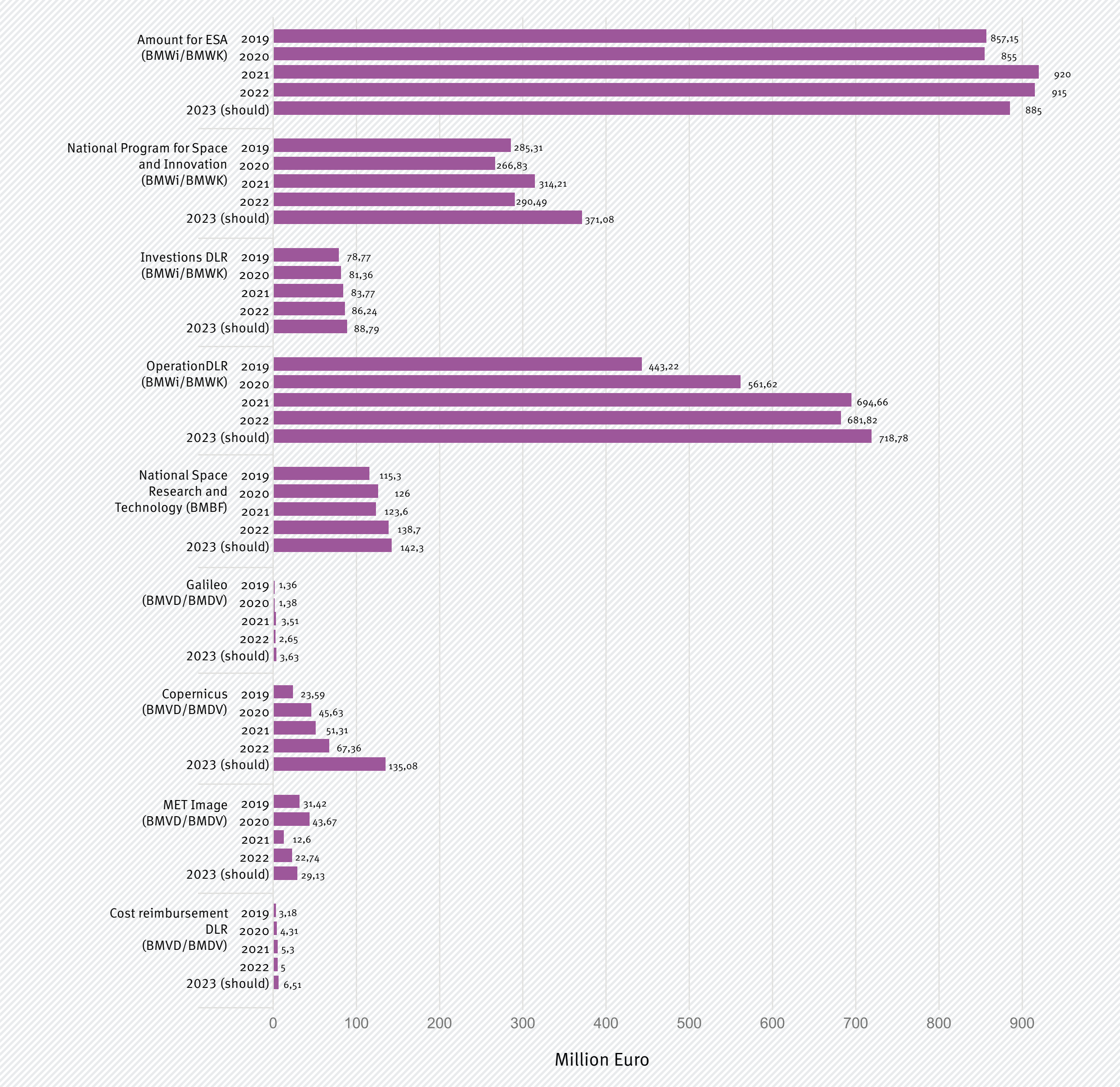
[5] The Federal Ministry of Defence is not included in the presentation, as military aspects are not part of the trend analysis.

[6] BDLI campaign on the benefits of space travel: https://www.die-raumfahrt.de/

proximity to research institutes and incubators, which are facilities to support start-ups, of the ESA Business Incubator Centre Programme (ESA BIC) programme plays an important role in gaining access to expertise as well as technical and financial support. Strategic networking between players from science, industry and politics also takes place within the framework of state-funded cluster initiatives[7] and industry networks, four of which focus on the aerospace sector: bavAIRia e.V. in Bavaria, AVIASPACE BREMEN e.V. in Bremen, the Transport, Mobility and Logistics cluster in Berlin-Brandenburg and the BodenseeAIRea cluster in Baden-Württemberg (Kind et al. 2020). (Kind et al. 2020).

Figure 6

Federal ministries' expenditure on space from 2019 to 2023, broken down by individual items



Source: Own illustration based on data from bundeshaushalt.de

[7] Further information on the cluster policy of BMWK and BMBF: https://www.clusterplattform.de/

3.3 Ecologically sustainable use of outer space - current discussion and system limits in the report

3.3.1 The extension of protected goods to outer space

On Earth, protected goods are now clearly defined; however,[8] when it comes to the utilisation and exploration of space, research and practice offer a range of responses to the question of protected goods.

The consensus is that protected goods include people, their health and their environment on earth. According to the Environmental Impact Assessment Act, the environment includes „animals, plants and biodiversity, land, soil, water, air, climate and landscape, cultural heritage and other material assets as well as the interaction between the aforementioned protected assets" (UVPG § 2). There is disagreement as to whether and to what extent the human environment beyond airspace, i.e. outer space, also counts as a protected good. The Outer Space Treaty of 1967 (see chapter 0), the centrepiece of the international legal regime on outer space, focuses on the free, equal, cooperative and peaceful use and exploration of outer space for the benefit of all. The Outer Space Treaty contains no provision on the protection of outer space (Newman and Williamson 2018). However, the provisions of the Outer Space Treaty also imply that outer space is not a legal vacuum, but that its use is governed by principles (Newman and Williamson 2018).

The Moon Treaty goes beyond the provisions of the Outer Space Treaty. However, none of the space nations have joined the treaty since it came into force in 1984; most of the contracting parties do not have their own space programme (United Nations Office for Disarmament Affairs (UNODA) 2020). The treaty stipulates that the exploration and utilisation of the Moon and other celestial bodies should also take into account „the interests of future generations" (translation by the authors, Art. 4 para. 1). In addition, the states parties should „take measures to prevent the disturbance of the existing balance of [the] environment [of the Moon]" (author's translation, Art. 7, para. generations" (author's transl; United Nations Office For Outer Space Affairs (UNOOSA) 2018b; I 6.). The guidelines relate to the Low Earth Orbit (LEO), which is defined in chapter 4.1.4.

Various scientists go beyond this focus on Low Earth Orbit and call for geostationary orbit (GEO), the cemetery orbit above it (i.e. the space above the GEO that is used for the disposal of space debris; see chapter 4.1.4) and other celestial bodies to be defined as protected assets (Kramer 2020). This is justified by the fact that, similar to the Low Earth Orbit, space debris in other orbits could also make utilisation and exploration more difficult or impossible for future generations. Experience with resource extraction on Earth shows that this often goes hand in hand with interference with the environment and environmental impacts (Newman and Williamson 2018). Other orbits and celestial bodies also represent a limited resource. Human intervention contributes to their pollution, as in the case of the Low Earth Orbit through space debris (Losch 2020). Impacts from human activities on other celestial bodies, such as the use of their equally finite resources, can lead to irreversible damage, which could hamper future exploration and utilisation (Galli and Losch 2019).

This trend report takes a closer look at the definition of protected goods in line with current scientific analyses. Based on previous analyses, it appears conclusive that the goods worth protecting are humans and their health, as well as the human environment on Earth and in space. The space environment includes the Low Earth Orbit as well as the geostationary orbit, the cemetery orbit and other celestial bodies. Like the terrestrial environment, these areas of outer space should be recognised as legally binding in their need for protection and thus become protected goods.

3.3.2 Utilisation and exploration of outer space - state of research and practice from an environmental perspective

The research landscape regarding the utilisation of space is changing, primarily triggered by climate change. Research is increasingly focussing on analysing the environmental impact of space travel. The United Nations Office for Outer Space Affairs (UNOOSA) is increasingly committed to the sustainable use

[8] In the following, the term „protected goods" is not used as a legal term, but to generally characterise which goods should be designated as worthy of protection.

1). This could be done „by the introduction of adverse changes into that environment, by its contamination by the introduction of substances not belonging to the environment, or by other means. States Parties also agree to take measures to prevent degradation of the Earth‘s environment by the introduction of extraterrestrial matter or otherwise“ (authors‘ translation, Art. 7, para. 1). Accordingly, sustainability issues of intergenerational justice and the preservation of the existing environmental balance are also addressed in outer space.

In the voluntary „Guidelines for the Long-term Sustainability of Outer Space Activities“ of the United Nations COPUOS (Committee on the Peaceful Uses of Outer Space), which were adopted by the Committee in 2019, Earth's orbit is described as a finite resource (United Nations Office For Outer Space Affairs (UNOOSA) 2018b; I 1.). The reason for this is that human interference in the Earth's orbit could have an impact on the long-term feasibility of spaceflight activities. Conversely, activities in space, such as Earth observation using satellites (see chapter 5.3), are important for achieving the goals of the UN 2030 Agenda for Sustainable Development. According to the guidelines, cooperation between states is necessary to „avoid harm to the space environment“ (translation by the authors; United Nations Office For Outer Space Affairs (UNOOSA) 2018b; I 1.). However, its voluntary nature makes it difficult to prevent space debris and further development of the legal framework is therefore required (Schladebach 2019).

COPUOS also formulates a sustainability principle for the utilisation and exploration of outer space. Accordingly, the sustainable utilisation and exploration of outer space in this context includes „maintaining the conduct of space activities for an indefinite period of time in such a way as to ensure equitable access to the benefits of the exploration and utilisation of outer space for peaceful purposes. This should fulfil the needs of present generations while preserving the environment in outer space for future generations.“[9] (Translation by the authors; United Nations Office For Outer Space Affairs (UNOOSA) 2018b; I 5.). It is thus explicitly emphasised here that the „space environment should be preserved, for present and future of outer space, taking into account the United Nations‘ Sustainable Development Goals (SDGs): for example, by adopting the „Guidelines for the Long-Term Sustainability of Outer Space Activities“ (United Nations Office For Outer Space Affairs (UNOOSA) 2018b) and the resolution adopted by the UN General Assembly on 25 October 2021 entitled „The Space2030‘ Agenda: space as a driver of sustainable development“, which explicitly focuses on the use of outer space to achieve the SDGs (see also chapter 6.2.4; United Nations (UN) 2021).

The utilisation of space from a sustainability perspective can basically be divided into three areas:

1. the application of technical systems on earth, e.g. for analysing earth observation data obtained in space,

2. the manufacture and disposal of these systems, and

3. all actions taking place in space (in-situ procedures).

- According to UNOOSA, the use of Earth observation and improved communication systems promises to have a positive impact on the SDGs (United Nations Office For Outer Space Affairs (UNOOSA) 2018a). Earth observation systems and simulations also improve the basis for further environmental research and political measures, for example to reduce greenhouse gases (Velden 2021).

- However, technical systems that are to be used for fundamentally positive interventions (primarily satellites) are associated with negative consequences for the environment through their production, their transport into space, their operation and their fate at the end of their life cycle (see chapter 4.2). This concerns, among other things, the depletion of resources required for production (Dallas et al. 2020b), emissions during launch (Durrieu and Nelson 2013) and the satellite‘s fate as space debris in orbit or the emissions produced when it burns up in the Earth‘s atmosphere (see chapter 4.2.4). The extent of these environmental

[9] The English passage reads: „The long-term sustainability of outer space activities is defined as the ability to maintain the conduct of space activities indefinitely into the future in a manner that realises the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, in order to meet the needs of the present generations while preserving the outer space environment for future generations.“ (United Nations Office For Outer Space Affairs (UNOOSA) 2018b, I 5.)

impacts is not least a consequence of the neglect of the sustainability perspective in the development of space travel to date.

Technical innovations such as lighter launch vehicles and satellites (Keronite 2023) and green propulsion systems (Bilby 2019) are intended to minimise the impact of space travel on the terrestrial environment. Research into the reuse of space debris is also intended to protect the Earth's orbit from pollution (see chapter 4.1). Although research into technologies for implementing sustainability principles in space travel is not yet widespread in practice, some companies see potential in the sustainable utilisation of space. This is reflected in the development of scaffolding systems that can carry several small satellites at the same time (German Orbital Systems n.d.), the development of a „rubbish collection system" for space (ClearSpace n.d.) and the folding sail „On Angels Wings" for slowing down satellites at the end of their life cycle, which favours complete burning up on re-entry into the atmosphere (High Performance Space Structure Systems (HPS) n.d.) .

- Another area of research focusses on activities in space, so-called in-situ processes. The commercialisation of space travel is driving research into the colonisation of celestial bodies, for example (Kramer 2017). As a sub-category of in-situ processes, „in-orbit operations" - i.e. procedures that can be carried out directly in Earth's orbit - enable the remote-controlled or autonomous repair of satellites and space stations and the assembly of technical systems (Sturm 2020).

  Operating the associated infrastructure during the useful life of the system (see chapter 4.2.1) makes a change in the night sky possible due to the large number of illuminated satellites in Earth's orbit (Seidler 2019) . Shielding the reflection should help to avoid light pollution (NOIRlab 2021) .

  Research is also being conducted into resource extraction in space. In view of future long-term voyages in space and greater distances, this can save on transport routes and open up further market potential. The consequences of resource extraction on site are viewed critically by scientists and are expected to have a major impact on the soil, water and climate of the celestial body (Kramer 2014). Even on shorter voyages, microorganisms that astronauts inevitably carry with them can lead to unforeseen consequences for the planet's existing ecosystem or distort exploration research (Johnson et al. 2017).

There is a strong interest in the utilisation of space on the part of private and state actors. However, to date, it is mainly state actors that have been concerned with the sustainability of their space activities, while private companies have rarely focussed on the consideration of possible environmental impacts and serious consequences. The World Economic Forum, in cooperation with other space actors, examines the environmental compatibility of individual missions using a „Space Sustainability Rating" in order to bring about a change in behaviour in the implementation of space flight activities (World Economic Forum n.d.). However, participation in the rating is voluntary. Individual government space organisations, including ESA, are already investigating the environmental impact of space activities with the Clean Space Initiative and alongside NASA. In Belgium and France, environmental impact assessments of space activities have been carried out, which also include the extraterrestrial consequences of space utilisation (cf. the presentation in Mustow 2018).

Due to the increasing urgency of the fight against climate change, the resulting rise in demand for remote sensing data and the need to further minimise negative environmental impacts, research into the sustainable use of space is also increasing. For the time being, the focus of the innovations developed is increasingly on new technical systems to minimise the use of resources in space travel. Sustainable strategies such as the environmental assessment of individual activities offer potential that has not yet been fully utilised. In future, this should be taken into account, or even be a top priority, before innovations and the further utilisation of space are pursued.

4

Space and the environment: impact of technical systems

4.1 Technical systems for space exploration

Technical systems that are required to open up access to space include

- ground-based infrastructure, i.e. systems used to control and monitor space travel, launch launchers, communication and data processing (see chapter 4.1.1),
- launchers (4.1.2),
- spacecraft, i.e. manned and unmanned spacecraft and stations (4.1.3)
- a large number of other so-called payloads, i.e. primarily satellites and space probes (4.1.4).

4.1.1 Infrastructure on the ground

Ground-based infrastructure is essential for space travel. Without suitable launch sites, launch vehicles would not be able to leave the ground. These so-called spaceports now exist in increasing numbers (currently 28 worldwide; see chapter 5.1) in various countries. However, not every location on Earth is equally suitable for operating a spaceport. The Earth's rotational speed can be used, for example, to give a launching rocket a basic speed. Launch sites near the equator are particularly suitable for achieving geostationary orbits with efficient energy expenditure. The operation of spaceports is associated with considerable risks in terms of the risk of accidents during rocket launches. For this reason, rocket launch trajectories are primarily located above sparsely populated coastal areas so that the risk of danger is minimised. Finally, the political and economic situation can also be a motivation for the construction and operation of a spaceport, as can the climatic conditions[10] under which regular launch operations should be possible (Albat 2011; p. 192ff.).

An example of the diverse requirements for the location of a space centre is the one in Kourou, French Guyana, which is currently used for the majority of European space travel (European Space Agency (ESA) n.d. g). Its location on French territory in South America offers a number of advantages over other spaceports. For example, at 5°3' degrees north latitude, it is close to the equator (European Space Agency (ESA) n.d. g; Lorenzen 2009). In comparison, the station in Kazakhstan is located at around 45 degrees north latitude (Nestler 2011). The closer a rocket launches to the equator, the more it can utilise the Earth's faster rotation there and thus save fuel (Lorenzen 2009); more cargo can also be transported into space (Nestler 2011). Apart from the rainy season, the proximity to the equator also offers stable weather conditions (Möthe 2010). Hurricanes or earthquakes are also unlikely at the location in French Guyana. Due to the coastal location, debris falls into the Atlantic Ocean in the event of an accident, where it poses less of a risk to people than at locations inland (Zimmermann 2013).

The ground infrastructure also includes the production and design facilities for all launch system components and payloads, training and research centres and facilities for testing rocket engines. These facilities are not always located in the immediate vicinity of the spaceports, meaning that launch system components and payloads still have to be integrated into an overall system and tested before the actual launch.

For certain launcher systems, in particular so-called microlaunchers (see chapter 4.1.2), mobile, floating launch systems from which missiles can be launched regardless of location and which are usually constructed on the basis of ships are also suitable (Albat 2011; p. 198; Etherington 2020). In Chinese space travel, for example, such ships are currently used

[10] Suitable climatic conditions include a low risk of earthquakes, a low number of thunderstorms or hurricanes and a predictable frequency of high-altitude shear winds (Ley et al. 2011; p. 192f.).

to launch small carriers into Low Earth Orbit (Clark 2022). Research is also being conducted into the use of mobile platforms in the air. In Cornwall, the first rocket was launched from a modified Boeing 747 at an altitude of 10 km in 2023 (Stoppel 2023) but the rocket crashed uncontrollably after a successful launch; the leading space company involved, Virgin Orbit, subsequently filed for bankruptcy (tagesschau.de 2023).

In addition to the launch and landing of rocket stages, ground-based infrastructure also ensures mission operations and communication between the ground and the spacecraft with the help of a global network of ground stations. This is also referred to as the ground segment (Wittmann and Hanowski 2011; p. 46f.). The processing of data (communication, navigation and earth observation data) from space is also part of the ground segment and is ensured with the help of corresponding receiving and transmission stations as well as data processing centres (so-called user ground centres; ibid., p. 47). While mission operations are usually carried out in a control centre (Hindlmaier and Kuch 2011; p. 458ff.), the ground station network is necessary for communication between the control centre and the spacecraft, space station or satellite. In addition to control rooms, the main components of the control centre are a computer and network architecture that includes external data interfaces, systems for data distribution and processing as well as data visualisation (Hindlmaier and Kuch 2011; p. 458). Computer architecture refers to the general structure of computers, i.e. hardware, software, components and their interaction (Rüdiger and Ostler 2020). The network architecture deals with internal and external communication, the flow of information within the individual systems (Risk 2021). Within data processing, the raw data obtained is processed into usable and interpretable results (Kaiser n.d.). Elements of the ground station network include transmitting and receiving antennas with which radio connections can be established for the transmission of telemetry (all measured values recorded by the spacecraft or the satellites) and telecommands (Häusler and Wiedemann 2011; p. 468ff.). Antennas and telescopes for laser distance measurements are also required for orbit determination (Montenbruck 2011; p. 87ff.). As a rule, globally networked ground stations are used for this purpose (Wittmann and Hanowski 2011; p. 47).

4.1.2 Launchers: from microlaunchers to heavy-duty launchers

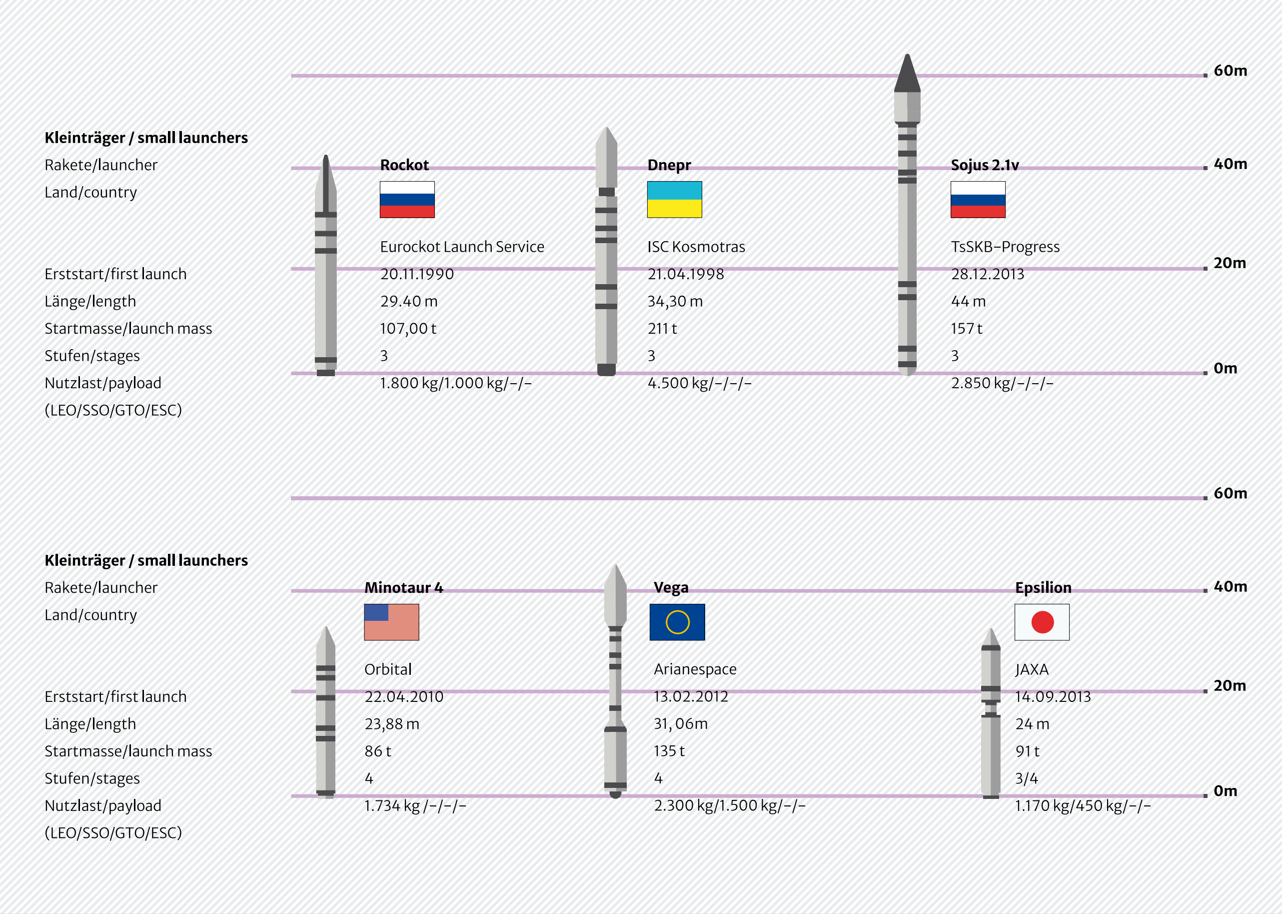
When utilising space, so-called payloads (spaceships, satellites or space probes; see below) are transported from Earth into space. Launch vehicles are used for this purpose. Launch vehicles consist of at least one (single-stage), but usually several rocket stages (multi-stage). A rocket stage usually consists of at least one engine, as well as fuel tanks and an electronic control system for navigation, attitude control and stage separation (Holsten 2011; p. 131). The individual rocket stages can be developed either for single use or as reusable systems.

There are different approaches to categorising launch vehicles, some of which overlap and are not always clear-cut. One possible categorisation is the division according to the available payload capacity (weight in kg) that can be transported by a rocket. The spectrum then ranges from microlaunchers to heavy-lift launchers. Which launcher is required depends on the mass and size of the payload and the orbit to be reached (Ley et al. 2011; p. 46). Single-stage rockets generally do not have the speed capability to reach an orbit. Therefore, all of the following types of launch vehicles consist of more than one stage, as well as laterally mounted additional engines (so-called boosters).

Microlaunchers or small carriers can transport payloads, especially satellites, of approx. 300 kg to 4,500 kg (Lassmann and Obersteiner 2011; p. 142; Kranz and Regenbrecht 2014; p. 16f.) and transport them into Low Earth Orbit. Intercontinental ballistic missiles have often been converted for this purpose as part of disarmament agreements, so that small carriers offer states an opportunity to enter the space sector due to their low technical complexity (Lassmann and Obersteiner 2011; p. 138).

Figure 7

Small launchers



Source: Own illustration based on Kranz and Regenbrecht 2014

Medium or medium-heavy launch vehicles are optimised for the transport of payloads between 1,200 kg and 10,000 kg into the entire width of usable Earth orbits. As with small launchers, multi-stage systems have been in use here for decades and will continue to be used in the future (Lassmann and Obersteiner 2011; p. 138). The Russian SOJUZ rocket was used by many nations as a launcher for satellites until 2022. However its use has been subject to international sanctions since the start of the Russian invasion of Ukraine in February 2022, and the number of SOJUZ launches has been significantly reduced due to the low remaining demand (Jones 2023b).Heavy-lift launchers are launch systems that are mainly used to transport communication satellites into geostationary orbits (GEO) (Lassmann and Obersteiner 2011; p. 138). Payload capacities range between 2,600 kg, which can be transported by the Russian PROTON rocket, and as much as 24,400 kg, which the now discontinued Space Transportation System, with which the US Space Shuttle was launched, was able to transport (Lassmann and Obersteiner 2011; p. 145f.).

Launch systems that are intended to reach space beyond the Earth‘s orbit and are used for manned space travel have been and continue to be more powerful than these rockets. The US Saturn V rocket of the Apollo programme was able to carry around 50,000 kg into Earth's orbit and ultimately to the Moon (Ulamec and Hanowski 2011; p. 559f.) and the Space Launch System (SLS) with a payload capacity of up to 130,000 kg (National Aeronautics and Space Administration (NASA) 2011; p. 14) is intended to enable another manned flight to the Moon. The reusable „Starship“ launcher system from SpaceX is also

Figure 8

Medium launcher

Source: Own illustration based on Kranz and Regenbrecht 2014

expected to be able to carry over 100,000 kg into Earth's orbit and beyond (SpaceX 2020b; p. 5).

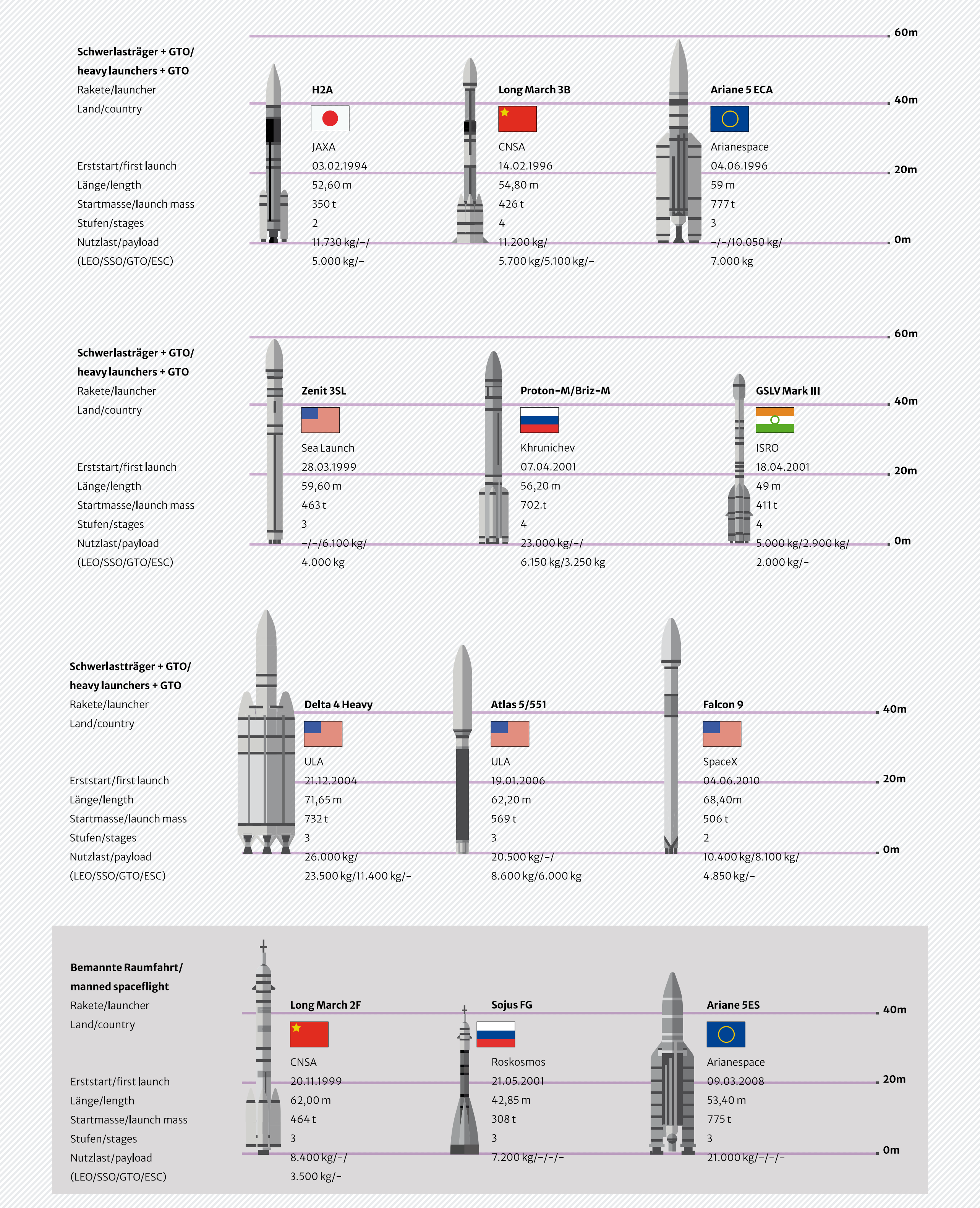
In order for them to be used for human spaceflight, launch systems must fulfil specific requirements and safety regulations (National Aeronautics and Space Administration (NASA) 2017). For example, abort and rescue mechanisms are integrated and the forces acting on the spacecraft - vibration, gravity and acceleration - must be minimised in such a way that people are not harmed.

Launch vehicles use solid propellant or liquid propellant engines, or hybrid engines in which both types of propellant are combined. Solid propellant engines are characterised by the fact that the combustion components are already mixed together and burn continuously after ignition (see chapter 4.2.3).

They are therefore often used as auxiliary power units (boosters). Separate tanks are required for liquid rocket fuel. Usually, certain combinations of highly cooled gases are used. The propellants are only brought together and react with each other in a combustion chamber. For engines that operate at ambient pressure within the Earth's atmosphere, liquid oxygen and paraffin (LOX/kerosene) are used. The combination of liquid hydrogen and liquid oxygen (LOX/hydrogen) has become established for upper-stage engines operating outside the Earth's atmosphere (Albat et al. 2011; p. 168f.).

Figure 9

Heavy-duty launcher



Source: Own illustration based on Kranz and Regenbrecht 2014

4.1.3 Spacecraft: spaceships and space stations

Launch vehicles are used, among other things, to transport spaceships and space stations or their individual components into various Earth orbits. Three different types of spacecraft are currently in use:

Unmanned spacecraft supply space stations with cargo and are not designed to transport people. They are used to supply the human crew on space stations, such as the ISS at present, in low Earth orbit with essential goods such as food, water, oxygen, but also materials for carrying out scientific experiments and additional fuel (Raatschen and Kern 2011; p. 425f.). They are also used to dispose of waste. For this purpose, the spacecraft loaded with waste are usually burnt up in a controlled flight in the Earth's atmosphere. Active spacecraft include the Russian Progress spacecraft, the American Dragon2 and Cygnus spacecraft and the Chinese Tianzhou spacecraft.

Manned spacecraft are missiles designed to transport people in space. The Soviet Vostok spacecraft is considered the first manned spacecraft, followed by the American Mercury and Gemini projects, among others. The Soviet Soyuz transport system, designed to supply space stations (e.g. Mir and ISS) and transport three people, has been active since 1967 and served as a model for the Chinese Shenzhou capsule, which has been active since 2003, which in turn supplies the Chinese space station and can transport three people (China Radio International (CRI) 2021; Osterhage 2021; p. 94). Also active is the US Crew Dragon (reusable, for up to four people), which is being developed as part of the Commercial Crew Development[11] programme (CCDev) programme by the SpaceX company for NASA. Since 2020, the Crew Dragon has completed seven successful flights with 26 astronauts (Sheetz 2021). Two further US spacecraft are currently still under construction: The reusable spacecraft CST -100 Starliner, also developed by Boeing as part of the CCDev programme, has successfully flown unmanned but not yet manned - manned launches having been postponed since 2017 and last postponed in June 2023 without a new launch date being announced (as of 04/07/2023; Boeing n.d.). NASA's Orion spacecraft (National Aeronautics and Space Administration (NASA) n.d. c) is about to make its first manned flight around the Moon as part of the Artemis 2 mission, which is currently planned for 2024 (Howell 2023). In general, manned spacecraft should not only ensure the survival of astronauts in space, but also enable a safe return to Earth. Landing systems for both water landings and landings on land are therefore part of the equipment. Spacecraft are usually slowed down by parachutes when re-entering the atmosphere. Another important component is the heat shield, which protects the spacecraft and its crew from the heat generated by friction (Hannemann and Longo 2011; p. 108).

Space stations are currently only in operation in low-Earth orbit. The International Space Station (ISS) was constructed in 1998 and is powered exclusively by solar energy. Two years after its construction, it was already home to its first astronauts (Osterhage 2021; p. 141ff.) . With a span of 109 metres, a length of 80 metres and a depth of 88 m, its mass is up to 450 tonnes. In 2021, the Chinese space programme began building its own manned station „Tiangong-1". Since then, the Tianhe core module has been expanded to include the Wentian and Mengtian science modules (Lorenzen 2022). The station has officially been in operation since the beginning of 2023 (Moller 2023). The Chinese are also currently planning to set up a space station in orbit around the Moon at . NASA, in cooperation with ESA, JAXA (Japan Aerospace Exploration Agency) and CSA (Canadian Space Agency) will build the so-called Lunar Orbital Platform-Gateway, which will serve as an intermediate station for manned Moon landings and support the testing of technologies for flights to Mars, among other things (National Aeronautics and Space Administration (NASA) 2019a). It is currently expected to be commissioned in November 2025 at the earliest (as of July 2023) (Mars 2023).

4.1.4 Other payloads: space probes and satellites

Payloads are those components of a space flight system that serve to fulfil the specific objectives of space missions. Mission objectives can be Earth and weather observation, communication, navigation, technology testing, basic research and planetary exploration including manned spaceflight (Wittmann and Hanowski 2011; p. 51ff.).

[11] https://artes.esa.int/edrs/overview

The exploration of planets is made possible by **space probes**. Depending on the mission objective, four types can be distinguished, each with specific technical subsystems:

- **Flyby probes**, such as NASA's Voyager 1 and Voyager 2 probes in the 1980s and the New Horizons mission, which passed the dwarf planet Pluto in 2015, fly from Earth to other astronomical bodies (planets, moons, asteroids) in the solar system and collect data during the flyby using integrated sensor systems and send it to Earth (Ulamec and Hanowski 2011; p. 563f.; National Aeronautics and Space Administration (NASA) 2019b). The flyby enables several targets to be approached, but is also due to the fact that there is not enough fuel available for braking manoeuvres (which enable the spacecraft to enter orbit). Unbraked, these probes then continue their journey as long as energy is available or the individual components remain functional. The probes usually contain solar cells and batteries which become necessary when solar cells become inefficient due to the distance from the sun.

- Unlike flyby probes, **orbiters** are used for the continuous exploration of astronomical bodies. They head for their targets and swivel into their orbits, such as NASA's Lunar Reconnaissance Orbiter or ESA's ExoMars Trace Gas Orbiter in cooperation with Roskosmos (European Space Agency (ESA) 2020b). The probes use their sensors to collect data about their target. Of particular importance is the thermal system, which serves to protect the technical components from the effects of the low temperatures in space. Because orbiters may be deployed in regions of the solar system where solar radiation is low, radioactive heating elements (RTGs) are used to generate energy and heat (Ulamec and Hanowski 2011; p. 567).

- **Landers** can be a component of orbiters and are used to explore the surface or subsurface of planets, moons and asteroids in the solar system. They can either be set down at a fixed point on the surface, such as during the InSight mission on Mars, or they can move around. In this case, they are referred to as rovers. Landers that remain in one place are equipped with instruments to explore the surroundings. These include cameras, sensors for measuring atmospheric conditions such as temperature, air pressure, etc., but also the composition of a possible atmosphere. Landing space probes on other planets poses a particular challenge for space travel. Depending on the presence of an atmosphere, parachutes can be used in combination with braking rockets (Ulamec and Hanowski 2011; p. 568).

- Sample return can be carried out in lander missions, such as the Japanese Hayabusa space probe (Amos 2010) or the American OSIRIS-Rex mission (National Aeronautics and Space Administration (NASA) 2016). The purpose of the return mission is to collect rock samples from asteroids, moons or planets and transport them back to Earth for analysis. Collected rock samples (e.g. by drilling) must be placed in sterile containers to prevent possible contamination by terrestrial substances. Finally, the sample containers must be launched again; depending on the atmospheric conditions, the launch systems must have specific aerodynamic properties, carry sufficient fuel for the launch and a possible rendezvous manoeuvre with another spacecraft in orbit as well as a return to Earth (Ball et al. 2009; p. 128f.).

Space probes serve very specific research questions and have to function under very different conditions. Because missions with space probes are technically and organisationally very complex, it often takes several years to decades before the desired results are available.

By far the most frequently transported payloads are **satellites**, i.e. artificial spacecraft orbiting planets. Regardless of their specific purpose, satellites typically consist of several technical subsystems: the mechanical structure of the satellite, its propulsion systems, a temperature control system to deal with the conditions in space, the power supply for operation and mission-specific payload components such as camera systems, transponders, spectrographs etc. as well as communication antennas (Maini and Agrawal 2014; p. 174ff.). Different types can be distinguished to fulfil commercial and scientific purposes:

- **Communication satellites** are used to transmit radio signals (radio and TV signals, telephone connections and data transmissions) (Maini and

Agrawal 2014; p. 473ff.). In order to cover the largest possible areas on Earth, these satellites are usually deployed in geostationary orbits. Communication satellites receive data from a transmitting unit on Earth and transmit it to one (point-to-point) or several (point-to-multipoint) receiving stations. Using a transponder in the satellite, the input signal (uplink) is amplified and transmitted back to Earth on a different frequency (downlink) (Maini and Agrawal 2014; pp. 475-476) and thus also enable telephone and radio reception in very remote areas. In the coming years, data will increasingly be sent to ground stations via geostationary relay satellites such as the European Data Relay Satellite System (EDRS)[12] . In the case of EDRS, two geostationary satellites are sufficient to provide permanent coverage of the Earth's surface and a permanent connection to ground stations in Europe. Data is first transmitted between the satellites before it is sent to the Earth's surface. This is useful, for example, in order to be independent of the use of other countries' ground stations; this technology also enables higher data rates and the distribution of data in „near real time" (European Space Agency (ESA) n.d. f). In the course of the miniaturisation of components and the possible series production of satellites, satellite constellations in lower orbits are planned to realise higher data transmission rates without signal loss (Maini and Agrawal 2014; p. 516) and to avoid the geostationary orbits that are already largely occupied today.

- **Earth observation satellites** are used to collect data about Earth. This can be data on the state of the atmosphere, oceans or land masses (forests, snow and ice, etc.), for example, but also data that is used for mapping, in agriculture or for early warning of and rapid response to natural disasters. For this purpose, the reflected or emitted energy of the observed objects is measured at different wavelengths using active or passive sensor systems (see chapter 5.3.1). The collected data is transmitted to receiving stations on Earth for further analysis.

- **Weather satellites** are a sub-category of Earth observation satellites and are used to produce short-term weather forecasts and collect long-term meteorological observation data. They were among the first applications of satellite technology (Dech et al. 2011; p. 505). As a rule, they are in geostationary orbits, i.e. they follow the Earth's rotation and are therefore always located above the same point and observe a specific section of the Earth (Maini and Agrawal 2014; p. 587). However, there are also so-called polar-orbiting satellites that cover the entire Earth (Herold 2021). The most important instruments used by weather satellites are radiometers, which measure electromagnetic radiation (light, infrared and heat) at specific wavelengths. Satellite images are created from the measurements. Other active sensors used include polar-orbiting RADAR- and LIDAR-devices (Maini and Agrawal 2014; p. 588ff.). Weather satellites can be used to detect cloud movements, rainfall,

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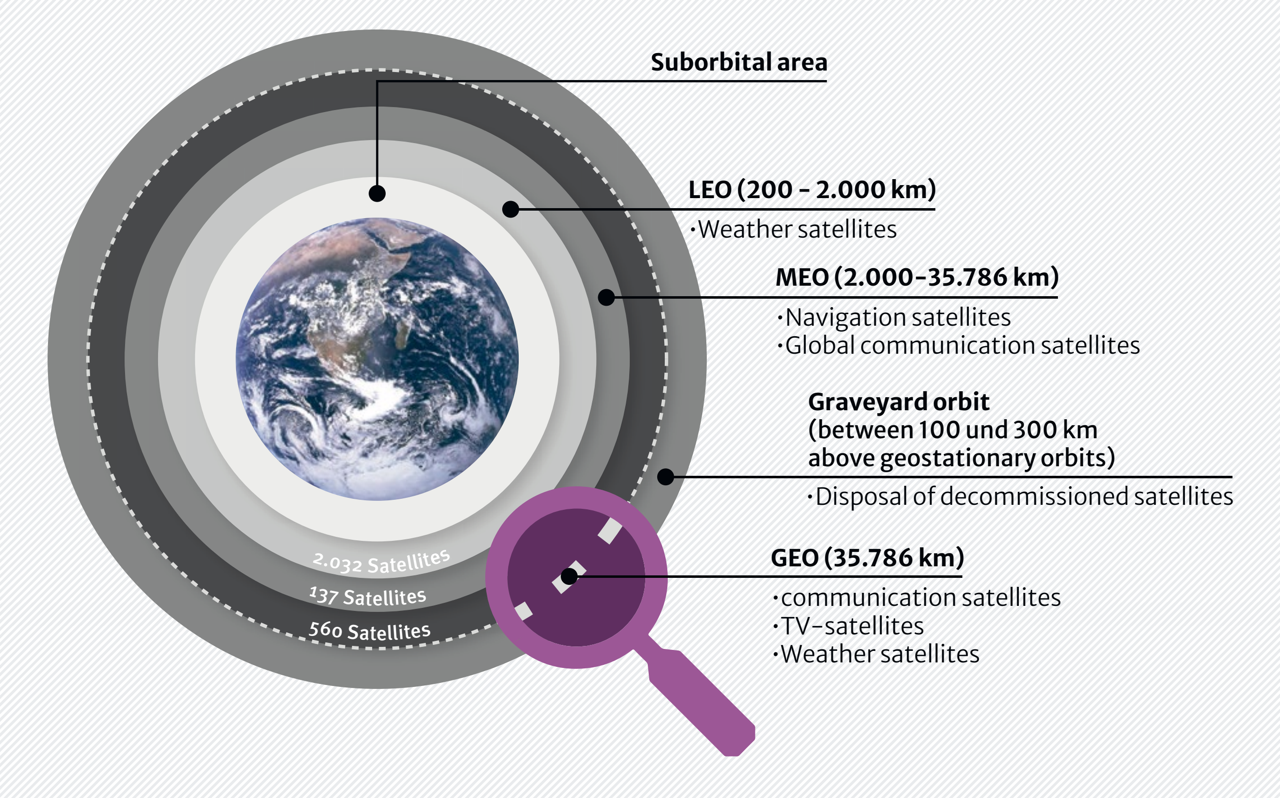
[12] https://artes.esa.int/edrs/overview

Figure 10

Earth orbits and their utilisation



Source: Own illustration based on data from Kind et al. 2020

- wind speeds and directions, as well as fog, air pollution, ocean currents, storm areas, etc. and generate short-term forecasts (24 - 48 hours).

- **Navigation satellites** make it possible to determine the position of vehicles, aircraft and ships (see chapter 5.2.1). For this purpose, position and time are determined on the basis of four satellites (three for three-dimensional positioning and one for time measurement). To do this, satellite orbits must be precisely executed and the satellites' internal clocks must be precisely synchronised (Sassen 2011; p. 536).

There are essentially three orbits or orbit ranges that can be considered for the use of satellites. There are also two other orbital regions worth mentioning (see Figure 10):

Due to the environmental conditions in near-Earth space (see chapter 3.1.1), satellites have a limited service life. Their service life is significantly influenced by the fuel they carry, which can be used for orbit corrections and is therefore used up at some point, but also by the degradation of electronic components due to radiation. Telecommunications satellites, for example, have an average service life of 15 to 20 years (Dodel 2011; p. 534; Maini and Agrawal 2014; p. 516) after which they need to be replaced. Currently (August 2023), 8,400 of the 10,550 satellites in space are still in operation (ESA 2023). Earth observation satellites that are in lower orbits are also exposed to atmospheric friction. The resulting orbital altitude loss can be compensated for by the fuel they carry. As soon as the fuel is used up, the satellite's lifespan usually ends and it is slowed down further and further by the Earth's atmosphere and eventually burns up. The company Planet Labs operates a fleet of miniature satellites that manage without a propulsion system and can maintain their low orbit through so-called „differential drag control", whereby the non-circular satellites reduce or increase their atmospheric drag through targeted rotation (Foster et al. 2015).

4.2 Environmental impact of technical systems on Earth and in space

The technical systems presented have a direct impact on both the environment on Earth and the environment in space. For example, resources are consumed on Earth to manufacture the technical systems, launch vehicles cause emissions in all layers of the atmosphere and disused satellites and rocket parts remain in space. There are currently only a few studies that analyse the life cycle of a complete space mission (Chanoine et al. 2017). Most studies focus on specific types of propellant and their impact on the environment (Pettersen et al. 2016) or individual phases, e.g. the manufacturing phase or the launch phase.

Current research shows that two points are particularly relevant from an environmental perspective. Firstly, the various emissions of rocket fuels and how these affect the ozone layer in the stratosphere (see chapter 4.2.3) (Ross and Vedda 2018; Dallas et al. 2020b). Secondly, space debris in Earth's orbit, which, if not actively removed, can make activities in space more difficult or even impossible in the future.

4.2.1 Ground infrastructure

As already explained in chapter 4.1.1, the ground-based infrastructure comprises numerous buildings whose construction and energy consumption have an impact on the environmental footprint over the entire life cycle of a space mission. Not only the launch pads, but also the facilities, production and construction for all components of the launch systems and payloads, training and research centres test facilities and data reception and transmission stations must be included in the resource requirements, as must the construction and operation of ground stations from which satellites and antennas are controlled in space.

Even the first phase, the development of complex technical systems such as launch vehicles or satellites, takes several years. As a result, the research and development process already involves a considerable consumption of electricity, gas, water, oil and other resources, whether for the use of offices, laboratories and test facilities or for travel by researchers (Geerken et al. 2018). The environmental consequences are significant at this point alone, as waste is produced, environmental media are polluted, greenhouse gases are emitted and finite resources are consumed.

When a spaceport is built and put into operation, it has a huge impact on the environment. Even if no precise figures are published, it is known, for example, that the operation of the European space centre in French Guyana requires a great deal of energy, around half of it for the production of propellants (for reasons, see 4.2.2) and the other half to cool the buildings on site (European Space Agency (ESA) 2020a). The station accounts for up to a fifth of the country's total electricity requirements, with annual electricity costs totalling several million euros (European Space Agency (ESA) 2020a). The air conditioning systems have to keep the industrial buildings at a precise humidity and temperature level all year round, as they contain technical equipment or satellites worth several million euros that could be damaged by the humidity and heat in French Guyana. Specialised systems that use refrigerants also have high greenhouse gas emissions (Pettit 2021). The use of renewable energy and improved energy efficiency in buildings can greatly reduce energy consumption and the resulting greenhouse gas emissions (Thiry and Chanoine 2017). ESA is now planning to operate the European spaceport in French Guyana using 90% renewable energy by 2025, with two photovoltaic power plants due to go into operation in 2023 and two further biomass power plants planned (European Space Agency (ESA) 2020a). This includes the energy supply for the facility, not the fuels used.

Other environmental protection measures are already being implemented in Guyana: ships transporting materials to the spaceport in Guyana are subject to special environmental protection regulations. For example, no fuel may be discharged into the sea, only certain ship routes are permitted and the personnel involved are specially trained to ensure environmentally friendly transport (Arianespace 2015; p. 17). The operating company Arianespace aims to reduce energy consumption and greenhouse gas emissions and regularly evaluates its success in this regard (Arianespace 2015; 17 ff.). A particularly high level of emissions is released by the combustion of fuel during rocket launches. At the French Guyana spaceport, measurements are taken at various distances from the launch area during each launch, including measurements of the concentration of hydrogen chloride, nitrogen dioxide, hydrazine and aluminium oxide. The measurements show that the effects are mainly limited to the vicinity of the launch area (<2.3 km), where high concentrations of hydrogen chloride and aluminium oxide are measured. At medium distances (up to 8 km) the effects are low, at greater distances of more than 8 km they are negligible. Impacts on water quality, vegetation and fauna are also monitored and no significant negative impacts have been identified to date (Durrieu and Nelson 2013; Centre National d'Etudes Spatiales (CNES) 2018).

At a more fundamental level, the sustainability of all companies active in the space sector must also be taken into account. It is evident here that the limited transferability of existing reporting frameworks to the space sector means that comprehensive sustainability reports from private space companies have only been published in isolated cases to date (Badalian 2023). A comprehensive analysis of the entire industry therefore first requires the creation of as comprehensive a database as possible.

4.2.2 Production of technical systems and fuels

Space activities require a large number of technical systems such as satellites, rockets, space probes and space stations. The production of the various components entails various environmental impacts (Chanoine 2015), including high electricity and heat consumption. Depending on the local energy mix, this results in different levels of greenhouse gas emissions. The raw materials required for the production of the components are also relevant from an environmental perspective. These include germanium, which is used for the production of photovoltaic systems that are installed in satellites and on space stations, for example (European Space Agency (ESA) 2022b). Mining pollutes the local environment and produces greenhouse gas emissions (Vercalsteren et al. 2018). Furthermore, the global availability of germanium is very limited and individual countries control the majority of mining: over 55% of global production comes from the People's Republic of China, followed by Canada (8.6%) and the United States (3.4%) (Barazi et al. 2023; p. 54). Due to the low global production volume of only around 170 tonnes combined with increasing technological demand, the market price for germanium is very volatile (Barazi et al. 2023; p. 54). The use of recycled germanium could improve the environmental balance and mitigate the aforementioned difficulties (Kurstjens et al. 2018). Gold and silver are also required for photovoltaic systems. Both are finite resources whose extraction is harmful to the environment (Maury et al. 2020). Innovative companies such as Relativity Space and the microwave plasma technology start-up 6K want to reduce environmental impact by 3D printing rockets from a material powder obtained from used materials, thereby minimising the need to mine resources (Wheeler 2020). The use of composite materials made from cork as heat protection in aerospace is another example of the use of innovative materials (Amorim Cork Composites 2020).

Since 1961, nuclear radioisotope generators (radioisotope thermoelectric generators, RTGs) have often been used as an energy source for space missions, as they do not have any moving parts. They are therefore very durable and less susceptible to faults. Due to the high decay heat of the frequently used plutonium-238 (0.56 W/g), they can be built compactly (World Nuclear Association 2021). Due to its stability, its insolubility in water and its high melting point of over 2,700°C, the risk of nuclear contamination by plutonium-238 in the event of a false launch or re-entry into the atmosphere is low; in the accidental re-entries of the Nimbus-B weather satellite (1968) and the lunar module of the Apollo 13 mission (1970), the RTGs survived the re-entry and the crash into the ocean undamaged and without nuclear environmental contamination (Siegel 2018). However, the use of nuclear energy sources also harbours dangers: in 1977, the Soviet weather satellite Kosmos 954 crashed over Canada due to a malfunction, scattering radioactive debris in a 600 km long debris field (D'Agostino 2021). The search and recovery work dragged on for eight months and led to an international dispute between Canada and the Soviet Union regarding the compensation to be paid (see chapter 3.2.3). In order to avoid risks when using nuclear systems in space travel, for example in the event of an accident during the launch of the spacecraft, nuclear reactors are only ignited after leaving the Earth's atmosphere (D'Agostino 2021). According to the current state of technology, some space missions can only be realised with nuclear energy sources, for example because the great distance from the sun makes it impossible to use solar energy (D'Agostino 2021). The foreword to the UNOOSA's „Principles Relevant to the Use of Nuclear Power

Sources in Outer Space", adopted in 1992, recognises that nuclear energy sources are particularly suitable or even indispensable for some space missions. At the same time, however, it calls for their use to be focussed on applications that are particularly suited to the advantages of nuclear technology and for the use of nuclear technologies to be accompanied by thorough risk and safety analyses (United Nations Office For Outer Space Affairs (UNOOSA) 1992).

In view of the predicted increase in rocket launches, fuel must be produced on a large scale, such as the liquid fuels hydrogen/oxygen or methane/oxygen (Harris 2021). In the case of SpaceX's new Starship/SuperHeavy rocket, this is a propellant made from liquid oxygen and liquefied methane. The total payload capacity is 4600 tonnes of propellant, only a fraction of which is reserved for re-entry (SpaceX 2022). Suitable infrastructure must be provided and operated for

the production of this cryogenic[13] propellant and the processing of natural gas into methane, including gas power plants and gas processing plants, gas pipelines and other facilities such as cooling towers. The production of the fuel is energy-intensive and involves high water consumption, CO_2 emissions and SO_2 emissions (Harris 2021). In an ArianeGroup test project, methane from biogas plants was used to reduce greenhouse gas emissions (Dutheil and Boué 2017). However, production in biogas plants on the necessary large scale would require considerable investment and equipment. Hydrogen-based fuels are used in most European rockets. The energy-intensive production of hydrogen releases a lot of CO_2 unless the energy required for production is obtained from renewable sources. However, so-called grey hydrogen is currently mainly produced from natural gas or coal (International Energy Agency (IEA) 2019). Both hydrogen/oxygen and methane/oxygen fuels use liquid gases. These must be stored at extremely low temperatures of up to -251°C for liquid hydrogen or -183°C for liquid oxygen. This requires fuel storage facilities that have a high energy consumption. As a result, the liquid gases for the individual rocket launches are, where possible, produced as required, whereby the production process for the required amount of fuel for the Ariane 5 rocket currently takes one and a half months. This consumes around 140 tonnes of liquid oxygen and around 28 tonnes of liquid hydrogen for the launch (Centre Spatial Guyanais 2023).

The life cycle analysis carried out by ArianeGroup for the operation of the new Ariane 64 launcher estimates that around 20,000 tonnes of CO_2 emissions will be generated during the life cycle of a future Ariane 64 launcher. The majority of the estimated emissions (46%) are associated with the production and refuelling of the propellants at the Guiana Space Centre. The launcher is fuelled with liquid oxygen and liquid hydrogen and an additional solid propellant, the latter contributing to 1% of CO_2 emissions during its life cycle. 30 % is attributable to other activities on the ground before and during the flight; 21 % to the manufacture and assembly of the structures in Europe. The remaining 2 % is caused by testing and transport (Arianespace 2022). If the production and assembly phases and the launch sites are geographically distributed, as is often the case with ESA space missions, for example, the components and technical systems sometimes have to be transported over long distances, whether over water or over land. This also results in greenhouse gas emissions, which are attributed to the space missions. However, as the life cycle analysis of the Ariane 64 launch vehicle shows, the proportion is rather small.

4.2.3 Rocket engines and their emissions

Activities in the start-up phase cause a particularly high level of environmental damage (Chanoine et al. 2017). Solid and liquid fuels give rise to different emission products and therefore different impacts on the environment (Dallas et al. 2020b). Challenges in the assessment of environmental impacts lie in the fact that emissions fluctuate depending on the measurement, as weather conditions and times of day must be taken into account here due to the chemical interaction of various elements in the atmosphere.

Solid propellant engines are often used for the launch phase of rockets as they have a high thrust. The propellant paste in the Ariane 5 and Vega launchers consists of fuel (aluminium powder), oxidant (ammonium perchlorate) and a binder (polybutadiene resin) (Centre Spatial Guyanais 2023). Combustion produces hydrogen chloride and aluminium oxide - gases that are particularly harmful to the ozone layer (Voigt et al. 2011). The Ariane 5 launcher produces around 91 tonnes of hydrogen chloride per launch (Arianespace 2022).

Kerosene-powered rockets as well as rockets with solid-fuel engines release CO_2 and soot directly into the stratosphere, which leads to greater radiative forcing due to the altitude and has an impact on climate change, as soot particles and aluminium oxides absorb heat and thus increase radiative forcing, i.e. the net radiation balance of the atmosphere (Dallas et al. 2020b).

In addition to the aforementioned environmental impacts during production, fuels with liquid hydrogen and liquid oxygen have a further environmental impact: the water vapour produced during combustion contributes to the formation of clouds in the stratosphere, but above all in the mesosphere, i.e. the atmospheric layer 50-80 km above sea level (Larson et al. 2017). This can cause increased radiative forcing and thus intensify global warming. Further research is

[13] Cryogenic fuels are liquefied gases that are cooled down to near absolute zero and are used for reasons of energy efficiency.

still needed to quantify the exact effects of increased water vapour input into the mesosphere and the associated cloud formation on the climate (Ross and Vedda 2018; Tian et al. 2023). The formation of clouds in the stratosphere only occurs under natural conditions in the polar regions (so-called polar stratospheric clouds, PSC); the ice particles in PSC contribute to the depletion of the ozone layer as a site of chemical transformation processes (Tritscher et al. 2021). Increased cloud formation in the stratosphere due to rocket launches would therefore also be harmful to the ozone layer.

Other fuels contain hydrazine or hydrazine derivatives, an unstable chemical compound consisting of a combination of nitrogen and hydrogen atoms. During combustion, nitrogen oxides are produced that persist in the mesosphere and stratosphere for several years, changing the composition of the atmosphere and depleting ozone. The production of hydrazine is energy-intensive and the liquid is highly toxic in its unburnt state (Dallas et al. 2020b). For this reason, hydrazine has been on the EU list of Substances of Very High Concern (SVHC) since 2011 and may be banned across Europe in the near future and therefore replaced (Kaboth and Werling 2021), for example, in the new Vega E launch vehicle, which transports light loads into space and is to be used from 2026 (Arianespace 2022). Researchers around the world are looking for an environmentally friendly replacement for hydrazine (German Aerospace Centre (DLR) 2023).

Little research has been done into the environmental effects of a new fuel made from liquid oxygen and methane, which is increasingly being used in new rocket systems. In contrast to kerosene-fuelled propulsion systems, no soot particles are produced. One theoretical advantage attributed to the new fuel is potential in-situ production on Mars using atmospheric carbon dioxide and water from regolith, the material on the surface of Mars. However, this scenario is still a long way off (D‘Aversa et al. 2016).

Effects on the ozone layer due to the release of various emission products are considered to be one of the most serious problems of space travel from an environmental perspective, especially in view of the expected increase in the number of rocket launches in the future (Dallas et al. 2020a). In contrast to commercial aircraft, which fly in lower atmospheric layers, rockets pass through the stratosphere, where the ozone layer, i.e. a particularly large number of ozone molecules, is located. All rocket fuels have the potential to damage the stratospheric ozone layer, as nitrogen oxides, hydroxides and water vapour react with ozone molecules (Ross et al. 2009). Solid-fuel engines cause even more ozone-depleting emissions, as they also release hydrogen chloride and aluminium oxide (Ross and Vedda 2018). In order to improve the data quality of the impact on the ozone layer caused by rocket launches, comprehensive global atmospheric models are required, which are currently only available to a limited extent. More research is therefore needed on this complex topic in order to quantify the concrete depletion potential of the ozone layer (Chanoine et al. 2017).

4.2.4 Space junk

Finally, space travel also has an environmental impact at the end of the life cycle of technical systems. With an increasing number of rocket launches and satellite systems in space, there is a high mass of material that burns up in the Earth‘s atmosphere, but also material that potentially remains in space.

During re-entry into the atmosphere, the heat produced creates water vapour and, in particular, nitrogen oxides, which change the composition of the atmosphere and contribute to the depletion of the ozone layer (Larson et al. 2017; David 2022). The mega-constellation of Starlink satellites is expected to release two tonnes of mass into the Earth‘s atmosphere every day. If other planned mega-constellations and rocket bodies already in use are included, 2742-8114 tonnes of anthropogenic material could enter the Earth‘s atmosphere every year from 2024 onwards, consisting mainly - and in contrast to the natural material of the small meteorites that enter the Earth‘s atmosphere as they fly by - of metals (Schulz and Glassmeier 2021). From an environmental perspective, in addition to the damage to the ozone layer, this is also problematic because satellites are largely made of aluminium, which is broken down into aluminium oxide when they burn up. Aluminium oxide reflects light, which changes the albedo of the Earth‘s atmosphere and thus further increases the greenhouse effect (Boley and Byers 2021).

Normally, 60 to 90 per cent of the mass of a spacecraft or other payload burns up during re-entry. Parts that survive re-entry land in a controlled entry in the Pacific Ocean between Chile and New Zealand in what is known as Point Nemo. Point Nemo is thousands of kilometres from land and is also known as the spaceship graveyard. As the point is so far from land that the wind can hardly carry any nutrients to it, it is considered the most biologically inactive place in the oceans. There are also ocean currents there that hold back nutrient-rich water (D'Hondt et al. 2009). Even if this location has good prerequisites, waste disposal in the ocean remains a matter for discussion, as it cannot be in the interests of sustainability to use environmental media as a landfill site. The total amount of metal that falls into the Atlantic during each Ariane 5 flight is around 90 tonnes. With an average of six flights per year, this equates to 540 tonnes per year (Arianespace 2022). There is a direct risk to the Earth in the event of uncontrolled re-entries, for example when old satellites can no longer be controlled and fall to Earth. This was the case in 2018, when the Chinese satellite Tiangong crashed in the South Pacific and some parts landed in the Pacific northwest of Tahiti (Kuo 2018) or in the case of the re-entry of the Phobos-Grunt satellite, which contained toxic propellants and therefore posed a danger to the local population in the crash region (Durrieu and Nelson 2013).

Accordingly, space debris, i.e. artificial and unusable objects in low Earth orbit, is a significant problem. The number of inactive satellites, rocket stages and other debris remaining in Earth orbit has been rising steadily for years. Near-Earth space is in danger of becoming a „space tragedy" due to over-utilisation of the Earth's freely available but limited orbit. According to the latest ESA Space Debris Study, there are approximately 36,500 pieces of debris larger than 10cm in Earth orbit and 1 million pieces of debris between 1cm and 10cm . If parts between 1mm and 1cm in size are recorded, there are as many as 330 million pieces of debris (ESA Space Debris Office 2021). Space debris also travels at enormous speeds (around 28,000 km/h). This poses a danger to satellites and space stations because even small pieces of debris can damage or destroy the objects on impact. With an increasing cascade of collisions of space debris, evasive manoeuvres also become more frequent, which in turn consume more fuel. And the more debris there is in space, the greater the risk that the pieces will collide with each other, creating more pieces. The Kessler effect (also known as the Kessler syndrome) describes the risk of the amount of debris in orbit reaching a critical mass, with each collision creating a cascade of further debris until the orbit is no longer usable for space travel. The problem is already present today: the ISS has already had to change course 32 times since its launch (as of December 2022) to avoid collisions with space debris (NASA Orbital Debris Programme Office 2022).

The following image is an artist's impression of space debris in both low Earth orbit and geostationary orbit. The objects are enlarged in the figure to make them visible, but the number is based on current data.

Satellites that are positioned in lower orbits have a shorter active service life than satellites in higher orbits, at only around seven to ten years, due to atmospheric drag (Borthomieu 2013).

When they enter the Earth's atmosphere, the majority of objects usually burn up almost completely. However, depending on the altitude at which the objects are located, it can take a very long time for the non-manoeuvrable satellites and debris to descend from their original orbit and enter the Earth's atmosphere. The dwell time varies due to the varying degrees of braking and gravity. At an altitude of 200 kilometres, it takes about a year for an object to enter the Earth's atmosphere; at an altitude of 500 kilometres, it can take up to 25 years. At 800 kilometres, however, the natural residence time increases to at least 150 years.

Most space debris is located at an altitude of 800-900 kilometres, i.e. in orbits that are used for Earth observation satellites, for example (Metz 2021). For most of the debris in low Earth orbit, passive descent is therefore not a solution and they must be actively moved towards the Earth's atmosphere in order to burn up there. Satellites should therefore be equipped with electric drives and thrusters or drag sails that allow the satellites to descend at the end of their operational life.

It is recommended that satellites in low Earth orbit are removed from orbit at the end of their operation to minimise the risk of collisions that would cause debris. This is set out in the international guidelines, the Space Debris Mitigation Guidelines of COPUOS (United Nations Office For Outer Space Affairs (UNOOSA) 2010a; p. 3), but many operators do not adhere to them as the guidelines are not legally binding . In low-Earth orbits, where atmospheric drag is not sufficient to naturally remove satellites from orbit within 25 years, less than half of space operators make attempts to dispose of their satellites sustainably (ESA Space Debris Office

2022). In geostationary orbit, however, almost all space actors attempt to remove the objects and manoeuvre them into graveyard orbit. This area is now highly commercialised, which means that there are clear financial incentives to keep this area free of space debris and safe for current and future missions (ESA Space Debris Office 2022).

The European Space Agency (ESA) has addressed the issue of space debris and launched the „Clean Space" initiative back in 2012 (Pettit 2021). The ClearSpace-1 hunting satellite, developed by the Swiss start-up of the same name (Mäurer 2020)works like a tow truck and collects defective satellites and larger debris with its gripper arms. This reduces the risk to active satellites. Research into adhesive materials is also very promising (Löfken 2021). At the end of 2020, so-called „Astrobees" - small flying robots - were tested on the International Space Station (ISS), which, thanks to their gecko-inspired adhesive materials, allow scrap parts to stick to them (Kanis 2016). Gecko technology has long been used in automated sorting and packaging in the food industry. Now it is being trialled in space. Furthermore, as developed in the NASA Brane Craft project, extremely thin and bulletproof spacecraft are being used. These look and behave like a film: space debris is wrapped and then navigated into the Earth's atmosphere to burn up (Howell 2017). Japanese and Finnish researchers are working on building nanosatellites (miniature satellites) made of wood. These burn up completely, but above all avoid aluminium entering the atmosphere (Harper 2020; Arctic Astronautics / Kitsat 2021). In addition, driven by both ESA and start-ups such as OKAPI:Orbits, solutions are being developed that control the satellites on the software side in such a way that collisions are prevented in order to increase their service life (Seeburg 2021).

By developing new methods for dealing with space debris, the European Space Agency is striving to reduce negative environmental impacts. The CleanSpace initiative is not only working on guidelines and ideas on how to remove space debris from space, but also - from a sustainability perspective - on solutions for avoiding future debris (Pettit 2021). This is a significant aspect of protecting the limited resource of space and making it usable for us in the long term (European Space Agency (ESA) 2021b).

© Space debris/European Space Agency (ESA) 2019b

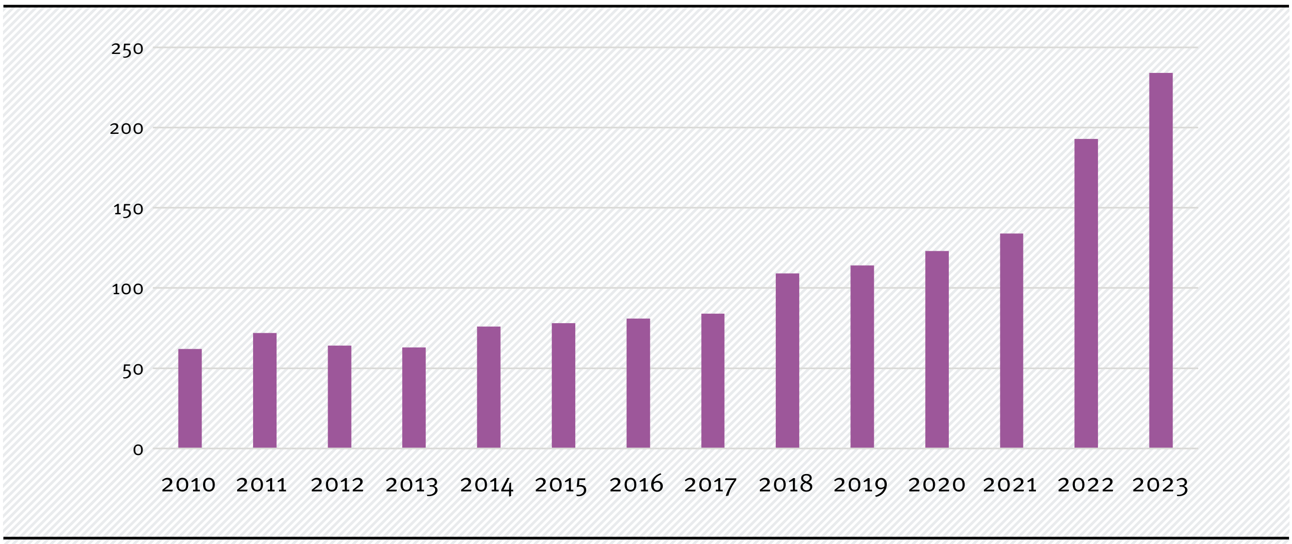
5

Current and future developments: potentials and risks for the environment

The following four key topics are trends with high environmental relevance. It can be assumed that the impact of these topics on the environment will continue to increase in the future: from the growing opportunities to access space, to new possibilities in the field of Earth observation and satellite navigation and communication, to the possible depletion of resources in space. For each of these topics, the environmental potentials and risks associated with them will be analysed. The focus is also on possible implications for environmental policy and environmental research.

Figure 11

Number of rocket launches worldwide since 2010



Source: Own illustration based on data from https://nextrocket.space/

5.1 Access to space

For many nations, access to space, i.e. the technical and institutional capacity to reach space, is not only an economic factor and an expression of their own innovative ability and technological leadership, but also a matter of national sovereignty or prestige.

5.1.1 Background and development

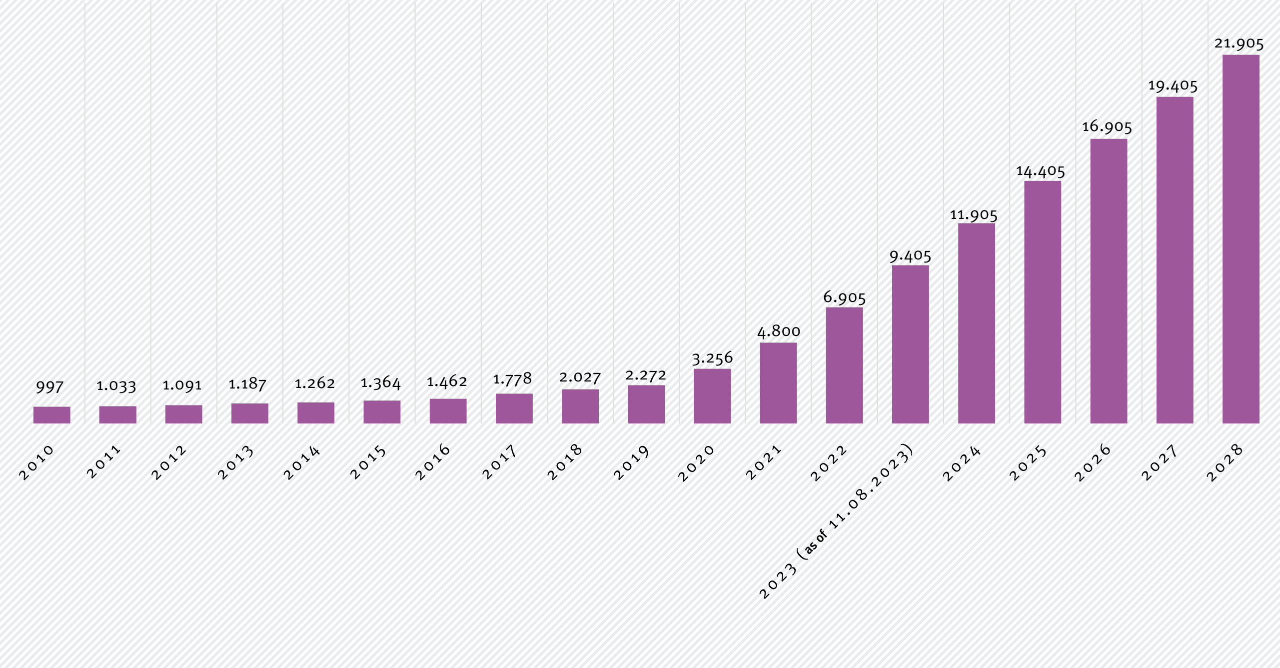
Since the launch of the Russian Sputnik satellite on 4 October 1957, access to space has become increasingly easy, as shown, for example, by the increasing number of rocket launches since the 2010s (cf. Figure 11).

More and more active satellites are orbiting the Earth: while the number was 997 in 2010, by mid-August 2023 it had already risen to approx. 8,400 by mid-August 2023 (European Space Agency (ESA) n.d. m).[14] This development is primarily driven by the construction of mega-constellations of small satellites (see chapter 3.1.2). SpaceX alone wants to launch 12,000 satellites into space in the future (Klapetz 2023).

[14] In addition to the number of active or functional satellites, there are also a large number of inactive satellites (approx. 2,150) orbiting the Earth as space debris. There are a total of 34,500 debris objects in space (as of 11 August 2023; European Space Agency (ESA) n.d. m).

Figure 12

Number of active satellites in Earth's orbit since 2010 and predicted trend until 2028



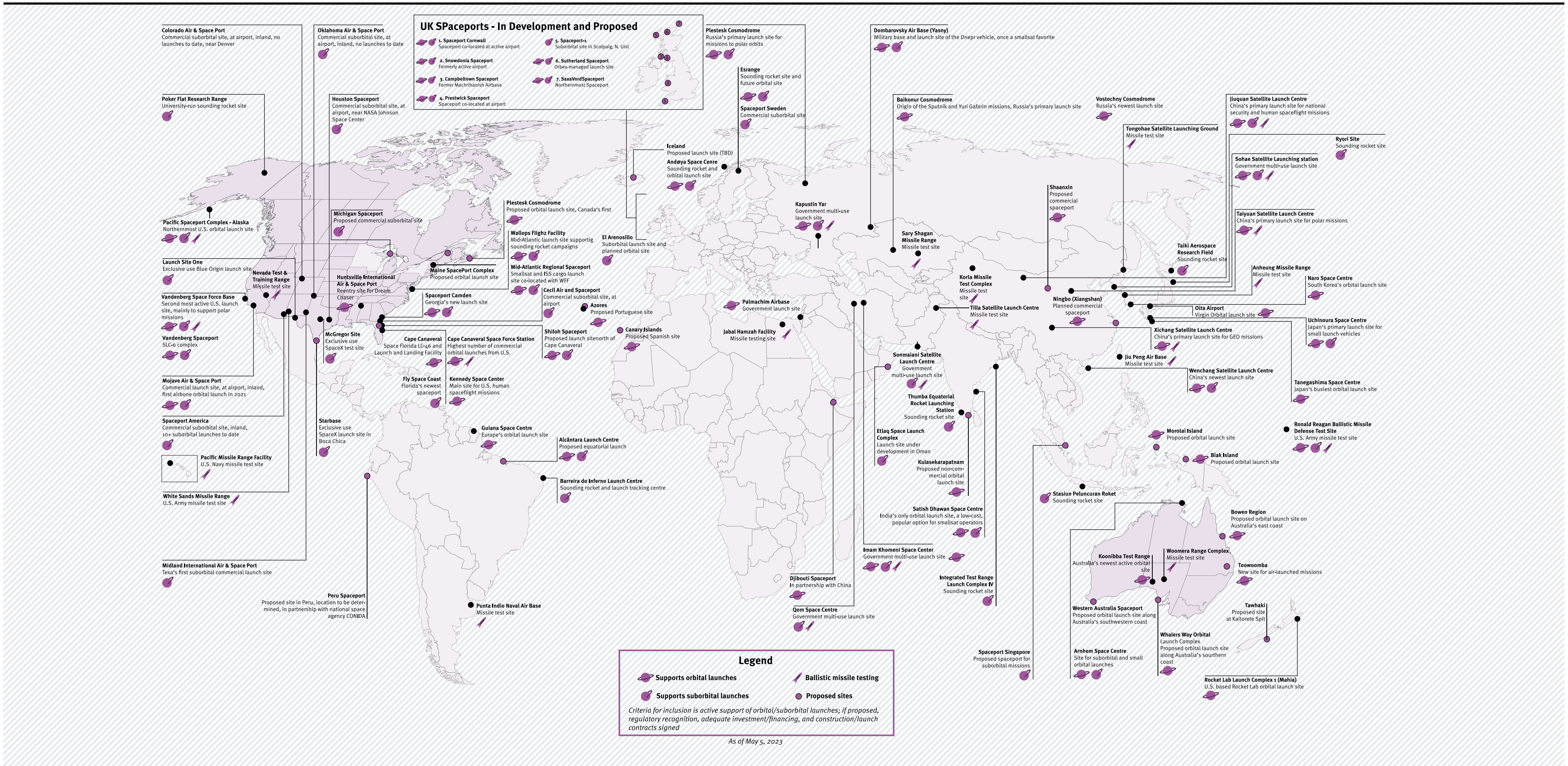
Source: Own illustration based on data from Statista GmbH 2023a, McDowell 2023, Euroconsult 2022

As already shown, the number of space-faring nations, i.e. countries that are able to reach space with their own launchers, has increased: a total of 14 nations, including the EU states in the ESA alliance, currently have the corresponding technical and institutional capabilities, out of around 90 nations worldwide that finance their own space programme (Moranta et al. 2021; p. 140). However, space agencies and companies do not always need their own launch systems to carry out unmanned space travel. Germany, for example, does not have its own launcher, but uses the Ariane programme of the ESA, among others. but carries its own payloads into space via the ESA's Ariane programme. Only a few countries have the technical capabilities for manned space travel. So far, only three nations - Russia, the USA and China - have succeeded in launching astronauts into space and back. The USA has provided two thirds of all space travellers to date (Bocksch 2021b). Astronauts from other nations are therefore reliant on participating in international endeavours, such as the International Space Station (ISS).

The launch facilities required for space travel are currently being expanded worldwide. There are currently 28 active spaceports (as at 31/01/2023, Roberts 2023). More spaceports, some of which are privately operated, are being planned (see Figure 13). One reason for this is that individual nations want to ensure independent access to space, such as the UK with a launch site in Cornwall (Spaceport Cornwall n.d.) , and on the other hand because some existing facilities have been in use for decades and need to be modernised or expanded. As a result, launch capacities will be increased, which will enable a greater variety of uses for different launch systems in the future (see chapter 4.1.2).

Figure 13

Location of active and planned spaceports and rocket launch sites



Source: Own illustration based on https://brycetech.com/reports/report-thumbnails/Bryce_Launch_Sites_2021.png/

Easier access to space allows more institutions, for example universities and other research institutions, to participate in the utilisation of space. The interest in accessing or utilising space is diverse in nature. In addition to states (communication, navigation), it is primarily research institutions (Earth observation, microgravity research, space exploration) and increasingly companies (communication, navigation, research and development, service tasks in orbit and, in the long term, resource extraction) as well as private individuals (space tourism, art) that are able to access space.

Looking to the future: a spaceport in Germany?

To date, Germany does not have its own spaceport or test site for rocket engines. Since the end of 2019, however, individual companies and stakeholders have been calling for the German government to support the construction of its own spaceport in Germany. This would reduce dependence on other countries and ensure Germany's own access to space. This would result in greater flexibility in the realisation of space activities (Gradwohl 2020).

In 2020, several German companies, including OHB SE, joined forces in the German Offshore Spaceport Alliance (GOSA)[15] to initiate Germany's first spaceport. However, a German spaceport was not to be built on land; instead, a mobile launch site in the North Sea is being considered (Handke 2020). From there, payloads of up to one tonne could be transported into Earth orbit using microlaunchers. Several companies in Germany (ISAR Aerospace,[16] Rocket Factory Augsburg[17] and HyImpulse[18]), supported by research funding from the BMWK, are already working on the realisation of the corresponding launcher systems and hope to open up new market potentials (Schulte and Sturm 2020).

However, the launch of a spaceport in the Wadden Sea is controversial. The high volume of shipping and the numerous wind turbines restrict the use of the German North Sea for rocket launches, and the airspace would have to be closed for each launch (Záboji and Plickert 2023). The expected environmental consequences of rocket launches and accidents, such as emissions, noise and scrap (see chapter 4.2.3), should be examined particularly critically in view of the three Wadden Sea national parks[19]. In contrast to spaceports close to the equator, from which the entire range of launchers can reach all orbits around the Earth, a mobile spaceport in the North Sea would only offer launch opportunities for small launchers. The German government emphasised the need for a European spaceport, but refused to commit to a German spaceport in the North Sea as a goal in view of the many uncertainties (Küpper 2023). The construction of such a spaceport has not yet begun.

5.1.2 Trends and drivers

As outlined above, there are many indications that access to space will widen in the future. The expansion of the necessary technical infrastructure will make it easier to carry out more rocket launches and transport payloads into space. The barriers to entry are also being lowered for non-spacefaring nations, as participation in space activities is being simplified through international cooperation between space agencies and companies. New business models are also allowing new players to enter the space market, such as the US company Space Perspective, which was founded in 2019 and is planning space travel for tourists from 2024 (Brinkmann 2022).

Increasing aerospace participation and co-operation

As already emphasised several times, space travel is hardly possible without international cooperation. The complexity of individual technical systems alone generally requires the co-operation of globally distributed suppliers. In addition, the limited number of spaceports requires international agreements to be concluded for their utilisation. Since 2011, for ex-

[15] https://www.offshore-spaceport.de/de/

[16] https://www.unternehmertum.de/start-ups/isar-aerospace

[17] https://www.rfa.space/

[18] https://hyimpulse.de/en/

[19] https://www.nationalpark-wattenmeer.de/

ample, it has been possible to launch Russian Soyuz rockets from the ESA/CNES operated Guyana Space Centre in French Guyana, in addition to the European Ariane rockets (Seidler 2011). (Seidler 2011). This collaboration ended in February 2022 as a result of the EU sanctions against Russia for its war of aggression against Ukraine (Nguyen 2022). Other non-European nations, space agencies and commercial customers can purchase launch capacities via the Arianespace company. Since 1979, over 300 rockets and over 1000 satellites have been launched into space from the European spaceport (Arianespace n.d.).

A frequently cited example of international cooperation is the International Space Station ISS, which is currently still in operation (see chapter 3.1.2). It was created as part of a partnership between the five space agencies NASA (USA), ESA (European partner countries), CSA (Canada), Roskosmos (Russia) and JAXA (Japan) (National Aeronautics and Space Administration (NASA 2015; p. 1). (National Aeronautics and Space Administration (NASA) 2015; p. 57). A total of 269 people from 21 nations have already lived and worked on it (as of August 2023; Garcia n.d.). Use of the ISS is therefore not only reserved for the participating nations, but is also open to other countries, research institutions and companies worldwide. For example, the company Nanoracks[20] offers microsatellite (CubeSat) launches from the ISS. As part of the KiboCube programme[21], UNOOSA enables non-spacefaring nations to launch their own microsatellites from the ISS and thus conduct independent research (United Nations Office For Outer Space Affairs (UNOOSA) 2021; p. 63). With its „Access to Space for All“ programme, UNOOSA also promotes the participation of non-spacefaring nations in space activities and enables technology transfer through its support in the development and testing of space hardware (United Nations Office For Outer Space Affairs (UNOOSA) 2021).

Increasing commercialisation of space activities

The growing commercialisation and privatisation of space activities - part of the „New Space“ trend - since the turn of the millennium is a noteworthy development. The previously predominantly state financing of space activities is increasingly being flanked by private sector investment. The resulting technical innovations, such as in the field of navigation systems (see chapter 5.2) and new business models, such as in the area of data-based services, are leading to an increasing spread of products and services from the space industry to other sectors (Kind et al. 2020).

Products and services, such as the entrainment of satellites during rocket launches, which arise in connection with space activities and increasingly diffuse into non-space industries, have proven to be growth drivers for the global space industry over the past two decades (Rencelj et al. 2023; p. 84ff.). Accordingly, the global market is considered to have great growth potential: according to estimates, the global market volume in 2021 was between USD 374.7 billion and USD 479.7 billion. Around USD 107 billion of this is accounted for by the budget of national space agencies (see chapter 3.2.2).

Although annual growth has slowed somewhat in the meantime (between 1.7 % and 2.2 % in 2018-2019 compared to 3.4 % and 8.1 % in 2017-2018; Moranta et al. 2021; p. 128), the opposite trend has recently been observed, with an increase from 6.3% to 19% from 2020 to 2021 (Rencelj et al. 2023; p. 138). Overall, it is expected that the global market for space-related products and services could be worth up to USD 1 trillion in the next two to three decades (Morgan Stanley 2020). This is attracting great interest and the number and volume of investments in space start-ups has increased significantly worldwide over the last 20 years. From 2000 to 2021, USD 52.2 billion was invested, with around 1,626 investors taking part. In 2021 alone, around USD 15.4 billion was invested in 212 start-ups worldwide, 69% of which was in the form of venture capital (BRYCE Tech 2022; p. 10; p. 23). In Europe, EUR 1.1 billion was invested in space start-ups in 2022 (Rencelj et al. 2023; p. 166).

Increasing diversity is expected in business areas and models (SpaceTec Partners and BHO Legal 2016). On the one hand, data-based business models are becoming easier to realise and promote in their implementation due to the constantly growing volumes of data and data transmission and processing capacities, e.g. through corresponding announcements as part

[20] https://nanoracks.com/products/iss-launch/

[21] https://www.unoosa.org/oosa/en/ourwork/psa/hsti/kibocube.html

of the European Horizon 2020 programme (Toth and Concini 2019; p. 56ff.). On the other hand, the development of space hardware, such as launch vehicles or small satellites, has also become an economic factor due to the growing demand for launch capacities and services, which will also enable cost reductions in the future. For example, the cost of a satellite launch has already fallen from around USD 200 million to around USD 60 million thanks to technical innovations and increasing competition. In future, satellite launches could even be realised for as little as USD 5 million (Morgan Stanley 2020).

Ultimately, the privatisation of previously publicly financed facilities such as the International Space Station (ISS) also offers private sector players the opportunity to invest money in research and development and generate returns. As the International Space Station (ISS) is currently only scheduled to operate until 2024, but is predicted to last 5 to 6 years longer, the extent to which the existing infrastructure could be partially privatised has already been under discussion for several years (Martin 2018; Gohd 2021).

Looking to the future: possible future market of space tourism

Space can fascinate people. Until now, however, only very few people have been able to go into space. Between 500 and 600 people from 38 countries have completed space flights, most of whom were professionally trained astronauts (Roberts 2021).

The first private individual to travel into space was the US entrepreneur Dennis Tito, who visited the International Space Station ISS from 28 April to 6 May 2001. He booked a seat on a Russian Soyuz spacecraft for around USD 20 million with the help of the company Space Adventures Ltd. He was followed by six other people over the next eight years, each of whom paid between USD 15 and 35 million for a space flight.[22]

On behalf of the company Axiom Space, SpaceX transported four people on the first purely commercial flight to the ISS with its Crew Dragon spacecraft in spring 2022 (8 to 25 April), at a cost of around USD 55 million per head (Spektrum.de 2022).

In addition to flights to the ISS, some suborbital flights (see chapter 4.1.4) have been carried out by Virgin Galactic and Blue Origin; however, regular business activities have yet to commence. In addition, SpaceX sent four private individuals into orbit for three days for the first time in September 2021, using a largely automated space capsule (Wall 2021).

The space tourism market segment is seen as having great economic potential, but no viable business models have yet been developed. The costs per person currently range from USD 250,000 (suborbital flight) to USD 80 million (longer stay on the ISS), meaning that this form of tourism will mainly be reserved for wealthy individuals in the near future (Kind et al. 2020; p. 58f.). In this context, it must be discussed to what extent space tourism can offer a social countervalue that justifies further enabling private space travel, given the significant environmental impact of space travel outlined in the report. The first space tourists (so-called „space flight participants“) visited the ISS as part of the routine crew rotation (Mars 2020) and therefore only made a limited contribution to the environmental impact of the respective mission. In the context of purely commercial or private space missions, the question of the fundamental necessity and meaningfulness of these endeavours for society is all the more urgent (see also chapter 6.1.4).

Upheaval in the rocket launch services sector due to technical innovations

The research and realisation of technical innovations in launch systems and payloads is crucial to facilitating access to space. In the case of launcher systems, for example, lightweight construction methods lead to a reduction in weight and therefore launch costs. In addition, the testing of reusable rocket components, in particular the individual engine stages, is well advanced and has been possible in regular operations at SpaceX since 2017 (SpaceX 2021). Reusability

[22] It should be pointed out at this point that no clear number can be specified, as there is no As ofardised definition of a boundary to outer space (see chapter 3.1.1). Therefore, there is also no consensus on what characterises a space flight and when space travellers are referred to as astronauts.

is intended to save valuable resources (see chapter 5.1.3) and reduce costs. Over the last 60 years, the price per kilogramme of payload has fallen from USD 177,900 (Delta E medium-lift launcher in 1965) to USD 1,500 (Falcon Heavy launcher in 2018) (Roberts 2022). The reuse of rocket stages also provides helpful data that can be used to further develop individual technical components and optimise the launch process.

As there is an increasing need to launch light payloads such as small satellites (see chapter 5.3.2), smaller launch vehicles are now being used more frequently (European Space Agency (ESA) 2018). Around 135 of these micro-launchers are either already in use worldwide or are still under development (Kulu 2021a), including by US companies such as SpaceX and Rocket Lab. Key innovation factors here are new propulsion systems and optimised fuel mixtures (Erwin 2020) as well as new launch concepts, such as that of the company Zero2Infinity, in which a balloon is initially used to launch a three-stage carrier system into the stratosphere before the rocket engines are activated (Marsiske 2016).

As demand for launch capacities increases, new launcher systems need to be developed or existing launcher systems need to be produced in larger quantities. Launchers already in operation, such as the European small launcher Vega, can be converted for new requirements by equipping them with satellite distributors, known as „dispensers“. Instead of a single large satellite, a Vega rocket can launch many small satellites into orbit and deploy them at different orbital altitudes. The first such „ride share flight“ was carried out with Vega in September 2020, releasing 53 small satellites.[23] The Small Spacecraft Mission Service (SSMS) dispenser from SAB Aerospace is currently designed for small satellites weighing between 1 and 500 kg.

These developments indicate that rocket launch services will become cheaper in the future and that technical innovations will make access to space even easier. This could lead to a further increase in the number of rocket launches in the coming years.

5.1.3 Environmental potential and risks

Access to space is facilitated by increased international cooperation, increasing commercialisation and technological innovation. The increase in activities in space has a negative impact on the environment in space and on Earth: through pollutant and greenhouse gas emissions during rocket launches, the threat to the ozone layer from launches and the burning up of rockets and satellites, and through space debris, i.e. non-reusable parts that remain in space.

Privatisation of space activities and environmental assessments

The large number of different players with different economic interests makes it more difficult to enforce binding rules. This is linked to the challenge that although launches can be carried out by individual states or private companies, the consequences can potentially have a global impact. At the same time, as described in chapter 3.2.3, there are no adequate international agreements to measure and limit the environmental impact of commercial space activities. Experts criticise the fact that most internationally ratified agreements on the regulation of space activities that were signed in the 1960s and 1970s no longer do justice to today‘s space industry with its numerous private sector players (Rauenzahn et al. 2020).

Binding framework conditions are needed that are innovation-friendly, but also are also in line with the precautionary principle and environmental and climate goals. At the moment, many initiatives are voluntary and are based on the approach of creating potential for environmental protection through increased cooperation between the various private-sector, scientific and national players. For example, various companies have joined forces as part of the „Space Safety Coalition“ and the „Consortium For Execution Of Rendezvous And Servicing Operations“ (CONFERS) and compiled a range of best practices for improving safety in space. There are now 57 proponents, mainly spacecraft and satellite operators. One, if not the central issue, is space debris, as this poses a threat to the activities of the companies themselves. Collisions with space debris are to be avoided through improved design and adapted operating concepts (Space Safety Coalition (SSC) 2019). Avoiding space debris must also be a core objective of future

[23] https://www.esa.int/Enabling_Support/Space_Transportation/Vega/Vega_return_to_flight_proves_new_rideshare_service

space activities from an environmental perspective (see chapter chapter 6.4), but these measures are voluntary and leave operators a lot of room for manoeuvre in their implementation.

A consortium of private-sector and scientific players has also driven forward the development of a voluntary label to combat space debris, the „Space Sustainability Rating“, which was published in June 2022. The label is intended to motivate stakeholders to act more sustainably when planning and implementing their space missions. It assesses space operators on the basis of various factors, including the extent to which their satellites are easily identifiable and detectable, whether they have taken measures to avoid collisions and whether they have developed plans for removing their satellites from orbit (World Economic Forum 2023).

At national level, there are regulations on the management and assessment of environmental impacts that can limit access to space. A recent example is an approval process that SpaceX recently had to go through for its Starbase facility. In order to carry out the newly planned operation of the Starship/Super Heavy programme at the Boca Chica launch site in Texas, SpaceX had to obtain approval from the US Federal Aviation Agency (FAA) Office of Commercial Space Transportation (Federal Aviation Administration (FAA) 2022). Approximately ten rocket launches and landings per year, fuelling tests, static fire engine tests, the expansion of the launch area and solar farm and the construction of additional launch-related infrastructure are planned. The granting of such licences requires an environmental assessment in accordance with the National Environmental Policy Act (NEPA). For this purpose, SpaceX had to present the environmental impacts of its operations, including greenhouse gas emissions, noise pollution, air quality, water quality in surface waters and groundwater, and the effects on biodiversity in the region. If SpaceX proposes changes to the described activities that go beyond the scope of planned operations, an additional environmental analysis must be conducted. SpaceX had to make more than 75 changes to its proposal for the facility to avoid additional review and ultimately receive a licence from the FAA to launch its new Starship rocket into orbit from this site. After the original licence was granted in June 2022 (Hanson 2022), a written re-evaluation based on new information in April 2023 also found in favour of SpaceX (Federal Aviation Administration (FAA) 2023). The European spaceport in French Guyana is also subject to regulations regarding its environmental impact. In 2015, the operating company Arianespace obtained ISO 14001 certification for the space centre‘s environmental management system and 50001 certification for its energy management system (Arianespace 2015).

ESA is not a regulatory authority and therefore does not authorise or monitor the national space activities of its member states. It does, however, supervise its own space missions. Each state is responsible for all space activities carried out by its state, private or commercial actors (see Space Treaty regulations, chapter 3.2.3). In Germany, DLR is entrusted with space planning, the implementation of German space programmes and the representation of German space interests vis-à-vis international partners, in particular ESA, on the basis of the Space Task Transfer Act (Federal Ministry of Justice (BMJ) 1998). ESA is the only agency worldwide that has developed a framework for carrying out life cycle analyses (LCA) of space missions in order to assess the environmental impact and possibly minimise it with the help of appropriate recommendations for action. The guidelines divide a space mission into five phases: design, production, launch, utilisation and disposal. As part of the life cycle analyses, ground infrastructure, launch vehicles and payloads/spacecraft are examined in all five phases (Morales Serrano et al. 2022). LCA requirements are therefore included in several ESA contracts, such as for Ariane 6, the Copernicus extension missions and the second generation of Galileo. All current ESA projects also fulfil the ESA‘s technical requirements for the reduction of space debris (Committee on the Peaceful Uses of Outer Space (COPUOS) 2022).

Technical innovations by private sector players

Technical innovations in the space sector are increasingly being driven by the growing number of players entering the market as a result of the privatisation of space activities. This is because competition with other companies is an incentive for propulsion systems in particular, but also other technological systems, to continuously become more efficient. Blue Origin and SpaceX, for example, use rocket propulsion systems that utilise a mixture of methane and liquid oxygen (Erwin 2020). The new fuel offers advantages for space operators in terms of the reusability of rocket stages, fuel storage and fuel production costs. From an environmental perspective, these propellants are advantageous as they release fewer ozone-depleting substances compared to solid propellant engines (see chapter 4.2.3). Microlaunchers also have greater poe tential to become more climate-friendly compared to conventional systems. The growing demand for small launcher systems is leading to the development of a large number of innovative and more environmentally friendly missile systems. Microlaunchers, such as the Spektrum launcher system from Isar Aerospace, rely on alternative propulsion systems based on liquid oxygen and propane (Isar Aerospace n.d.). Further advantages result from miniaturisation and the lightweight construction process. Because the components are smaller, fewer resources are required for production. And the smaller size and lower weight go hand in hand with lower fuel requirements and a reduced risk of collision and resulting debris in orbit (Vercalsteren and Holsters 2017; Maury et al. 2020).

Other innovations in recent years include reusable launch systems (Kind et al. 2020). The reusable rocket components used are more material-efficient than conventional rocket parts. Reusable rockets are also more energy-efficient, as they require fewer primary energy sources and raw materials over their life cycle. If rocket stages are not reused, valuable resources are lost - in the case of the Ariane 5 rocket, for example, this amounts to 76 tonnes of steel (Durrieu and Nelson 2013). From an environmental and sustainability perspective, reuse makes sense in any case, but the reprocessing and reuse of launcher systems is also very labour-intensive and therefore costly. The launch costs of reusable rockets will only be amortised once a sufficiently high launch rate has been achieved. If this point is reached, the potential cost savings in turn pose the risk of a rebound effect, which could mean an increase in the number of payloads launched into space due to falling prices for the transport of payloads.

Overall, it can be said that innovations by private sector players have the potential to contribute to increasing efficiency, falling costs and positive environmental effects. Although these would be desirable developments, it should not be forgotten that this could also lead to a sharp increase in space projects whose negative environmental impact could ultimately outweigh the positive aspects (the so-called rebound effect).

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5.2 Satellite navigation and communication

Today, space travel is an elementary component of a large number of technical, social and economic applications. This is particularly evident in the field of navigation and communication on Earth, which rely on a (growing) number of satellites (see chapter 5.1). Exnamples of this are satellite television, satellite-based mobile communications and satellite-based localisation. Current developments show that the number of satellites, especially communication satellites, placed in low-Earth orbit is growing significantly, while the size and weight of satellites is simultaneously tending to decrease (see chapter 5.3.2).

5.2.1 Background and development

Navigation satellites for determining the position of land, water and air movements currently operate in medium Earth orbits at an altitude of approx. 20,000 km (see chapter 4.1.4). The measurement systems of navigation satellites are used globally for measuring the Earth's surface (geodesy), for navigation and time measurement, as well as for synchronising computer networks and mobile phone networks, for example. Almost every modern vehicle, every smartphone, every traffic and logistics management system and every autonomous system is dependent on functioning satellite technology - especially if it is to work regardless of location (e.g. autonomous driving). The importance of this should not be underestimated. The European Commission assumes that around 10% of Europe's gross domestic product is dependent on the availability of satellite navigation (European Commission 2022). The diverse applications include navigation in the transport and traffic sector (on land, in the air and on water) as well as, for example, the synchronisation of energy networks (European Commission 2014).

The most important globally orientated and high-precision navigation satellite systems include the 24-satellite GPS (USA), the 21-satellite Russian GLONASS-system (Langley 2017), the 28-satellite Chinese BeiDou system (Ran 2019) and the European GALILEO system, which in its final configuration is designed for 30 satellites (Sassen 2011; Maini and Agrawal 2014; Chatre and Benedicto 2019). Currently, 22 of these satellites are already in operation.

Technical developments in the field of satellite navigation and communication, such as higher regionalised resolution, miniaturisation, series production and the use of As ofardised components, are drivers for various innovative areas of application. While navigation satellites are primarily used to control future mobility systems, including their applications in transport and logistics, communication satellites will enable global internet coverage in the future. To date, communication satellites have often been positioned in geostationary orbits, where they play a major role in the energy-efficient transmission of radio and television signals. However, they are only suitable for transmitting internet signals to a limited extent. Due to their distance from Earth, there is a delay in data transmission, known as latency, which is particularly disruptive for modern internet-based applications such as video telephony or the streaming of audiovisual content (Voelsen 2021; p. 11).

5.2.2 Trends and drivers

Against the background of the developments described above, there will be great potential for navigation and communication technology in the coming years, e.g. through increasingly easy access to space and the associated increasing number of modern navigation and communication satellites (see chapter 5.1). This will allow larger amounts of data to be collected and better utilised (e.g. in real time) and new data-based applications to be established (see chapter 5.2). Further progress could be the establishment of a broadband internet supply from space based on mega-constellations of small satellites. Global satellite navigation systems will also improve and be merged with 5G technology in the future (European Space Agency (ESA) 2021c).

Broadband internet supply for the global communication of tomorrow

Around 63% of the world's population use the internet, whereas around 3 billion people have no access to the internet (Statista GmbH 2022). While the expansion of fibre-based internet coverage is progressing, various companies have launched projects to establish broadband internet coverage with the help of satellites. As a rule, these are mega-constellations, i.e. satellite swarms consisting of hundreds to thousands of small satellites (Podbregar 2021). They are deployed in low Earth orbits and enable comprehensive and permanent network coverage of the Earth. The potential supply of fast broadband internet not only offers new economic and political opportunities, but should also give private individuals better access to internet-based products and services.

Current projects include (Voelsen 2021; p. 14ff.):

- The Starlink project of the US company SpaceX, which already has 1,739 satellites in operation (as of 16 May 2022; McDowell 2022). In its largest planned expansion stage, up to 42,000 satellites could orbit the Earth (Gebhardt 2021). Starlink has attracted a heightened level of public attention since 2022 due to its use in the Ukraine war, as it enables the internet to be maintained in Ukraine despite the destruction of relevant infrastructure and is used by the Ukrainian armed forces as well as the civilian population. In June 2023, SpaceX concluded a contract with the US Department of Defense to continue funding the provision of internet access to Ukraine through Starlink (Stone and Roulette 2023).
- The Kuiper project of the US company Amazon is to comprise around 3,236 satellites (Fuest and Hegmann 2019).
- The British company OneWeb has begun building a satellite constellation of the same name, which will comprise 648 satellites, 428 of which are already in orbit around the Earth (OneWeb 2022).
- Chinese state-owned and private companies have also announced similar projects, although little information is publicly available on individual projects. In addition to two state projects („Hongyun“ and „Hongyan“), there are also reports about the Chinese car manufacturer Geely, whose planned satellite constellation (approx. 240 satellites) will provide both internet coverage and positioning for the company‘s vehicles (Rixecker 2020).
- Finally, the EU Commission has also announced that it will set up its own satellite constellation from 2023, consisting of around 200 satellites in LEO (Hegmann 2020; Schmutz 2022). Six billion euros are to be invested in the project called Iris² (Infrastructure for Resilience, Interconnectivity and Security by Satellite) by 2027. This autonomous satellite network, which is protected against external influences, is intended to guarantee secure, state-run internet and communication services in the EU (European Commission n.d. b).

These efforts could accelerate the technical development dynamics in satellite technology, particularly in the context of miniaturisation (see chapter 5.3.2), but also in the efficient provision of launchers (see chapter 4.1.2). This development also leads to a certain pressure to act in terms of network policy. This is because a private-sector global internet infrastructure in space is also about questions of access, security and resilience - and not least about global power relations. The EU Commission‘s plans to build up its own satellite fleet should be categorised from this perspective in particular. Own-controlled satellite fleets enable, among other things, tap-proof and interference-free communication[24] between governments, the military and authorities (keyword: GOVSATCOM; European Union Agency for the Space Programme (EUSPA) n.d.), independent of other satellite networks or private commercial interests.

The number of projects planned and already being implemented raises the question of the extent to which global satellite networks established by the private sector are relevant from a regulatory perspective. After all, for the states in which the companies involved are based, this means growing control over the global internet infrastructure and thus increasing influence. While the future development can only be estimated to a limited extent at this moment in time, various political areas are already emerging (Voelsen 2021; p. 17ff.):

- Suitable procedures must be found for the increasing number of satellites within the framework of frequency allocation, as the original procedure was designed for a smaller number of satellites.
- Market access for satellite constellation operators is regulated in the World Trade Organization‘s rules and regulations for telecommunications ser-

[24] One technological development mentioned in this context is quantum technologies, in particular quantum communication and quantum cryptography. Quantum communication is intended to contribute to more reliable and trustworthy satellite navigation. The superposition of particles - typically light photons for data transmission - enables much denser and more secure data transmission. Satellite-supported quantum computing solutions are already being trialled in autonomous driving in particular (Suckau 2021).

vices, but could be specified with regard to the operation of internet satellite constellations, for example by imposing the principles of net neutrality on operators.

- Opportunities for public funding are interesting for satellite operators, for example in the area of international development co-operation.
- Finally, the development of As ofards and software protocols is necessary if satellite constellations, whose individual satellites are always in motion, are to enable data transmission between the users and the satellite constellations.

Satellite-based transport and logistics control

Transport and logistics are the core areas of navigation and communication satellite-based applications. Even today, logistics and traffic management would not be possible without satellite navigation. Precise positioning data is the basic prerequisite for efficient and traceable fleet management, for example for haulage companies. The situation is similar in rail transport, e.g. in the area of train control or route tracking in freight transport.

In future, logistics companies not only want to be able to track their goods, vans and lorries in real time, but also to align their delivery routes on a daily basis. This is particularly useful in regions with dense traffic, as well as in cities on the so-called „last mile", i.e. the delivery routes between regional logistics centres and recipients. The aim is to use AI tools to predict future shipment distributions - i.e. how many parcels will arrive where and when - in order to optimise route planning accordingly. This involves analysing data on shipment and delivery information as well as traffic volumes, location data and weather data.

Autonomous logistics concepts, both in warehouses and on the road, are another future field that is currently being developed. High-precision, reliable navigation data is required for autonomous driving (Belabbas 2020). Knowledge of the exact position of vehicles or drones, for example on which side of the carriageway and how far away from the edge of the road a vehicle is located, determines the safety and operational capability of autonomous systems. Car manufacturers, such as Geely, have already started to set up a satellite constellation that will be used for the autonomous control of logistics and car fleets in the future (Sokolov 2022).

However, navigation and communication satellites are becoming increasingly important not only on the road, but also in intralogistics, i.e. in logistics centres. High-precision positioning is necessary for robotics navigation so that logistics robots can navigate warehouses autonomously.

Satellite backhaul for autonomous factories

The combination of terrestrial and satellite-based internet opens up a lot of new potential, for example in urban areas or for smart factories. Communication satellites can already be used to connect areas with poor mobile phone coverage, linking mobile phone stations with each other and connecting them to the overall network. To do this, the provider's core network is connected to the radio masts via satellite instead of the fibre optic cable that has been used to date (satellite backhaul); Sawall 2021). This is a key driver for the roll-out of a globally available 5G network and a technical prerequisite for autonomous factories. In future, the base station will no longer be required as a communication mediator in order to make the system even more resilient. To this end, technologies are being developed that enable direct communication between satellites and 5G-capable end devices (Heyn and Hofmann n.d.). This should enable the satellite itself to act as a base station. Depending on availability, machines in an autonomous factory could in future exchange data and information via a conventional base station or directly via satellite.

However, the fusion of the 5G terrestrial mobile communications As ofard with satellite-based networks is not only seen as paving the way for future autonomous factories. Structurally weak regions, in which the terrestrial expansion of the mobile network has so far stalled for cost reasons, could also benefit from this development. In densely populated urban areas, the fusion of satellite networks and 5G is also seen as desirable. This is because dense (and tall) buildings sometimes mean that satellite availability is limited and satellite geometry is unfavourable. Great potential is also seen in the specific provision for company networks in production or agriculture if they require high 5G positioning accuracy. In the future, local or so-called campus networks for 5G controlled from space could be created on company premises for machine and vehicle control (Del Peral-Rosado et al. 2018).

The digitalisation of the economy has been progressing at an ever-faster pace in recent years, bringing autonomous production facilities ever closer. The technical basis for this are intelligent, digitally networked IoT („Internet of things") systems, which can be used to implement largely self-organised production. In order for the autonomous control of future factories to run smoothly, data and information must be networked, exchanged and processed between a large number of „actors"; these include driverless transport systems, learning machines, sensors, cameras, drones and IT systems.

In such autonomous factories, machines collect production data around the clock and exchange this pre-processed data with each other or send the data to a control centre for evaluation via the internet. AI can be used to predict problems in production or necessary adjustments. On this basis, production is planned and controlled independently in autonomous production systems. Unlike automated production, which is based on an „if-then logic", autonomous factories can also react to complex events that are difficult to predict (Messe München GmbH 2022). An essential prerequisite for the coordination of machines and processes in the autonomous factory is real-time machine communication.

In order to enable real-time communication between machines with minimal latency times, the 5G mobile communications As ofard must be available across the board, as it enables the transmission of high data rates of up to 20 Gbits/s - similar to autonomous mobility and logistics control. Since 5G, like its predecessor LTE (Long Term Evolution), will probably not be available everywhere on Earth in the same quality (keyword: coverage), the convergence of the terrestrial mobile communications As ofard with satellite-based networks will be necessary to compensate for „dead spots". The integration of satellites into the 5G mobile communications As ofard was already taken into account during its development. Such „Non-Terrestrial Networks (NTN)" have no limitations in terms of range and coverage.

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5.2.3 Environmental potentials and risks

The importance of satellites and the associated technical advances in digitalisation, e.g. for the Internet of Things (IoT) or autonomous driving, are already omnipresent today and have implications for environmental and climate protection that will become even more relevant in view of the trends outlined above.

Digital technologies (such as the 5.3.1 GALILEO satellite system described under 5.3.1 as well as robotic systems and autonomous navigation, among others) can help realise a range of potential ways of increasing resource efficiency and protecting the environment (German Agricultural Society (DLG e.V.) 2018).

In addition to the aforementioned potential, e.g. for the Internet of Things (IoT), autonomous driving and autonomous factories, there are also risks. The technologies described require new hardware and the construction of the necessary infrastructure on Earth, both of which are associated with resource consumption and emissions during production and operation. This also extends to the satellites themselves, the increasing number of which will lead to more space debris in the medium term and put a strain on the Earth's limited orbit (see chapter 4.1.4 and chapter 4.2.4). In addition, the utili4 sation of the data obtained (see chapter 5.1 and chapter 5.2.1) on Earth requires an IT infrastructure for storage and processing, which must also be considered in terms of its energy and resource efficiency. Last but not least, the risk of rebound effects must also be taken into account for the fundamentally environmentally friendly changes made possible by satellite communication and navigation.

Efficiency gains and rebound effects through intelligent control of autonomous driving

Autonomous passenger and freight transport (automation of vehicles and ships) can reduce fuel consumption in the transport sector and increase efficiency. The automation of private means of transport and lorry freight transport as well as improved traffic management (such as congestion detection, navigation services) could not only make road traffic more efficient (fewer traffic jams), but also safer (fewer accidents by eliminating human error at the wheel). In addition, for example, personnel costs and possibly operating costs (due to lower expenses for accident insurance policies) can be saved (Enzweiler et al. 2018). The more efficient driving style of fully autonomous and connected vehicles in passenger and freight transport is reflected in the reduction in braking and acceleration processes (Krail et al. 2019). This is expected to result in fuel savings and consequently lower CO_2 emissions (Enzweiler et al. 2018). This can be expected to have a positive impact on the environment. At the same time, experts assume that better satellite-controlled traffic management will result in more intensive use of transport routes (Krail et al. 2019). As a result, autonomous driving is more of a driver for increased traffic volumes. The positive effects achieved by automation may therefore be reduced again (Enzweiler et al. 2018).

Companies and private individuals can complete longer journeys in autonomous vehicles in less time, as there is no need for people (and the threat of fatigue) at the wheel (Milakis et al. 2017). By relieving the burden on the driver and possibly offering greater comfort, autonomous driving means private vehicles will be able to compete with local public transport. Increased numbers of empty buses and trains could be the result (Taiebat et al. 2018). Here, too, autonomous driving is more likely to be seen as a driver of higher traffic volumes.

The shift towards automated and connected driving in passenger and freight transport is not entirely positive from an environmental perspective (Milakis et al. 2017). Some experts assume that the use of autonomous vehicles could increase both passenger and freight transport (Köllner 2019; Gensch et al. 2019). This rebound effect could even counteract the positive impact of the savings effects in the private and business sectors (Krail et al. 2019). The operation of autonomous vehicles requires considerable computing capacity, and the operation of the required data centres in turn causes CO_2 emissions. According to a study by the Massachusetts Institute of Technology (MIT), 0.14 gigatonnes of CO_2 would be attributable to the = operation of autonomous vehicles alone in 2050[25] - without taking into account other sources of emissions, such as the operation of sensors in the vehicle or vehicle production (Sudhakar et al. 2023). This would correspond to the current annual emissions of a country like Argentina (Brien 2023).

More resource conservation through smart farming

The automation of agricultural processes based on satellite data harbours a number of opportunities for environmental protection. At the same time, the production and operation of smart farming infrastructures is associated with high resource consumption. The positive environmental effects of smart farming on soil, water, air and biodiversity must be weighed against the negative effects.

Precision agriculture (PA), an environmentally friendly and resource-efficient form of agriculture, is made possible by the use of the latest technologies, e.g. for object identification, georeferencing, measurement of specific parameters as well as for global navigation satellite systems (GNSS), connectivity, data storage and analysis, advisory systems, robotic systems and autonomous navigation. The aim of PA is to reduce production costs and improve and increase food production. This should make it possible to produce more output with fewer resources. PA is already being used in arable farming, vegetable growing and dairy production and is currently utilised by around 25% of farms. However, smart technologies have not yet realised their full po-

[25] Model assumptions of the study: In 2050, 95% of all vehicles will drive autonomously and will be used for an average of one hour a day.

tential, as further innovations and areas of application in agriculture are to be expected (Schrijver 2016).

Other examples of applications include sensor-based monitoring systems, crop condition warning systems, harvest forecasts, feeding robots and precision milking machines (Schrijver 2016). The ecological benefits are just as diverse as the possible applications. For example, automatic machine control via GPS can reduce the CO_2 footprint. This can save 10 % of fuel used during field work. In addition, soil compaction can be minimised because fewer heavy machines are used. Instead, lighter swarm robots can be used that work where and when required (Schrijver 2016). With automatic machine control, it is also possible to work at precise times in favourable weather conditions. In addition, PA enables permanent plant growth at key points and field edges through automatic tracking and contour cultivation along contour lines or on uneven terrain. This reduces erosion, minimises the risk of flooding and reduces surface water and fertiliser run-off (Schrijver 2016).

Thanks to the Internet of Things, physical objects can be networked with the digital world and other smart devices to take on various control tasks. In the field of agriculture, IoT applications offer a wide range of possibilities; livestock farming and arable farming can be organised more efficiently. For example, digital sensors can indicate how far a plant has grown and thus determine the nitrogen requirement. These measurements can then be used to determine the amount of fertiliser required. This means that fewer raw materials are used and fertilisers and pesticides can be used in a more targeted manner (Dupree 2015). At the same time, it must be borne in mind that the technology required for PA (sensors, smart devices and machines) requires additional resources for production and operation compared to conventional agriculture, which must also be taken into account in the environmental balance sheet.

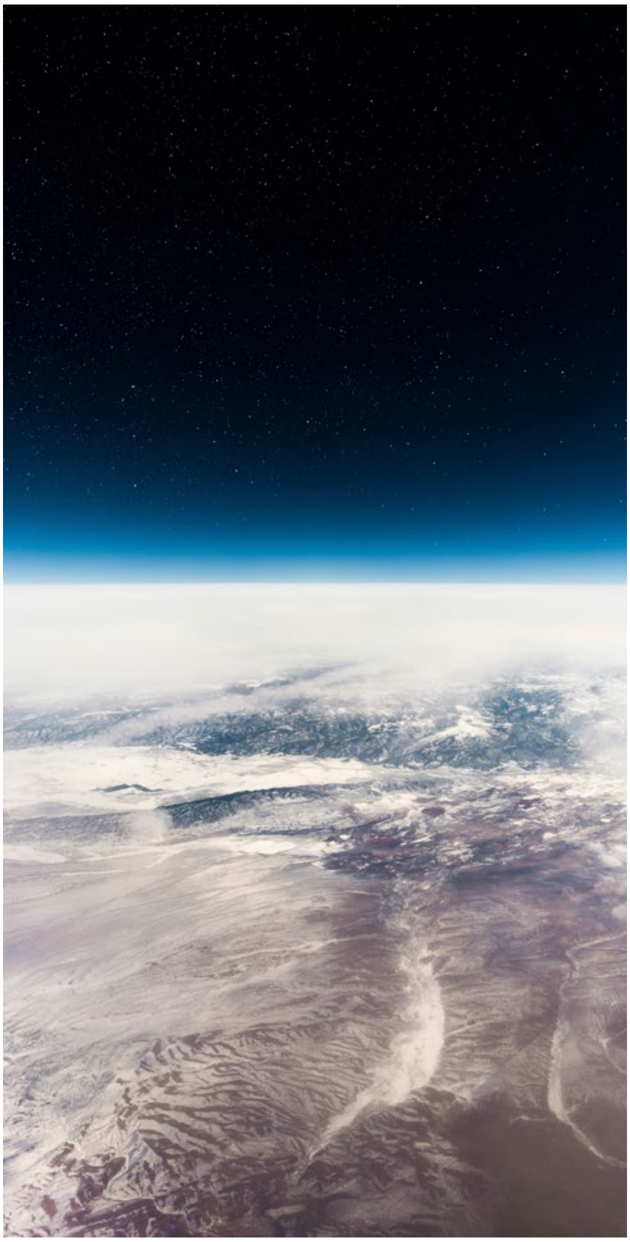
Resource efficiency in smart cities

Another area of application for communication and navigation satellites is cities. The concept of smart cities is based on the IoT. The aim is to create an intelligent, interconnected urban network. By utilising communication and navigation satellite data, areas of infrastructure, energy, water and heat supply, waste disposal, traffic control, infrastructures for information and communication technologies and other urban areas can become smart. Smart functionality means that, for example, more efficient electricity and heat generation in the city can be ensured or traffic can be monitored (in this case, users could be informed via an app) to enable a smoother flow (Dupree 2015).

This can create potential for urban environmental protection. The energy consumption of cities can be reduced by optimising existing infrastructure systems with the help of digitally networked solutions (Preuß et al. 2020). For example, real-time data becomes available and can be used to make citizens aware of energy savings. A reduction in urban pollution is also possible and can be achieved by promoting alternative forms of mobility such as electromobility. However, there is also a risk of rebound effects with smart solutions. For example, the increase in efficiency can lead to increased demand or utilisation. The environmental benefits of the smart city concept can only be fully realised if risks are taken into account and favourable framework conditions are created, for example by further researching resource-efficient technologies and strengthening sustainable procurement by local authorities. In addition, As ofardised processes for evaluating and monitoring smart city measures must be established at municipal level (Preuß et al. 2020).

5.3 Earth observation

The observation of the Earth‘s surface and its atmosphere from a height of a few hundred to several thousand kilometres is known as Earth observation. The technical basis for this is provided by so-called Earth observation satellites (see chapter 4.1.4). These are launched into space with the aid of carrier rockets, where they collect data and send it back to control centres on Earth. As a rule, this data is only analysed on Earth and fed into climate models, for example. However, there are also initial approaches to analysing data partially „onboard“, i.e. while still in space, in order to sort out unusable data in some cases (European Space Agency (ESA) n.d. l).



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5.3.1 Background and development

The first Earth observation satellites began their service in the 1960s and were used to observe meteorological processes and for weather forecasting. Since then, the technology for Earth observation and the possible applications have developed and diversified considerably. Today, Earth observation satellites are used to measure a wide range of parameters and properties. For example, the measurement data can be used to measure certain chemical substances, such as the composition of water and air, the condition of crops or forests, to record soil movements in the millimetre range and to determine the surface temperature of the oceans (see below).

Basically, there are two types of Earth observation satellites: those that are geostationary at an altitude of around 36,000 kilometres above the equator and those that orbit the Earth at a shorter distance (between 430 and 930 kilometres altitude) in around 90 to 110 minutes. While geostationary satellites, which are distributed at equatorial positions, permanently cover approx. 90 % of the Earth‘s surface (the poles are not covered), Earth-orbiting satellites require several orbits for a „complete picture“. Their data, on the other hand, is recorded in a higher geometric resolution.

Satellites are equipped with various recording systems for Earth observation, primarily optical sensors and microwave sensors. A distinction is made between active and passive systems (Maini and Agrawal 2014; 524ff.).

Passive systems, such as thermal cameras or spectrometers, receive radiation and record it, for example the radiation emitted by the Earth‘s surface or other objects, as well as the reflected solar radiation. Passive sensors not only cover the frequency range visible to humans, but also the entire electromagnetic spectrum. They can therefore collect data in the infrared range, for example, which can be used to identify healthy vegetation on satellite images (GISGeography 2015). The presence of individual trace gases in the atmosphere can also be determined by measuring the individual „spectral fingerprint“ of the gases, which blocks a specific part of the reflected light spectrum.

In contrast, active sensors themselves emit radiation such as microwaves, laser beams or radar waves in the electromagnetic range and measure the reflected radiation component and/or, via the time interval between emission and reception of the radiation, the distance of the reflecting surface from the sensor. This makes it possible to create precise elevation maps of the Earth‘s surface, e.g. as part of NASA‘s „Shuttle Radar Topography Mission“, which recorded the first near- complete elevation model of the Earth‘s surface in 2000 (NASA Jet Propulsion Laboratory 2023). In contrast to passive systems, active sensors are not dependent on solar radiation, which means they can also be used at night. Depending on the sensor technology used, active sensors can also be used in clouds and bad weather. Compared to passive sensors, however, the operation of active sensors is more energy-intensive (GISGeography 2015).

Earth observation satellites can record several gigabytes of data per second. By way of comparison, streaming a film in HD-quality consumes around 3 gigabytes per hour. The Earth observation data is compressed and temporarily stored on board before it is transmitted at a data rate of currently max. 320 Mbit/s to payload ground segments on Earth. These payload ground segments are designed specifically for each mission. There are similarities to other payload ground segments, such as those used to operate navigation satellites, particularly in terms of their technical structure. The key difference, however, is that payload ground segments for Earth observation satellites must be suitable for processing large amounts of data, i.e. both data rates and data volumes (Dech et al. 2011; p. 515). In these specific payload ground segments, (1) the data is processed to higher-quality processing stages, (2) the (raw) data is archived and catalogued, (3) access to existing data or further processed Earth observation products is made possible for users and (4) order management for new data to be recorded is organised. Relay satellites (see chapter 4.1.4) allow the exchange of higher data rates, which makes it possible to transmit data from space almost in real time (European Space Agency (ESA) n.d. f).

A decisive factor for the realisation of Earth observation missions are the launch costs for transporting the satellites into orbit. These are in the range of tens to hundreds of millions (see chapter 3.2.2). Due to these high launch costs, rocket operators are increasingly selling „rideshare opportunities“. This reduces the overall launch costs and enables other players to launch smaller or less complex satellites into orbit for Earth observation at low cost.

Earth observation: current fields of application

In the field of Earth observation and remote sensing data, there are already numerous fields of application for the utilisation of the collected data. The data is used, for example, to investigate climate change and the composition of the Earth‘s atmosphere, for agriculture and food, forestry, infrastructure, resources and transport, as well as for analysing oceans and water bodies. Examples of such data utilisation include

- **Climate change/atmosphere:** Data on temperature, temperature trends and air quality support the long-term monitoring and analysis of climate change (Yang et al. 2013). The consequences of climate change can also be modelled and analysed on the basis of remote sensing data, such as the risk of flooding due to newly forming mountain lakes as a result of melting glaciers (Furian et al. 2021). Geographically precise analyses of the possible consequences of climate change are also essential for the planning and implementation of adaptation strategies (see e.g. Paul et al. 2020).

- **Agriculture/nutrition:** Data helps make predictions on the speed of plant growth, shows the type of land use, helps make logistics efficient and fertilisation environmentally friendly (Copernicus 2021a) and is used in the creation of growth maps (see also chapter 5.2.3). Remote sensing data also enables, for example, the mapping of crop failures due to natural disasters such as flooding and supports subsequent processes such as the payment of insurance to affected farmers (Shofiyati et al. (Shofiyati et al. 2022).

- **Forests/forestry:** Data allows the precise spatial determination of drought damage or specific pests (e.g. bark beetles). It helps the responsible forest administration draw up action plans for the deforestation or reforestation of forest areas (Seitz 2021) and in fighting forest fires by generating maps with fire hotspots (Copernicus 2021b). Data can also be used to map illegal deforestation and thus contributes indirectly to the protection of the environment (Mitchell et al. 2017).

- **Waters and oceans:** Data enables mapping and monitoring of the seabed, for example with regard to mussel populations or sediment types (Reimers 2021), temperature recording and the assessment of water quality based on observable parameters such as visibility depth, turbidity and the chlorophyll content of the water (Deller 2021). This helps identify marine areas or inland waters with heavy algal blooms or suspended (ibid; Le Traon et al. 2021).

- **Infrastructure, resources and transport:** Exploratory data supports the analysis of risks to infrastructure from natural events, e.g. in flood risk analyses (Löw 2021) or analyses of ground movements, such as landslides (Anderssohn 2021) in determining the navigability of sea routes through ice classification (Rabenstein 2021) and traffic forecasting (Hilti 2021). Satellite data can also be used to identify and quantify resources used in settlements and infrastructure (Schug et al. 2022) as well as in the identification of informal settlements (Niebergall et al. 2008) and the outlining of their water supply (Rausch et al. 2018). In the event of disasters (such as earthquakes, fires or floods), Earth observation data serves as a basis for rapid action by the emergency services (Denis et al. 2016).

5.3.2 Trends and drivers

Earth observation is a highly dynamic field. The key drivers here are technical innovations such as the series production of small satellites (CubeSats) and the availability of miniaturised, low-power and cost-effective sensors for mini or nano-satellites (see definition below) which can be used in low-Earth orbit for Earth observation applications. This is accompanied by the emergence of new business models based on data-based services that are also relevant for non-space players. New satellites from private and state providers also offer advances in sensor technology, for example the spatial resolution of the images produced is becoming ever higher and the individual pixels smaller. The spectral resolution of the data is also increasing, i.e. data is captured in more clearly delineated channels. This enables a more precise classification of results.

Increasing number of small commercial satellites for Earth observation

Between 2021 and 2030, over 15,000 satellites will be launched into space, up to 90% of which will be small satellites. It is becoming increasingly cheaper to launch small satellites into space using specially designed launch vehicles; they can also be used in large missions as „additional cargo“ (Wagener 2022).

Small satellites are mainly used for commercial Earth observation (Funke et al. 2016). They are a key driver for the forecast developments in the market for Earth observation applications. This is expected to double from around EUR 2.8 billion to over EUR 5.5 billion in the next 10 years. The segment of data-related value-added services, which is expected to account for 85% of the market in future, is a key factor here.

In order to tap into market potential, satellites are equipped with a wide variety of sensors - often including those that have not been specially developed for space applications. As a result, „As ofard off-the-shelf“ sensors for space are increasingly being installed.

Small satellites are categorised as minisatellites (100 to 500 kg), microsatellites (10 to 100 kg), nanosatellites (1 to 10 kg) and picosatellites (0.1 to 1 kg) (Bärwald and Brieß 2011; p. 676). However, there is no internationally recognised, As ofardised classification, so the boundaries remain blurred. The number of small satellites in orbit has increased significantly since the early 2010s (DelPozzo et al. 2019; Bocksch 2021a). One starting point for this development was the CubeSat As ofard defined by Stanford University and California Polytechnic State University in 2003 (Funke et al. 2016). This was intended to make it easier for universities to access space. In the meantime, however, small satellites are increasingly being used commercially due to their advantages over conventional satellites (low budget requirements,[26] short development and manufacturing times and small user communities).

In recent years, small satellites have made the step from technology demonstration to commercial application and also offer an alternative for large missions. Used in formations or swarms, they can also compensate for the sometimes-poorer sensor resolution or limited data rate of the communication systems compared to conventional satellites. However, small satellites often have a shorter service life because

[26] Mission costs generally include material, personnel, testing and qualification costs as well as launch fees. For a small satellite mission, these costs are less than 1 million euros per satellite (Funke et al. 2016).

the miniaturised elements, as well as many As ofard electronic components, fail more quickly under space conditions (radiation, temperature fluctuations) (see chapter 4.1.4). Small satellites therefore have to be replaced more frequently. Furthermore, they do not have integrated propulsion systems, meaning that there is no way to burn them up in the Earth's atmosphere in a controlled manner after use (Speicher 2014).

New services are emerging in the downstream sector

The growing number of small Earth observation satellites in orbit equipped with high-resolution sensor technology means that potential users have access to ever larger volumes of data. This data must be „refined" into data products before it can be used in order to make it interpretable. Services that are based on the exchange, further processing and analysis of space-based data are referred to as the „downstream sector". The downstream sector refers to those areas of the space industry in which products and services based on satellite-based communication, navigation and Earth observation data are commercially utilised on Earth (Kind et al. 2020; p. 40).

The market for remote sensing products and services is currently developing very dynamically and had a market volume of between USD 2.7 billion and USD 3.3 billion in 2021 (see Rencelj et al. 2023; p. 126). In addition to the growing supply of data, the sector's other main growth factor is the ever-improving local resolution of new Earth observation satellites. In addition to government and scientific players, companies and start-ups are playing an increasingly important role in the interpretation and processing of data.

Space agencies as well as space companies, micro-satellite operators and start-ups have recognised the exploitation potential of Earth observation data. They develop services based on Earth observation data and offer them to the public sector, companies, the scientific community and private users. An important basis for this is the free accessibility of data (Jordan 2021). Space agencies such as ESA already enable such free access via the platforms Copernicus Open Access Hub,[27] EO Browser or ESA Earth Online. NASA offers this via the Earth Data platform[28] . Private companies are often interested in open access. However, if they collect or process satellite data themselves, this is often part of their business model and not freely accessible.

Another important business area in the downstream sector is AI systems for analysing and interpreting high-resolution satellite images and other Earth observation data. For example, machine learning algorithms are trained to recognise certain structures or patterns so that they can find them efficiently and quickly in huge data sets. For example, the open platforms OpenSurface[29] and OneSoil[30] have been developed to monitor land use. They offer AI services that can draw conclusions about the condition of forests based on satellite images or map the agricultural use of the Earth's surface.

In the coming years, the „Destination Earth" initiative will also enable new data-based Earth observation services (European Commission n.d. a). The initiative was launched by the European Commission in 2021 as part of the Digital Strategy under the EU Green Deal. The aim is to create a precise digital image of the Earth by 2030 - a so-called digital twin. With the help of „Destination Earth" and other twin simulations, such as the Digital Earth Project (Ruhnke et al. 2022), it will be possible to develop and test high-resolution local scenarios for sustainable development, extreme events and climate development in the future. In addition to Earth observation data, other data on human activities relevant to the climate system will be integrated into the Digital Earth model (Ulmer 2021). This will provide a more realistic simulation of humanity's impact on the planet.

5.3.3 Environmental potentials and risks

Precise observation of various environmental areas makes it possible to take targeted measures to improve the environment. Earth observation tools can make an important contribution to nature conservation by visualising environmental damage and making it traceable over time. The resulting potential

[27] https://scihub.copernicus.eu/

[28] https://earthdata.nasa.gov/

[29] https://opensurface.io/

[30] https://map.onesoil.ai

is valuable. However, from an environmental perspective, the actual benefits of monitoring tools are strongly linked to the success of the political actions derived from the data.

The fields of application (see chapter 5.3.1) show a great deal of potential to have a positive impact on the environment. For example, programmes such as Google Earth Engine can show the changing Earth in fast motion. The programme can be used to observe the melting of glaciers, the rise in sea levels and the death of forests since records began in 1984. These visualisations can further raise public awareness of the climate crisis and the relevance of environmental protection. Satellite observations provide facts for monitoring the progression of climate change. The combination of meteorological and geographical, historical and current data offers enormous potential for environmental research and policy to identify the need for action with regard to climate change and the monitoring of international agreements and resource management. This is also useful for the implementation of environmental measures (Feddeck et al.).

However, the generation of Earth observation data is associated with environmental impacts, as it relies on cost- and resource-intensive technical systems and creates unwanted emissions and space debris (see chapter 4.2). The trend towards Earth observation data with ever-higher spatial and temporal resolution is leading to a sharp increase in the volume of data to be processed, which in turn increases the environmental footprint of the technologies used and the resulting findings.

The following section describes areas of application in which Earth observation can make a contribution to environmental and climate protection.

Monitoring the environment and ecosystems

Earth observation data can support measures against the loss of biodiversity. This data is used to detect forest fires (Crowley et al. 2023) and oil leaks and spills in the world's oceans (Jafarzadeh et al. 2021) and serves as a basis for emergency measures to protect people and nature. Long-term recordings also show the loss of habitats, the deterioration of soil, air and water quality and climatic changes in certain regions (Kramer 2016). These changes mean that animals and plants are no longer adapted to their previous habitats and therefore have to move to other areas (Bates 2020). Satellites have the potential to document the northward shift of species by producing high-resolution image material, for example. Weather data, soil moisture and the nutrient richness of a region can predict the migration or extinction of a species (Stoner et al. 2016).

Although climate change is the most important factor in habitat displacement, data - even if it does not contribute to the fight against climate change itself

can lead to regional measures to support individual organisms in finding an adapted habitat. One example of this is assisted migration. This involves removing plants from their previous habitat and planting them in a suitable climate in order to increase their chances of survival (Handler et al. n.d.).

The fragmentation of ecosystems is increasing due to the expansion of infrastructure, as well as the sealing and enclosure of agricultural land. This makes it more difficult for creatures and organisms to find new sources of food or to utilise the full potential of a region for themselves (Zambrano et al. 2019). To ensure species conservation, it is necessary to connect habitats with bridges, for example. Earth observation data can be used in a variety of ways here. Earth observation provides ecosystem and traffic data to facilitate the targeted creation of living corridors such as hedges in agriculture, a nature-supporting footpath foundation or green bridges. Finally, species can be better protected by measuring light pollution from space using Earth observation data. The targeted dimming of light sources in the vicinity of living habitats means that the rhythm of living creatures is less disturbed (Beißwenger 2021). However, satellites, especially planned mega-constellations with tens of thousands of satellites such as Starlink, contribute massively to light pollution, especially in Central Europe, Canada and Central Asia (Holland 2021).

Earth observation is also used in a variety of ways in agriculture. Data on soil moisture, nutrients and crop failures can be used, for example, to return low-yield areas to nature.

Control of political measures

Data from Earth observation offers great potential to support states and institutions in monitoring established political measures and programmes. For example, data can be used to monitor political agreements such as the Ramsar Convention (Leeuw et al. 2010), which aims to protect wetlands of international importance (Ramsar Convention on Wetlands Secretariat 2023). The effectiveness of protected areas with regard to the designated conservation objectives can also be evaluated with the aid of satellite data (e.g. Geldmann et al. 2019). In order for European farmers to receive EU agricultural payments, it must be determined and monitored whether they are managing their land correctly and thus whether they are complying with requirements relating to environmental protection or the reduction of soil erosion, for example (Federal Ministry of Food and Agriculture (BMEL) 2019). Implementation can be considerably simplified by means of Earth observation.

Earth observation data can contribute to a meaningful monitoring method for individual states through the various linking possibilities of the different satellite technologies, paired with artificial intelligence and strong computing power. Countries can significantly reduce the cost of monitoring SDGs and targets and simplify reporting for governments operating with limited resources (Japan Aerospace Exploration Agency (JAXA) 2017). Human rights violations or the pollution of protected assets could be permanently tracked through the real-time transmission of Earth observation.

Recognising and sanctioning environmental damage

Environmentally harmful behaviour can only be sanctioned if it can be proven and the perpetrators can be identified. Earth observation can make an important contribution to this. Observation satellites can document wind patterns and nutrient flows and indicate the vitality of ecosystems (Feddeck et al.).

Globally, health damage from air pollution alone cost 5.7 trillion US dollars in 2016 (The World Bank and Institute for Health Metrics and Evaluation 2016).

To date, it has mainly been chemical analyses, which can be taken from the pollutant release and transfer register, that have shown the negative impact of industries on the environment (Federal Environment Agency (UBA) 2021a). While these figures are very abstract and no specific ecological damage can be attributed to individual companies, satellite images could enable a more precise classification.

The exact origin of chemical substances can be reconstructed by algorithmically classifying the image data. For example, the report „Environmental Racism in Death Alley, Louisiana“ by Forensic Architecture shows how industrial pollution can be precisely defined by analysing exhaust gases (Forensic Architecture 2021). In combination with health data, the presence of pollutants can be confirmed and air pollution from individual companies can be proven. Political measures such as reparations can then be decided for the affected areas (Taubenböck et al. 2020; Forensic Architecture 2021).

Earth observation data can also help to find leaks in abandoned or dry boreholes. For this purpose, imaging precision spectrometers in the visible infrared range are installed on satellites (Carbon Mapper Inc. n.d.). Around a third of all oil wells on Earth pose a risk of ongoing methane emissions due to their proximity to gas fields (Vielstädte et al. 2017). Earth observation could be used to detect these holes and seal them in a controlled manner. This would reduce global methane emissions by around 1 % (Lauvaux et al. 2022). The companies responsible could potentially be held liable for the resulting ecological damage, damage to the health of the population and economic restrictions, as has been demanded in other cases (Forensic Architecture 2021).

Earth observation could also help to detect planned environmental destruction. By documenting environmentally damaging interventions with the help of satellite images, countermeasures can be taken if necessary before damage becomes irreversible. In the past, for example, an illegally planned extensive forest fire to make way for agricultural land for the palm industry in Indonesia was discovered using such methods. The accurately placed rows of firewood, which were discovered through Earth observation, indicated arson. According to the Forest Stewardship Council, the company in question was violating the human rights of indigenous peoples and damaging the country‘s biodiversity (Forensic Architecture 2020). By analysing image data, environmental crime can be detected at an early stage and prosecutions can be initiated. Preventive measures can also be developed for the future (Rodriguez Lopez et al. 2016).

Create environmental forecasts

With the help of the planned digital twins of the Earth, the „Destination Earth“ project should make it possible to implement climate adaptation measures in a more targeted manner and to recognise possible effects of measures even before they are implemented (European Commission 2022). For example, the effects on the environment of various new methods of energy generation, such as the storage of internal geothermal energy, can be simulated (European Commission 2021a). Planned dyke construction projects can be checked in relation to expected future flood events and validated more reliably. Droughts, heatwaves or tsunamis can also be predicted by combining Earth observation data and simulations, allowing counties or municipalities to test relief measures for the safety of the population (European Commission 2022).

A digital planet simulation also offers great potential for environmental policy to assess the impact of human activity on the environment in advance, supported by technology (Nativi and Craglia 2020). Digital twin simulations of the Earth can be used to assess applications for resource extraction for their environmental compatibility or to make recommendations on resource management and recycling activities. Based on these statements - formulated by the AI of the digital twin - political guidelines could be drawn up that take into account the limited nature of resources or reflect existing measures (European Commission n.d. a). The Earth‘s natural resources can also be balanced. Specific spectral data measured by satellites can be used to find indications of mineral deposits in the Earth, for example. Satellite-based detection of raw materials is much more time-saving and can be applied over a larger area than traditional field investigations. In addition, inaccessible areas can also be analysed for the presence of raw materials from space (see e.g. Mohamed et al. 2021). Precise knowledge of the resources available on Earth is essential for the resource management approaches outlined above and the assessment of the environmental impact of their extraction.

5.4 Mining of raw materials in space

The mining of raw materials in space („space mining“) is a vision of the future that has long been part of the realm of science fiction. There are potentially two fundamental goals: counter the shortage of raw materials on Earth and make space travel less dependent on supplies from Earth.

5.4.1 Background and development

The mining of raw materials in space can therefore be viewed from two perspectives:

1. Initially in the narrower sense as the extraction and utilisation of raw materials for (manned and unmanned) space travel (e.g. to reach distant destinations).

2. In a broader sense, however, this also includes the mining of raw materials in space and their utilisation on (or for) Earth (Institute of Technology Assessment of the Austrian Academy (ITA) and Austrian Institute of Technology (AIT) 2018).

In the first case, in addition to solar energy and helium-3, the raw materials required for rocket fuel (water, oxygen) as well as raw materials for the construction of space hardware (metals, non-metals, minerals) and for the life support of space travellers (water, oxygen) come into question.

In the second case, in addition to solar energy, the focus is also on raw materials in order to counteract the scarcity of resources on Earth (Federal Government 2019b). Although the first discussions on the use of raw materials from space were held in the 1960s as part of the Apollo programme in the USA, it has not yet been possible to achieve the technical, regulatory (see chapter 3.2.3) and economic challenges have not yet been solved.

In order to be able to mine raw materials in space, they must first be detected. Asteroids and planets in the solar system are thought to contain raw materials of various kinds. There are 17,000 so-called NEOs (near-Earth objects) which are known to date: Asteroids, comets and meteoroids that come very close to Earth in their orbit and can be detected (Wachter et al. 2018). The various raw materials can be tracked down using remote sensing methods, for example (Elvis et al. 2017). Missions are currently being carried out to take samples from asteroids and transport them to Earth (Luxembourg Institute of Science and Technology (LIST) 2021; p. 3f.). Although other research objectives (e.g. the composition of the solar system during its formation) take centre stage, this can still provide relevant findings for the future search for raw materials.

In order to reach asteroids, their exact orbit must first be calculated so that space probes can be placed on correct trajectories (Luxembourg Institute of Science and Technology (LIST) 2021; p. 22). It therefore seems more obvious to first consider the Moon as a potential source of raw materials, as its proximity and accessibility has already been demonstrated several times (Byrne 2019; Chavy-Macdonald et al. 2021).

Mining raw materials in space is technically challenging. The raw materials can be located on or under the surface of an asteroid, a moon or a planet or contained in the surface. However, extractability, i.e. the way in which mining would have to be carried out, has not yet been part of investigations into raw material deposits (Lamboray et al. 2019; p. 7). Knowledge from the mining sector is essential for the development of technical solutions for the extraction of raw materials (Lamboray et al. 2019; p. 9). In 2017, for example, a multidisciplinary graduate programme was established at the Colorado School of Mines in the US, which is explicitly dedicated to the topic of raw materials in space (Heller 2021). Drilling on the Moon or Mars cannot be carried out with equipment that can also be used in mining on Earth, because both the nature of the subsurface and the environment in which mining takes place differ from those on Earth (Luxembourg Institute of Science and Technology (LIST) 2021; p. 25). Other possible types of mining include the extraction of oxygen through thermal reduction (Luxembourg Institute of Science and Technology (LIST) 2021; p. 16) of water through heating (Sowers and Dreyer 2019) and digging with (robotic) shovels (Gilbert 2021) or even mining with the help of microbes (Cockell et al. 2020). In each of the cases mentioned, the development and testing of special mining technologies is therefore required, ideally without human control on site. Robotic or unmanned space mining currently appears to be the most obvious course of development.

The central hurdle in the utilisation of resources on Earth is logistics, i.e. transporting the extracted resources back to Earth, which can be very energy-intensive and therefore costly depending on the extraction site. It would therefore be preferable to utilise resources on site (in-situ resource utilisation [ISRU], see Seite 78). If very limited resources on Earth were to become more widely available through mining in space, this would shake up the resource markets considerably, as supply would increase significantly and price allocation would change considerably (Edwards 2017).

In its last answer to date[31] to a minor enquiry on the topic of space mining, the German government assessed the chances of the economically viable extraction of raw materials from space as low in 2019 (Federal Government 2019b). The reasons given for this were the considerable complexity of the task and the lack of technical prerequisites; in addition, compatibility with the German government's climate protection goals was questioned. Against this backdrop, research into technologies for the further exploration of space was prioritised.

Research and development activities for the mining of raw materials in space are currently gaining momentum. This is partly due to the growing number of companies (see below) that are endeavouring to exploit the presumed economic potential, but also to the increased interest of national space agencies in making the use of raw materials a component of long-term space programmes (Blair et al. 2005; Gilbert and Bazilian 2020).

Extraterrestrial life

The question of whether life exists in the universe somewhere other than on Earth has preoccupied mankind for thousands of years. As early as 400 BC, the Greek philosopher Metrodoros of Chios wrote in his work „On Nature" that the assumption of a single living world in the infinity of the universe was unnatural (Papagiannis 1985). He thus adopted one of two fundamental positions on the possible existence of extraterrestrial life, which still hold true today: either (1) the circumstances and the emergence of complex, multicellular life on Earth are unique (Rare Earth Hypothesis, Ward and Brownlee 2000), or (2) this process on Earth is not unique and extraterrestrial life should be present due to the expansion and age of the universe and the high number of stars, planets, etc. (Fermi paradox, cf. Leman 2020). Based on the Fermi paradox, the astrophysicist Francis Drake formulated an equation named after him, which should make it possible to calculate the number of technical, intelligent civilisations in our galaxy, the Milky Way. However, as many of the equation's parameters are currently unknown, the equation can at best be used as a heuristic method to estimate the possible number of intelligent extraterrestrial civilisations (Webb 2010; p. 19f.).

The search for extraterrestrial (intelligent) life is inspiring scientists worldwide. In addition to targeted searches, such as those conducted as part of SETI since 1960 (Anton and Schetsche 2023), there is the possibility of encountering extraterrestrial life, or at least indications that it exists, during the search for and extraction of resources: On the one hand, it is conceivable that traces of resource use by an alien extraterrestrial civilisation could be discovered during the search for usable resources in space (Forgan and Elvis 2011). This could be past or ongoing utilisation. On the other hand, it is conceivable that the search for usable resources could provide evidence of the existence of extraterrestrial life itself, for example in the form of organic compounds (Willis 2016).

Whether the search for extraterrestrial life is successful depends on various factors, not least on how highly developed this life is and what traces it leaves behind or has left behind. As early as 2015, leading NASA scientists formulated the expectation that microbial life would be discovered in our solar system within the next 20 to 30 years, as the necessary knowledge and technology are now available (Calamur 2015). Various institutes around the world are involved in the search for extraterrestrial life, such as the SETI Institute in California (Shostak 2021), the Green Bank Observatory in West Virginia (Malusky 2023) the FAST research centre in China (Normile 2016) and other international research centres.

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[31] Until September 2023.

5.4.2 Trends and drivers

The longer and the more people spend time in space, the more important supply issues become. Being able to utilise resources available on site (in space) directly could play an important role here. Another development that deserves closer consideration is the mining of raw materials in space and their transport to Earth in order to counter the scarcity of individual resources. Ultimately, it is already becoming apparent that with the increasing amount of space debris, there is also a source of raw materials for recycling in the immediate vicinity of Earth.

ISRU (in-situ resource utilisation)

The acronym ISRU As ofs for „in-situ resource utilisation“ and refers to the extraction of resources and their use at the same location (National Aeronautics and Space Administration (NASA) 2008). ISRU is likely to play a key role in maintaining a permanent presence in space, for example in the form of a permanently manned base on the Moon (Stoll and Dietz 2020). Such a base would have to be supplied with all essential materials, which in turn would generate logistical costs. In order to minimise this effort, it makes sense to make use of the raw materials available on site. This can include the production of construction materials, e.g. from the loose material regolith,[32] , which can be used to build a base using additive manufacturing, as demonstrated in the RegoLight research project[33] (Luxembourg Institute of Science and Technology (LIST) 2021; p. 14).

Furthermore, volatile substances such as water and oxygen can also be extracted to ensure breathing air and drinking water supplies for crew and to produce rocket fuel. The MOXIE project (Mars Oxygen ISRU Experiment; Hecht et al. 2021) showed for the first time that it is possible to produce oxygen from CO2 present in the atmosphere. In the future, this technology will be used to produce rocket fuel on a large scale (see chapter 5.4.1) so that it can be produced for a return flight to Earth does not have to be carried on an outward journey to Mars. In order to reduce the mass of raw materials to be carried, the aim of such projects is to demonstrate that the necessary resources can also be obtained locally in the respective environments. The RegoLight and MOXIE projects are just two of many examples that are advancing the development of technologies for resource extraction in space.

Space mining is still a long way from commercialisation, although eleven companies worldwide are currently involved in ISRU (Kulu 2021b). They are trying to increase the economic potential in this field, for example by developing technologies for extracting oxygen, hydrogen or helium-3. NASA is also focusing on the economic potential in its goal of establishing a permanent human presence on the Moon and, as part of its Artemis programme, has selected ten companies to develop technologies to extract ice on the Moon and convert it into oxygen, water and rocket fuel (Gilbert and Bazilian 2020; Williams 2020). In this respect, it is likely that the extraction of raw materials and their utilisation on site will play an important role in space travel in the future.

Looking to the future: colonisation of the Moon and Mars

The colonisation of the Moon or even Mars presupposes that locally available resources can be utilised. A continuous supply of food, oxygen, water, raw materials, fuel, etc. from Earth (as is currently required on the ISS) is too costly and risky. There are currently various plans to establish a permanent human presence at least on the Moon.

The vision of a „Moon Village“ propagated by former ESA Director General Johann-Dietrich Wörner since 2016 (European Space Agency (ESA) 2016) represents a form of colonisation; a habitat that is built with the help of local resources and can be inhabited by astronauts to conduct research there.[34] NASA‘s Artemis programme also aims to establish and operate a permanent human presence on the Moon and involves the use of local resources (National Aeronautics and Space Administration (NASA) 2020a; p. 23; National Aeronautics and Space Administration (NASA) 2020b; p. 4f.). The main advantage is the comparatively short distance to Earth, so that in the event of

[32] Regolith here refers to the material on the lunar surface, a fine, grey mixture of various components ((Meyer 2003)).

[33] https://regolight.eu/

[34] Cf. for further information: https://moonvillageassociation.org/

an emergency, a permanent supply could be ensured from Earth and help could be provided promptly. On the other hand - as with the discussions about the continued operation of the ISS or space exploration per se - the question arises as to the extent to which a colonisation of the Moon is necessary at all and whether the use of robotic systems is sufficient in view of the risks and the presumed effort involved.

A manned flight to Mars has not yet been realised, but has been an aspiration since the manned Moon flights in the 1960s and 1970s (Portree 2001). In the course of establishing a permanent colony on Mars, enormous technical hurdles would have to be overcome. The flight to Mars is already a huge undertaking due to its great distance from Earth. Suitable launch windows from Earth to Mars can only be found around every 2.13 years due to various factors such as the planetary constellation and the respective positions of the celestial bodies in orbit around the sun (Ulamec and Hanowski 2011; p. 566). With an energy-optimised Hohmann transfer - which means that the start (Earth) and destination (Mars) are exactly on the same path to the sun - the travel time is around 9 months (for the outward and return flight). Due to Mars' orbit around the sun and the associated suitable launch windows for such a flight, space travellers must survive a longer stay on Mars (approx. 500 days). In order to reduce the amount of energy required for the journey, one idea is to dispense with carrying all the necessary supplies and instead produce oxygen, water and rocket fuel on Mars for the return flight, for example.

The landing of astronauts on and a safe return journey from our neighbouring planet is currently still an unresolved technical, economic and political challenge. The extremely hostile conditions on Mars, combined with the considerable effort required to transport personnel, resources and equipment, make the establishment of a Mars colony an extremely costly and risky endeavour. Accordingly, publicised efforts to colonise Mars, such as the goals of the SpaceX company (SpaceX 2020a), and the now cancelled and highly controversial MarsOne media project (Hühn 2019) should be viewed with scepticism. The colonisation of Mars is currently a distant vision of the future of manned space travel at best. Nevertheless, manned expeditions to Mars are currently being planned by NASA, alongside SpaceX (NASA Jet Propulsion Laboratory and NASA Mars Exploration Mission 2023), the Russian space agency Roskosmos (TASS Russian News Agency 2020) and the Chinese national space agency (Jones 2021b).

Utilisation of raw materials mined in space on Earth

The return transport of resources mined in space involves enormous expense and is not economically viable under the current circumstances. Nevertheless, approaches are being pursued to utilise raw materials mined in space on Earth in order to counter local resource shortages. Possible options include the supply of (precious) metals such as platinum or the expansion of renewable energies through the improved utilisation of sunlight using space-based technologies.

Based on the assumption that (precious) metals, such as iron, nickel, cobalt or platinum, are very common on C- and M-class asteroids (carbonaceous or metallic asteroids), efforts are being made to track down these deposits, mine them and transport them to Earth for further utilisation. One conceptual approach to this is a so-called „ Asteroid Capture and Return (ACR)" mission, in which a space probe captures an asteroid and transports it into near-Earth orbit. This makes it possible to access the suspected resources, mine them and distribute them to Earth using less energy (for a detailed description, cf: Tantardini et al. 2012). In addition to unresolved questions of technical feasibility, the economic benefits play a decisive role. While there are still unknown deposits of specific raw materials on Earth, their development and utilisation are sometimes associated with very high costs, so it makes sense to compare the necessary investments in asteroid mining with the costs of developing new mines on Earth. In a case study focussing on platinum, for example, Edwards (2017) concludes that setting up a new platinum mine on Earth would incur considerable costs of up to USD 1 billion. However, the realisation of an ACR mission would be more than twice as expensive, with estimated costs of around USD 2.6 billion (Tantardini et al. 2012; p. 40). At this stage, such an ACR mission is not yet technically feasible.

The development of new sources of raw materials on Earth also appears to be more advantageous from an economic perspective. However, if - as in the case study cited above - access to a platinum source located in space could be realised, this would result in a significant disruption on the global raw materials market. An oversupply of platinum would lead to a price collapse (Edwards 2017).

One resource from space that is already being utilised on Earth is solar energy. Efforts are being made to increase the yield through space-based technologies, so-called space-based solar power (space-based solar power , SBSP) (Potter 2021). The Earth‘s rotation means that photovoltaic systems are not exposed to sunlight for part of the day. In addition, some of the sunlight reaching the Earth is also lost through the Earth‘s atmosphere. This results in a loss of efficiency. A space-based system could at least partially compensate for these efficiency losses. The solar energy collected with space-based reflectors must then be converted and transmitted to Earth in the form of microwaves. Suitable receiving antennas must be erected on Earth (Wood 2014). In March 2023, a research project at the California Institute of Technology (CalTech) succeeded in transmitting energy from a solar module in space to a receiver module in Earth orbit as well as to the Earth‘s surface for the first time using microwaves (Perkins 2023). In the 2040s, the United Kingdom is planning to launch a corresponding system into Earth’s orbit (Space Energy Initiative 2022).

Future development - both in terms of space-based solar energy and further research into technologies for mining metallic raw materials - not only requires technical hurdles to be overcome, but economic factors also play a decisive role. It is therefore currently unclear whether and what significance the utilisation of resources from space will have in the future.

Recycling space debris

The increasing amount of space debris already poses an enormous threat to space travel (see chapter 4.2). For this reason, approaches are increasingly being sought to solve this problem. The limited service life of space hardware (rocket stages, satellites, payload covers, etc.) means that it must be moved out of orbit at the end of its service life so as not to pose a risk to other space objects (see chapter 4.1.4). For satellites, this usually means a transfer to a so-called graveyard orbit (see Seite 82), in which the satellite remains permanently, or to a re-entry orbit, which results in the satellite burning up in the Earth‘s atmosphere (Hirzinger et al. 2011; p. 612). Recycling is another option (European Space Agency (ESA) 2019a). A graveyard orbit can theoretically be accessed again in order to recycle the space debris located there. In particular, satellites that are already being used in geostationary orbits are transported to graveyard orbits. The fuel required for this is usually contained in the satellite. For satellites or rocket stages in low Earth orbits, re-entry into the Earth‘s atmosphere is planned, as this is more energy-efficient than transfer to a graveyard orbit. There is a time window before satellites or rocket stages can be re-entered during which they can be recycled. For example, Starlink satellites are expected to burn up in the Earth‘s atmosphere within a year of the end of their respective missions (Brodkin 2017). They would therefore have to be recycled before this time.

It is estimated that around 8,000 tonnes of space debris are currently in orbit and offer recycling potential.[35] This includes inactive satellites, some of whose hardware components or metal parts can be reused. Burnt-out rocket engines can also be recycled, for example by reusing the aluminium they are made of. According to calculations, the 64 Ariane upper stages alone could provide around 250 tonnes of aluminium (Koch 2018). The aluminium obtained in this way could be used to support the construction of a permanent base on the Moon and thus reduce the financial outlay. It can also be used to cast tools and objects, also on the Moon, or as a fuel component (Koch 2021).

Established companies such as Airbus (Airbus 2021), as well as start-ups such as Orbit Recycling (Orbit Recycling 2023), have recognised the potential of recycling space debris and are developing technologies to tap into this potential. These include spacecraft equipped with robotic arms or satellites equipped with harpoons that capture space debris, as well as additive manufacturing technologies designed to work with metallic recyclates (recycled raw materials) (Lim 2021). In addition, five start-ups are currently conducting development projects and technology demonstrations (Kulu 2021b) in cooperation with na-

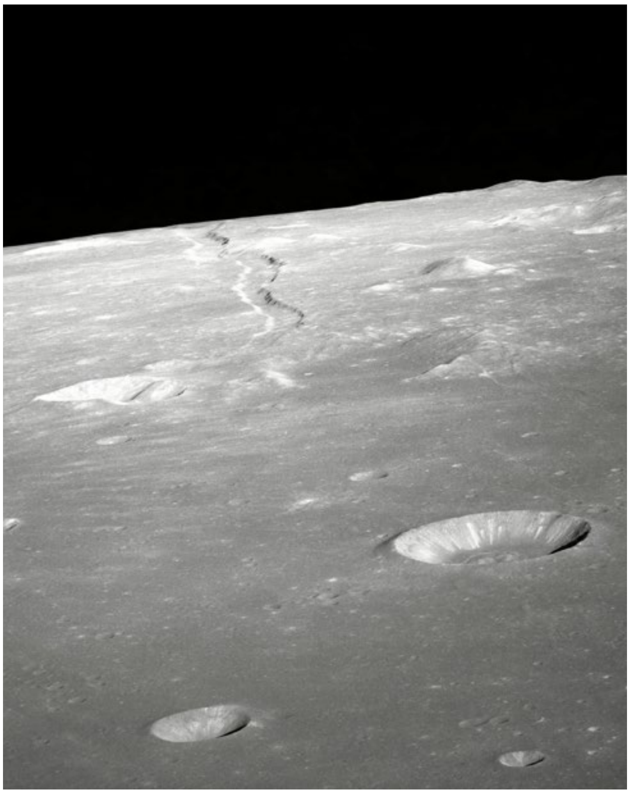
[35] So far, this only applies to the disposal of intact satellites by placing them in a graveyard orbit or controlled crash - there are currently no technical solutions for the disposal of small debris.

tional space agencies and the ESA (Sahba El-Shawa et al. 2021).

The recycling of space debris not only makes economic sense, but is also part of the international strategies of the United Nations (United Nations Office For Outer Space Affairs (UNOOSA) 2010b), the ESA (European Space Agency (ESA) n.d. j) and the USA (National Aeronautics and Space Administration (NASA) 2019c) on the handling of space debris. This is because the recycling of space debris creates economic incentives to actively remove it from orbit and reprocess it (Lucas-Rhimbassen et al. 2019). This also potentially reduces the risk of collisions and the amount of new space debris generated. It can therefore be assumed that this development will become increasingly important in the future.

5.4.3 Environmental potentials and risks

Just like mining on Earth, mining in space is associated with massive environmental interventions. The mining of raw materials has a direct impact on other celestial bodies and the transport of raw materials and the increase in rocket launches and entries into the Earth's atmosphere have an impact on the environment.



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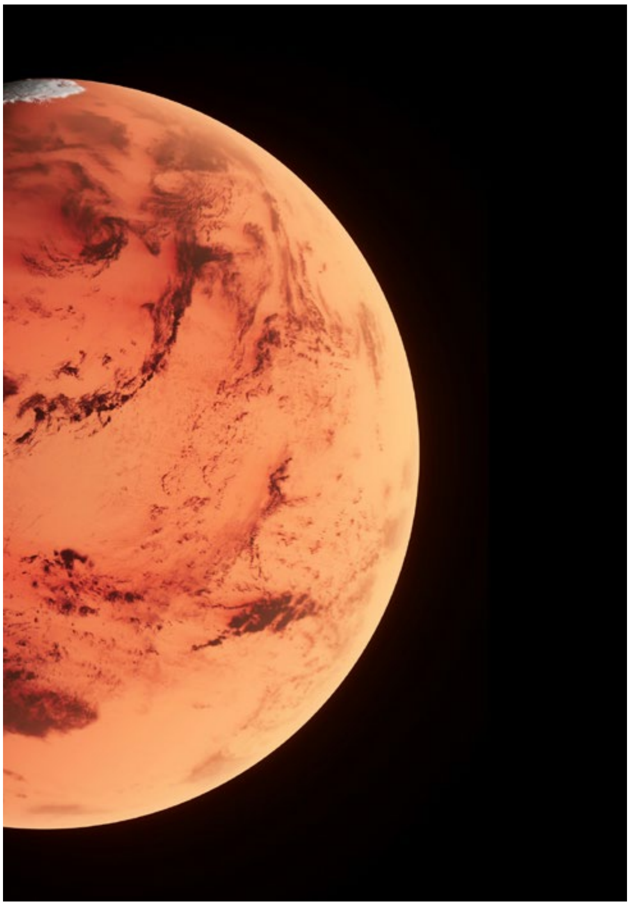

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With regards to, the environmental impact of transport and the increase in rocket launches, there are two opposing developments. If raw materials are mined and utilised in space, they do not have to be transported from Earth to space in an energy-intensive manner - with all the environmental impacts that this entails. For example, water can be extracted directly from asteroids or the Moon and used for life support in space and for the production of hydrogen-based rocket fuel, rather than being transported into space as a payload from Earth. On the other hand, an advanced space mining industry will ultimately lead to an increase in rocket launches: to bring the necessary infrastructure into space and to transport extracted raw materials back to Earth. As described in Seite 83, space activities (in this case for the extraction of extraterrestrial resources) trigger various environmental impacts, for example through the consumption of resources in the production of spacecraft and infrastructure, the emissions during launch and re-entry into the Earth's atmosphere and the damaging effects on the ozone layer (Ross et al. 2009; Maury et al. 2020).

In the case of mining missions and the associated environmental impacts, it is important to consider both the emissions generated during the transport of raw materials and the direct impact on the surface and soil, water balance, atmosphere and climate of the planet, moon or asteroid. These direct effects and initial comparisons of mining on Earth and in space are described in more detail below.

Environmental interventions on other celestial bodies

Extraterrestrial mining permanently and irrevocably alters the surface of asteroids, the Moon and even Mars through resource extraction (Galli and Losch 2019). There are increasing voices warning of a repetition of the mistakes of terrestrial resource extraction and thus permanent damage to the extraterrestrial environment (Kramer 2017; Newman and Williamson 2018). Although there is an abundance of raw materials on other celestial bodies, the resources there, as on Earth, are non-renewable and therefore finite. The probability of repeating mistakes made on Earth in space is therefore high. In this case, there are potentially only 400 years until the resources in space are almost exhausted. (Elvis and Milligan 2019).

Missions to the Moon and Mars aimed at extracting resources and establishing human settlements may not only completely change the characteristics of these pristine environments. The interventions would also affect the atmosphere and climate of these celestial bodies (Mustow 2018). Dust is present in high concentrations on the surface of both the Moon and Mars. Development of the surface and mining activities can lead to this dust being stirred up and released into the atmosphere, thus changing the atmospheric composition. This could consequently destabilise the complex system of a planet (Del Bianco et al. 2021).

Secondly, biological contamination by humans can have an impact on the condition of celestial bodies. Activities on Mars or other celestial bodies on which extraterrestrial life forms, their precursors and remnants are therefore subject to restrictions aimed at preventing biological contamination (Committee on Space Research (COSPAR) 2021). However, it has been shown that contamination by terrestrial compounds and dormant microorganisms from previous (non-astronautical) missions can already be found in the atmosphere of Mars (Mustow 2018). Future, larger-scale human activities on the Moon must therefore take into account the fragility of the lunar atmospheric layer (National Research Council (NRC) 2007). The situation is different on asteroids, as they do not have an atmosphere that could be altered by mining activities. As it is assumed that small astronomical bodies in the solar system are highly unlikely to contain traces of extinct life due to their nature and are also not the habitat of extraterrestrial life, asteroids are subject to fewer restrictions to protect them from biological contamination (Committee on Space Research (COS) 2007). (Committee on Space Research (COSPAR) 2021; Coustenis et al. 2023).

Other problems can arise from hardware being jettisoned or left on the surface or from an increase in space debris in orbit (Paton 2017; Newman and Williamson 2018). For example, in lunar orbit, unlike Earth orbit, the targeted lowering of satellites cannot be used as a measure to reduce space debris, as the satellites would not burn up completely in the atmosphere of the Moon (Williamson 2006). The unburnt satellite parts would hit the lunar surface and remain there.

The mining of raw materials will require infrastructure on the surface: for example, facilities for storing and treating water or for processing regolith, facilities for generating energy, as well as landing and launch facilities for spacecraft. Consideration must therefore be given to how the infrastructure is handled, how the lessons learnt from mining on Earth can be used and how the infrastructure can be designed sustainably and according to circular principles from the outset (Kramer 2017).

Another interesting aspect that will also play a role in in-situ resource tilization in the future is how ISRU-manufactured parts, for example made of regolith, can be recycled on the surface of the Moon or Mars. It is also still unclear how multiple recycling will affect the properties of the parts and the processability of the materials (Del Bianco et al. 2021). It remains to be clarified to what extent it is possible to set up a corresponding recycling infrastructure on site from a sustainable perspective.

Looking to the future: protection zones in space

Assuming exponential growth in extraterrestrial resource utilisation (as was the case with resource depletion on Earth), it could potentially take only 400 years before we approach depletion of resources in our solar system (Elvis and Milligan 2019).

One possible model envisages limiting human activity to a small part (one-eighth) of our solar system, thus preserving the large remainder in the status quo and leaving it untouched for future scientific missions (Elvis and Milligan 2019). This, they argue, would allow enough time to react early to exponential growth and develop measures to reduce resources.

In order to preserve the unspoilt nature of certain regions, it has also been suggested that so-called „planetary parks“ should be established in regions with diverse landscapes on the Moon and Mars, in which humans would not be allowed to carry out economic activities or build settlements (Horneck and Cockell 2010).

Environmental potential of the utilisation of extraterrestrial raw materials on Earth

The extraction of minerals and metals on Earth has various negative social and environmental consequences. However, critical raw materials[36] are needed for global decarbonisation, including for the generation and storage of renewable energies. Raw materials from space could potentially meet this demand and thus facilitate the expansion of technologies (Dallas et al. 2021). If extraterrestrial raw materials are not additionally mined, but rather substitute terrestrial raw materials are used instead, the utilisation of extraterrestrial minerals and metals could reduce environmentally harmful mining on Earth in the future. Platinum, selenium and gallium in particular are raw materials that would be suitable for mining on the Moon and on near-Earth asteroids, as they are available in great abundance. Silver, indium and tellurium are also found on the celestial bodies, but only in low concentrations. The extraction of lithium and rare earth minerals is also not very promising due to their low availability (Dallas et al. 2021) and the question of the possible price collapseSeite 85) remains.

Platinum is currently the focus of research because, in contrast to the Earth‘s crust, it is present in high concentrations on near-Earth asteroids and is relatively easy to find compared to other minerals (Dallas et al. 2021). The mining of platinum on Earth is associated with environmental interventions, for example high water and energy consumption and severe water pollution (Glaister and Mudd 2010; Graedel et al. 2015). Primary production currently releases around 40 tonnes of CO_2 equivalents per kg of platinum, and 2 tonnes of CO_2 equivalents in secondary production (Saidani 2018). An initial study on this topic concludes that mining platinum in space, including transporting it back to Earth, emits fewer greenhouse gases than platinum extraction on Earth. The threshold at which the advantages outweigh the disadvantages is measured by how much platinum is brought back to Earth; for primary platinum, this should be at least 0.3 % of the mass of the spacecraft. However, the study only considers the direct CO_2 emissions, not the effect of rocket launches on the stratosphere, the ozone layer or other indirect consequences. The low availability of platinum on Earth and the associated high costs of this raw material are cited as obstacles to the spread of certain green technologies. One example of this is fuel cells for energy storage, which are dependent on platinum (Sealy 2008). Even though alternatives to platinum are currently being researched, the procurement of extraterrestrial platinum could tend to promote the expansion and widespread use of renewable energies, but would probably also lead to a fall in the price of platinum on the global commodity markets (see Seite 85) (Dallas et al. 2021).

At present, the potential to better recycle the critical raw materials extracted on Earth is also largely unutilised. Recycling efforts could decrease if the availability of raw materials increases through extraterrestrial extraction. Sustainable resource management of both terrestrial and extraterrestrial raw materials is therefore essential (Dallas et al. 2021).

[36] Critical raw materials are raw materials that are essential for technological progress and the development of modern society (United Nations Educational, Scientific and Cultural Organisation (UNESCO) 2014).

The use of space-based solar energy could make a major contribution to global decarbonisation after 2050. All satellites are already powered by solar energy because it is constantly available in space. The prices for transporting payloads into space and for the production of photovoltaic modules have fallen dramatically in recent years. In the future, solar energy can help to balance out decarbonised grids dominated by renewable energies and at the same time provide access to energy anywhere in the world (Bazilian et al. 2019). There is potential for environmental protection in ships on the high seas, for example. Here, solar energy can replace fossil fuels for propulsion due to its decentralised area of application. Solar energy could also be used in remote villages or islands, replacing the need to build up fossil fuels or depend on fossil fuel imports (Bazilian et al. 2019).

On the other hand, there are various technological disadvantages: For example, due to the relatively low energy output of each individual satellite, a larger number of satellites would have to be used to generate a substantial amount of energy. This would not only entail considerable costs, but also a large number of launch manoeuvres from Earth. In addition, the transmission of energy to Earth using lasers or microwaves would not be equally possible in all weather conditions (due to poorer penetration of the atmosphere in clouds and rain). And the long distance of the satellites from the Earth would make any repairs considerably more complicated (Wood 2014). However, some of these problems could be mitigated by other developments outlined in this report, e.g. new launchers could transport several satellites at once and reduce the number of rocket launches required.

Regulatory measures for the mining of raw materials in space

There are already attempts to establish binding international guidelines for the sustainable extraction of raw materials that take economic, social and ecological aspects into account from the outset. The following four points could be incorporated into the design of such guidelines (Dallas et al. 2020a):

- International co-operation between space mining nations and developing countries should be encouraged to reduce the space gap. The space gap is the economic inequality between countries that arises when socio-economic opportunities cannot be realised due to the lack of a national space industry (Way 2018). Space mining can potentially widen this space gap, as the economic benefits only accrue to the spacefaring nations. area remedy for this in the future could be international mechanisms that distribute the profits or a proportion thereof to countries that do not have access and financial resources for space activities.

- Mining permits should be issued and monitored by a supranational organisation, similar to deep-sea mining.

- Impact analyses of environmental interventions should be carried out both on Earth and in space. The precautionary principle should be applied.

- Civil society and science should be involved in decision-making processes on space mining and receive scientifically relevant data.

In order to speed up the implementation of mining missions and clarify outAs ofing legal issues (see chapter 3.2.3), it is also proposed that international As ofards be drafted by interested companies themselves and that their implementation be reviewed by them (Kramer 2014). However, there is a risk here that the requirements for environmentally sound mining could be watered down in favour of economic interests while disregarding the precautionary principle. If mining activities are carried out by private actors who consider the scientific data obtained for mining to be their property, this could also lead to information asymmetry and the loss of important data for the scientific community, for example in astrogeological investigations or soil/rock samples (Dallas et al. 2020a).

The extraction of extraterrestrial resources is still in the future. Whether this can be done sustainably is also a moral question. This is because the extraction of resources entails, almost by definition, a permanent change to the celestial bodies. It is therefore essential to address the question of the extent to which humans should intervene in the extraterrestrial environment at all and what significance the integrity of the celestial bodies should have both for science and as the cultural heritage of mankind.

6

6 Space - a topic for the environment department? Conclusion, political starting points and research questions

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Figure 14

Overview of policy recommendations for the environmental department

Source: Own illustration

The introductory quote of this report contrasts space travel with the human utilisation of the seas and oceans of planet Earth. Oceans played a crucial role in early human history as a source of raw materials and food, and human colonisation of the Earth followed resources along coastlines (Rincon 2006). Oceans enabled travel and trade and were a fundamental part of the historical development of humankind (Gillis 2012). Due to technological limitations, the environmental impact of these uses long remained limited to local or regional ecosystems - a situation comparable to the early phase of space travel. However, with industrialisation and new, more scalable technologies, rapid population growth and globalised trade, human use of the oceans has increased to an extent that exceeds the oceans‘ natural capacity for regeneration. An equally exponential growth curve, driven in part by analogue developments, can also currently be observed in the space sector (see chapter 3.2). In the oceans, this development has led to a long list of effects that have a negative impact on the environment and humans. Overfishing of endangered fish stocks and decimation of seabird populations, endangered livelihoods in developing countries due to the displacement of domestic fisheries, coral reefs damaged by plastic waste and the threat to marine life from oil spills are just some of the current problems. Although there is sufficient scientific knowledge about the impact of human activity on marine ecosystems, efforts to make human use of the seas and oceans sustainable after the fact are complex and slow.

For space, many of these developments are still hypothetical, but some are already acutely visible (see chapter 4.2). In contrast to the use of the oceans, however, it is still possible and urgently necessary to proactively steer the use of outer space in a sustainable direction in line with the precautionary principle - especially in areas where there is still little scientific knowledge about the potential consequences of its use.

The historical mistake of gearing political action with regard to the utilisation of an ecosystem solely to current, short-term needs and attaching no importance to the consequences for the environment must not be repeated in space.

In the following, options for action are presented for all the environmental impacts identified in the report, which are necessary for the sustainable use and exploration of outer space and should pave the way for holistic environmental policy regulation.

6.1 Applying the principles of environmental and sustainability policy

6.1.1 Sustainable use of space as a guiding principle

Similar to the exploration of the world‘s oceans in the 15th and 16th centuries and the colonisation of the North American West, especially in the 19th century, which, despite their dark sides, were glorified and connoted with the subjugation of nature and the „taming of the wilderness“, space travel is also associated with a pioneering spirit.

Astronauts are ascribed a cultural „representative position“ that represents a generic achievement of humanity as a whole (Janich 2000; p. 161). To this day, names such as Yuri Gagarin and Neil Armstrong are inextricably linked with pioneering achievements in space travel (Williams 2015)and SpaceX founder Elon Musk presents himself as a pioneer of humanity as an interplanetary species (Stirn 2019).

A commercial from the „1%“ campaign by Fridays for Future U.S. from 2021 plays with this framing: an expressive male voice is used to advertise relocation to Mars in the style of a tourism commercial: „56 million square kilometres of untouched nature, breathtaking landscapes and fantastic views“, a planet without wars, crime, pandemics and pollution that offers the freedom to create a new way of living together. It appeals to the viewer‘s adventurous spirit and ultimately poses the question: „Will you spend the rest of your life on Earth or will you become a pioneer?“ The advert concludes with the twist: „And for the 99% who will stay on Earth, we‘d better get climate change under control“ (Fridays for Future U.S. 2021).

In the 1980s, sociologist Ulrich Beck drew the picture of a so-called „risk society“ characterised by the „imperceptibility of dangers“, the „supranationality“ of possible risks and the „dependence on knowledge“ with regard to them (Beck 1986; p. 10). This „risk society“ only becomes reflexive through its self-produced risks, which was dramatically confirmed by the Chernobyl disaster in 1986 (Beck 1986; 10; 26). In the course of this reflection on the technical and ecological risks of modernity, the powerful political model of space travel in Germany in the 1990s was „space travel for the Earth“, which was intended to provide usable findings for climate and environmental research.

In recent years, a new paradigm has been added to that of „space travel for the Earth“: „space travel for the market“ (Marsiske 2005; p. 8). The situation described with these words in 2005 has become even more acute since the adoption of the German space strategy in 2010 due to the enormous growth of the sector and the increasing involvement of the private sector as part of the New Space Initiative. It is therefore all the more urgent to establish a social discourse on the overarching objectives of space travel, in particular its relationship to the environment and sustainability goals. Sustainability is a joint task, and working together across sectors and countries requires certainty of direction, communication and cooperation between all parties involved. Certainty of direction means that all stakeholders, both public and private, must share a common definition of sustainability in the context of space, on which common goals and actions are based. The development and anchoring of this common vision is essential for a successful development towards the sustainable utilisation of space.

Educational mission on the opportunities and risks of space travel

The dissolution of the supposed separation between utopian space travel and dystopian development on Earth must be one of the core objectives of a new vision of sustainable space travel. In order to break through the prevailing narrative, the opportunities and risks of space travel outlined in the report must be considered in their entirety, taking into account the existing uncertainties and research gaps. On the one hand, it must be emphasised that space is also endangered by human activity if used carelessly and that the apparent infinity of space is limited from a usage perspective. On the other hand, however, the existing potential offered by the sustainable use of space to meet challenges on Earth should also be emphasised.

In order to enable an informed social discourse on the risks, benefits and scope of the utilisation of space, the available scientific facts and findings must be accessible to the public in their entirety. They must be prepared in an informative way and for people without specialised knowledge. Possible starting points here range from anchoring in curricula to public information campaigns. Prominent faces of space travel with a proven interest in sustainability and environmental issues, such as the German astronaut Alexander Gerst (see chapter 3.2.1), could also be ine volved to raise awareness of the opportunities and risks of space travel.

Social discourse

The previous lack of focus on sustainability meant that the utilisation of space was primarily concentrated on the aspect of „conquering“ unknown terrain and restrictions only existed in the fact that something was not (yet) technically feasible. The sustainable use of space has also not been a relevant topic for the environmental movement to date and, unlike terrestrial sustainability issues, has not been prioritised. Although climate change and environmental protection are widely discussed topics in society, the environmental consequences of space utilisation are often ignored in public discourse.

The participation of civil society in the public debate on the future use of outer space is crucial. A transparent dialogue with environmental organisations, scientists and representatives of various interest groups can help lead to comprehensive and balanced decisions. Issues relating to sustainability, the prevention of environmental damage in space and the fair distribution of resources in space are topics that should not only be decided by experts, but should also be brought to the attention of civil society.

In this context, the German Bundestag plays an important role as an essential institution for the democratic legitimisation of new legal frameworks for space travel in Germany. Political representatives are responsible for representing the interests and concerns of citizens and ensuring that space activities are in line with the shared values and goals of society. The Bundestag can initiate debates, enact laws and promote policies that ensure that space exploration is pursued in a sustainable and responsible manner. It is therefore essential that the German Bundestag provides a platform for discussion and decision-making where fundamental issues relating to the utilisation of space can also be negotiated.

In particular, the involvement of younger generations in the discourse on the objectives of space travel and the question of the extent to which space can also be significant for environmental protection on Earth is essential. After all, the future usability of space for tomorrow's generations depends on today's activities and decisions. Therefore, future fields of space use should also be analysed as early as possible so that they are not unnecessarily restricted by today's space activities. This relates, for example, to minimising the possible windows of a rocket launch due to space debris, the lack of space for necessary satellite systems in Earth orbit or the extraction of resources on a potentially colonisable planet. Consideration for future generations could, for example, mean involving youth environmental organisations more closely in research projects or in the development of future space regulations.

6.1.2 Preserving planetary boundaries

Current sustainability strategies are largely focussed on the Earth's finite reserves of raw materials. According to the „Earth Overshoot Day" concept of the Global Footprint Network (Global Footprint Network 2023) the amount of resources theoretically available for sustainable use for a calendar year will be exceeded well before the end of the year.[37] According to this calculation, the global resources available for the whole of 2023 were exhausted on 2 August 2023 (Global Footprint Network 2023). This concept compares the resources that nature renews with the resources consumed by the world's population (Lin et al. 2023). One criticism is that the calculation starts from zero every year, which would mean that all „over-consumed" resources from previous years would have been replenished (Deutschlandfunk Nova 2023). Even if the method has weaknesses, this and comparable representations of finite resources have contributed to an increasing underAs ofing of planetary boundaries in society. Now, with the depletion of resources in space, a door is being opened that jeopardises previous sustainability efforts because the painstakingly established limits are seemingly being overridden. If there are still enough resources in space, there is no need to limit ourselves on Earth (yet).

However, the resources available in space are by no means unlimited. According to a study by Elvis and Milligan (2019), it could potentially take only 400 years before we approach the depletion of resources in our solar system, assuming exponential growth in extraterrestrial resource

[37] The calculation includes renewable resources such as wood, but also CO_2 storage capacities and available urban space as sub-areas of human demand.

utilisation (analogous to terrestrial resource depletion) (Elvis and Milligan 2019; see chapter 5.4.3). Expanding the scope for human action would not solve the problems caused by the unsustainable exploitation of the Earth's resources, but would postpone their solution. In addition to the issues discussed in chapter 5.4.3 that extraterrestrial resource ex3 traction would have on Earth, the consequences of resource extraction on other celestial bodies are still largely uncertain. Resource extraction on Earth led to industrialisation and caused global warming, land degradation and air and water pollution. Similar consequences are conceivable for resource extraction on other planets.

The extraction of resources in space is extremely resource-intensive, which must be considered in economic and ecological terms when weighing up the costs and benefits. If the mining of extraterrestrial raw materials is nevertheless possible in the long term, the new resource area of space should be communicated as a means of combating climate change. This requires the definition of legitimate utilisation goals for the extracted resources, e.g. to minimise the extraction of equivalent resources on Earth and thus protect ecosystems and populations. The amount of raw materials that may be extracted must also be defined. For such regulation, research must be conducted in order to develop key figures for resource extraction that is sustainable in terms of the affected environment and future generations. The use of digital twins is conceivable here, with which simulations of resource extraction processes and supply and transport chains would also be possible. Once the desired goal has been achieved, the consequences would have to be evaluated in order to determine a further course of action based on sustainability principles.

6.1.3 Precautionary principle in space utilisation

The experience gained from the (over)utilisation of environmental media on Earth should be incorporated into the guidelines for space exploration so that the use of space can be managed from the outset in such a way that negative consequences for the environment and future generations are largely avoided. To this end, it is essential to observe the precautionary principle. When defining the precautionary principle, the Federal Environment Agency distinguishes between risk prevention and resource precaution (Federal Environment Agency (UBA) 2021b):

- **Risk prevention** is understood to mean that „in the event of incomplete or uncertain knowledge about the nature, extent, probability and causality of environmental damage and hazards, preventive action should be taken to avoid them from the outset" (Federal Environment Agency (UBA) 2021b). This approach can also be found in the 1992 United Nations Rio Declaration on Environment and Development: „Where there is a threat of serious or lasting damage, lack of full scientific certainty should not be a reason for postponing cost-effective measures to prevent environmental degradation" (United Nations (UN) 1992, Principle 15).

With regard to the utilisation of outer space, compliance with the precautionary principle presupposes that the actors involved base their actions on sound scientific knowledge and that unregulated utilisation is restricted. Only in this way is it possible to minimise the currently unforeseeable effects of the use of outer space and enable sustainable use. This would mean humanity limiting itself in space and renouncing the extensive utilisation of space (see chapter 6.1.4) as long as no sustainable technologies are available which can help prevent environmental damage. In this context, comprehensive knowledge of the environmental impact of the technical systems used is important (see chapter 6.3) in order to prepare risk analyses for space projects and assess whether these can be implemented in compliance with the precautionary principle.

- **Resource conservation** means the careful use of natural resources in order to preserve them for the future (Federal Environment Agency (UBA) 2021b). With regard to space, this applies both to the limited space available in Earth orbit (see chapter 3.3.1) and makes the avoidance and removal of space debris necessary (see chapter 4.2.4 and chapter 6.4), but also applies equally to the extraction of resources in space (see chapter 5.4). On the one hand, resources in space are ultimately not infinitely available, and on the other, extraterrestrial resource extraction would have implications for the use of available resources on Earth. In order to monitor and limit the consumption of resources in space, the establishment of an international regulatory authority is necessary (see chapter 6.2.1).

The impact of space travel on the ozone layer can serve as an example of the application of both principles. The ozone layer in the stratosphere filters out most of the UV radiation from sunlight that is harmful to humans and other living organisms and is therefore vital for life on Earth (European Commission n.d. c). As already explained, various space technologies harm the ozone layer: emissions from the combustion of rocket fuels deplete ozone (see chapter 4.2.3) and the burning up of space debris releases ozone-depleting substances (see chapter 4.2.4). Both effects are further intensified by the direct introduction of pollutants into the ozone layer during rocket launches and de-orbiting. However, research into these interactions has not yet been fully completed (Chanoine et al. 2017). In terms of risk prevention, it would therefore be appropriate to reduce the volume of ozone-depleting space missions as far as possible and to encourage further research on the topic and take its findings into account. In the context of resource conservation, preserving the ozone layer for future generations is elementary, meaning that a restriction of harmful behaviour is also necessary from this perspective.

Both components of the precautionary principle must therefore be taken into account in the future use of space in order to minimise both known and unforeseeable risks of space use for the environment and resources and thus also for future generations.

6.1.4 Protecting space from the Anthropocene through sufficiency

In 2000, the winner of the Nobel Prize in Chemistry, Paul J. Crutzen, spoke of the Anthropocene era (Will 2021; p. 11). This term is intended to express the fact that human activities have become a geological factor that is changing the nature of the planet to such an extent that these changes have ushered in a new geological era. This is mainly due to the current levels of production and consumption. Reducing these key figures is the top priority of sufficiency. Sufficiency aims to save materials and energy. It is therefore not about more efficient production, which regularly leads to increased production due to rebound effects and thus to the negation of the resource savings achieved, but about actual restrictions (see e.g. Bund für Naturschutz und Umwelt in Deutschland (BUND) n.d.). This is an important principle with regard to future space activities. With current regulations, which are not able to cope with the rush of utilisation, we run the risk of changing space comprehensively and irrevocably in the same way as we have changed Earth, before any consequences have been researched and are foreseeable (see chapter 6.1.3).

Space as a protected good

To prevent this, outer space must be defined as a protected good. In addition to humans and their health, animals, plants, biodiversity, environmental media (such as air, soil, etc.), cultural heritage and other assets of outAs ofing social importance, space is also a unique asset worthy of protection. Space offers unique opportunities for scientific research, and its sustainable utilisation can contribute to solving problems on Earth. Only if space is protected by political measures can it be ensured that future generations can also benefit to the same extent from the potential of space. The protection of outer space should include conservation, damage prevention and restoration measures in order to preserve its pristine condition as far as possible. The protection of outer space for the benefit of humanity as a whole should take clear precedence over national or private economic interests.

Protection options include, for example, keeping the Earth‘s orbit free of further space debris, which will pose a considerable problem for future generations in the utilisation of outer space if not counteracted (see chapter 4.2.4). The untouched nature of certain regions in space can also be protected, for example by defining so-called „planetary parks" in morphologically diverse regions, e.g. on the Moon and Mars, where human activity is prohibited (Horneck and Cockell 2010). (Horneck and Cockell 2010). The expansion of protected goods on Earth can also have an impact on the utilisation of outer space: The existing „Dark & Quiet Skies Initiative"[38] raises awareness of light pollution on Earth from satellites - a problem for humans, plants and animals - but is not yet legally binding. Such approaches would benefit from the designation of outer space as a protected good in the sense of a directive, as would research and further legislation on outer space in general.

[38] https://www.eso.org/public/germany/about-eso/dark-skies-preservation/?lang

Self-limitation in space travel

Taking the principle of sufficiency into account inevitably means that fundamental issues regarding the utilisation of space must be negotiated. The costs, uncertainties and risks of current space activities outlined in this report are at odds with the goal of reducing resource consumption. Against this background, it must be questioned to what extent space activities should not simply be abandoned in many cases beyond the use of more sustainable technologies and the creation of sustainability-orientated framework conditions. This is all the more true given that the enormous quantities of economic, human and material resources used in space exploration could also help solve terrestrial problems, such as the protection of fragile ecosystems (rainforests, oceans) - especially as these are also unique and irreplaceable in the universe as we know it.

Applying the principle of sufficiency in the utilisation of space would not necessarily mean a complete renunciation of space travel, but would require careful consideration of the costs and benefits of each individual mission - not only for humans, but also for the environment. While satellite missions that serve to analyse climate change, for example, could still be justified in this context, a more fundamental analysis of the necessity for humanity would be appropriate for missions with greater costs and environmental impacts as well as unclear outcomes and benefits, such as the colonisation of Mars.

Banning space tourism

The development of space tourism must be viewed particularly critically in the light of the precautionary principle, self-restraint and sufficiency. Although this type of space travel has all the negative environmental impacts mentioned in the report, it does not generate any benefits for the general public and none of the potential uses of space travel are realised. The limited market segment of space tourism has so far been associated with enormous costs and is therefore reserved for a particularly high-income target group (see chapter 5.1.2). Nevertheless, further growth can also be expected here. Against this background, space tourism should be strictly regulated or banned completely, as it is fundamentally at odds with the sustainable use of space.

6.2 Strengthening and expanding political regulation

6.2.1 Developing international governance structures

To date, access to space can only be regulated at a national level (e.g. via conditions in authorisation procedures). According to the Outer Space Treaty, state actors are free to utilise space while respecting the non-discrimination and equal rights of other states (see Article 1 of the Outer Space Treaty). Non-state actors, on the other hand, are dependent on state authorisation in accordance with Article 6 in order to ensure compliance with the regulations of the Outer Space Treaty. Voluntary labels, such as the „Space Sustainability Rating", which was published in June 2022, are intended to motivate actors to act more sustainably (World Economic Forum 2023). However, sustainability guidelines for the use of outer space would have to be legally binding in order to ensure their implementation. While national measures make sense in terms of implementation and monitoring, given the global environmental impact and implications of space travel, space travel should be regulated at an international level. This is all the more true as purely national regulations are an incentive for companies to locate their business activities in less regulated countries. Another reason why an international agreement is absolutely essential is the fact that the resources available in space are of international interest.

No single state has sovereign rights in outer space - and current international regulation does not do justice to the growing interest in its utilisation. Although states already assume national responsibility for regulating the space projects of private companies, an international restriction on the utilisation of space could steer economic development. Earth orbit could be used by all states on an equal footing as a common good of mankind. Another possibility is an agreement on the economic utilisation of outer space. Earth orbit could be defined both economically and fiscally as a common good that is managed by representatives of all states. Such an agreement should necessarily be based on an international sustainability strategy. The International Seabed Authority (ISA), which regulates the extraction of raw materials in the world's oceans, could serve as a model for the establishment of the necessary international regulatory authority.

UN Secretary-General António Guterres presented the report „Our Shared Agenda" in 2021 (Secretary-General of the United Nations (UNSG) 2021). In the accompanying policy brief 7 „For all humanity - The future of space governance", two options are recommended to UN member states to utilise the potential of space to achieve the SDGs while mitigating risks (United Nations (UN) 2023; p. 23):

- On the one hand, the Committee on the Peaceful Uses of Outer Space (COPUOS) could develop a As ofardised set of rules to promote sustainability in space. This could strengthen transparency, confidence-building and the interoperability of space missions.

- On the other hand, the Committee on the Peaceful Uses of Outer Space could also develop separate regulatory frameworks for different aspects of sustainability in outer space. These frameworks would contain separate but mutually reinforcing measures and would have to be developed in co-operation with the relevant UN bodies. In terms of content, they should deal with the regulation of space traffic, the removal of space debris and the mining of space resources. In addition, an international coordination mechanism would be required to coordinate the application of these various regulations, taking into account the UN's existing space treaties.

In both cases, great importance is attached to the broad involvement of operational stakeholders, for whose participation a platform is to be set up.

In view of the increasing relevance of non-state actors in space, member states are also encouraged to facilitate the inclusive participation of actors from business, civil society and other relevant contexts in intergovernmental processes relating to space (United Nations (UN) 2023; p. 23).

In addition to state and international regulations, voluntary commitments by the industry also offer an opportunity to make space travel more sustainable. In addition, a comprehensive commitment to sustainability reporting should be established in the space sector, whose players are still largely non-transparent with regard to their environmental impact.

International cooperation in science as well as in business and politics is the basis for sustainability endeavours in the use of outer space. Only on this basis is it conceivable to implement the political starting points developed in this report to the extent necessary.

6.2.2 Agenda 2030 and Sustainable Development Goals

Another approach to the regulation of space utilisation is the consistent application of the principles of the 2030 Agenda, which aims to promote sustainable development worldwide by linking economic, social and environmental aspects. The 2030 Agenda sets out 17 Sustainable Development Goals (SDGs), which are designed as measurable targets for sustainable development, cooperation and environmental protection and apply to all countries in the world.

Outer space has not yet been explicitly anchored in the 2030 Agenda, but many aspects of the human use of outer space can be assigned to individual SDGs. Opportunities for extraterrestrial energy generation (chapter 5.4.3), for example, touch on SDG 7 (affordable and renewable energy), while the considerations on equitable access and stronger regulation are linked to SDG 16 (peace, justice and strong institutions) and SDG 17 (partnerships to achieve the goals). In addition, the objectives of SDGs 9 (industry, innovation and infrastructure), 12 (sustainable consumption and infrastructure) and 13 (climate action) are reflected in all aspects of this report.

On 25 October 2021, the UN General Assembly adopted a resolution submitted by UNOOSA entitled „The ‚Space2030' Agenda: space as a driver of sustainable development“, which explicitly focuses on the use of outer space to achieve the SDGs (United Nations (UN) 2021). It formulates four core goals:

1. Increasing the economic benefits of space and strengthening the role of the space sector as an important driver of sustainable development;

2. Utilising the potential of space to solve everyday challenges and using space-related innovations to improve the quality of life;

3. Improving access to space for all and ensuring that all countries can enjoy the socio-economic benefits of scientific and technological space

applications and space-based data, information and products to support the achievement of the Sustainable Development Goals;

4. Building partnerships and strengthening international co-operation in the peaceful use of outer space and in the global governance of space activities.

These goals are strongly focussed on the use of outer space in line with the SDGs. Other relevant aspects, such as compliance with the precautionary principle and the sustainable use of outer space itself, are not covered. A possible update of the 2030 Agenda should therefore go beyond this and integrate outer space into the existing framework in order to give it the same protection provisions as protected terrestrial areas. This would also enable an integrated view and consideration of the use of outer space in the context of global sustainability issues - as a protected good but also, where possible, as a driver for positive developments towards greater sustainability.

6.2.3 National space law

There is an urgent need for environmental policy agenda-setting on space at national level. In Germany, the discussion about a national space law is still ongoing. In 2019, the Federation of German Industries (BDI) published its Berlin Space Declaration with eight recommendations for action to politicians in order to guarantee competitiveness in the future market of space. The aim of such a law should be to „protect and promote national commercial activities and at the same time make them justiciable, also with regard to potential effects on other states or their space infrastructure“ (Wachter et al. 2019; p. 13). As the successor to the 2010 space strategy, a new space strategy was presented in 2023, in which the topics of space debris and satellite-based Earth observation also play a role. Earth observation is intended to visualise changes in the environmental media in order to use these findings for climate protection. However, there is disagreement on the question of whether German space travel should be regulated at national or European level (Sürig 2021a).

The current update of the German space strategy and the planned draft of a space law (see chapter 3.2) offer the opportunity to initially anchor the sustainable use of outer space at national level. While this alone will not be sufficient to transform the utilisation of outer space, this step would nevertheless be an important political signal and could serve as a model for other nations. An international consensus would in turn be a prerequisite for the creation of international regulations.

6.3 Sustainability of infrastructure and technical systems

Most of the environmental impacts of spaceflight today arise as a direct result of the technical systems used. Therefore, regulation that addresses the design and implementation of the technical aspects of spaceflight has a direct impact on the extent to which an increase in space activities damages the environment on Earth and in space. In addition to the regulation of environmentally harmful technologies, the political focus should also be on research and the promotion of sustainable innovations that address social and ecological problems and not just serve technical progress per se, given the need for new systems for a more sustainable use of space.

6.3.1 Mandatory life cycle assessment of ground infrastructure

In the context of ground infrastructure, a mandatory comprehensive life cycle assessment can help better balance the environmental impact of future new buildings with the expected benefits and thus favour the continued use of existing systems. The assessment should not only cover construction, but also operation and dismantling, i.e. the entire service life of the infrastructure. In addition to buildings and infrastructure directly associated with space travel, such as launch sites, research facilities, etc., data archives and cloud infrastructures that are required to analyse the data volumes generated and consume considerable amounts of energy during operation should also be taken into account. The resulting products should also be eco-balanced on this basis, as energy consumption and emissions are associated with their calculation and storage. Possible false starts and complications prior to launch could also be included in the assessment, as these sometimes cause considerable environmental damage.

6.3.2 Development of alternative fuels

A significant proportion of the environmental impact of a rocket launch is caused by the combustion of the fuel during the launch phase (see chapter 4.2.3). Some of the alternative fuels described, which are already under development, are more environmentally friendly than the variants used to date, both in terms of their production and emissions during combustion. In addition, the impact of space emissions on the upper atmosphere (including the ozone layer) is of particular relevance.

There is currently a research gap with regard to the interactions between the high atmosphere and the emissions produced during the launch and re-entry of spacecraft into the atmosphere. This gap must be closed in order to accurately assess the consequences of the expected increase in space utilisation in this area. However, the known effects (e.g. CO_2 emissions) already offer a reason for regulation due to their increasing relevance and quantity. This can be done in a similar way to international civil aviation, for example by including emissions from space travel in the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) (German Emissions Trading Authority (DEHSt) 2021) or in the European Emissions Trading Scheme EU ETS (European Commission n.d. d). When developing alternative fuels, it should be ensured that the chemicals used fulfil the EU's „Safe and Sustainable by Design“ criteria (see European Commission, Joint Research Centre et al. 2022) and also contribute to the EU action plan on the „Zero Pollution Ambition“ (European Commission 2021b).

Further research into the environmental effects in the atmosphere is necessary for comprehensive regulation, taking into account all potential risks. Research into alternative, more environmentally friendly fuels could also result in relevant innovations for the transport sector on Earth.

6.3.3 Sustainable production facilities

The launching into space of the systems used for space travel (launch vehicles, spacecraft, satellites, etc.) generates emissions. However, they also generate environmental impacts during their resource-intensive production (see chapter 4.2.2). This problem can be countered by using the methods described in chapter 6.3.1 for the sustainable reorganisation of existing systems. For example, an energy supply from renewable sources, optimisations in cooling and heat management or the joint use of production facilities by various players are conceivable in order to reduce the number of cost- and resource-intensive new buildings. In addition, the impact on the existing environment should be given greater consideration when constructing new sites in order to avoid environmental impacts in particularly endangered ecosystems.

6.3.4 Opportunities and limits of the space cycle economy

Current space systems are often designed for one-off use and, after their utilisation, are either brought into the atmosphere in a controlled manner, where they partially burn up and change the composition of the atmosphere through the release of degradation products; or they remain in space, where more and more space debris accumulates in low Earth orbit (see chapter 4.2.4). Against this background, the focus should be on ways of making the required systems recyclable or reusable. In addition to the options described in chapter 4.2.4, a fundamental reorganisation of space travel in the sense of a circular economy would be conceivable so that the systems and resources used can be reused.

While this is a sensible theoretical consideration, its feasibility must be viewed critically, particularly with regard to the current status of terrestrial circular economy endeavours. These are demonstrably limited by physical and technical factors, and the concept of a circular economy has not yet been widely implemented on Earth. Implementing a functioning circular economy under much more difficult conditions in space would therefore be considerably more complex.

Nevertheless, the consideration of circular economy principles in the development of new technologies offers the opportunity to conserve the environment and resources compared to the status quo and to make at least some aspects of space travel more environmentally friendly, for example through recyclable technical systems. Compared to Earth, economic aspects in particular can play a role here, as the reuse or further utilisation of the often extremely expensive technologies, if technically feasible, would also be in the interests of the operators.

6.3.5 Promoting new utilisation concepts

The utilisation of space also offers potential for increased consideration of sustainability aspects. Ride sharing can reduce environmental impacts. This involves transporting several payloads into space with a shared rocket, thus saving resources and emissions. In the interests of sustainability, satellite constellations must be used simultaneously by different users or for different purposes, which reduces the number of satellites required. Ride sharing is already an established practice for bringing commercially used satellites into LEO, for example by the German company Exolaunch (Exolaunch 2022). However, from an environmental perspective, it should become the primary or only method for launching payloads into space. Economic incentives could lead to even more cooperation in the use of technical systems. Regulation is also conceivable, but would be difficult to implement under market economy conditions.

In addition to the shared use of spacecraft, the shared use of manufacturing and operating infrastructure in particular also offers a further opportunity to save resources and emissions. In principle, this approach would be feasible for all of the projects described in chapter 4.1.1 and, in addition to the positive environmental effects, would also give smaller players access to infrastructure that would not be economically viable for individual players. Here too, economic incentives could be a means of establishing increased cooperation in the space sector (McKinsey & Company and World Economic Forum 2022).

In terms of sufficiency and efficiency, the focus can be placed on optimising the use of the resources used and questioning the meaningfulness of ever new systems and the associated environmental consequences. This would also relieve the increasingly „full“ and therefore more difficult to utilise Earth orbit, which in turn would make both the current and future use of space easier. In addition, the consumption of resources resulting from the storage of the huge amounts of data produced by a constantly growing number of satellites could be reduced. The environmental impact of such an approach would also include a reduction in light pollution from satellites, which has a negative impact on living creatures on Earth that orientate themselves by the starry sky, for example, and also limits the human ability to observe space.

6.4 Dealing with space debris

The increasing use of Earth orbit minimises the space available in Earth orbit, which is increasingly proving to be a finite resource (see chapt ter 3.3.1). In addition to intact satellites, defective satellites or satellites that have been switched off at the end of their life cycle make up a large proportion of artificial objects in Earth's orbit. The total number of objects greatly increases the risk of collision for systems in operation. This means that more and more interventions are required in the control centres on Earth, which in turn consume resources.

The removal of existing space debris and the regulation of new objects launched into space is not only necessary to avoid unforeseeable consequences of collisions, but also because communication and Earth observation satellites, with their diverse applications and environmental potential, are dependent on the utilisation of low-Earth orbits. In addition, the window for future rocket launches is shrinking due to the increasing amount of space debris, which limits the room for manoeuvre in space for future generations.

Although political instruments already exist that address the problem of space debris (Guidelines for the Long-Term Sustainability of Outer Space Activities - chapter 3.3.1, Space Debris Mitigation Guidelines - chapter 4.2.4), the implementation of the goals formulated there has not yet been sufficient. In view of increasing space activities, this is becoming an ever-greater problem that requires political intervention - for example by enshrining the previously voluntary guidelines in law. Regulation must take place at international level - in order to do justice to Earth's orbit as an area of global importance, and because the co-operation of all space players is necessary to solve the problem of space debris.

6.4.1 Ban on new space debris

In order to get the current situation in Earth's orbit under control, the first step is to limit the growth of new space debris to the greatest extent possible. This can be achieved by reducing the number of systems launched into space, either by limiting the number of authorised rocket launches or by focusing on the use of one satellite for different purposes, thus bundling uses that would previously have required several launches and satellites.

However, guidelines also need to be created on what to do with satellites at the end of their life cycle. The previous approach of leaving them in place has led to the current problem of space debris on relevant Earth orbits. All new satellites launched into space must therefore be equipped with end-of-life technologies that enable the object to be removed from Earth orbit at the end of its life. The satellites must be burnt up by controlled descent into the Earth's atmosphere - even if this procedure has its own negative environmental impacts (see chapter 4.2.4). Against this background, in addition to revising the technologies used to make them more sustainable, the need for new systems must also be fundamentally scrutinised as part of a cost-benefit analysis that includes the environmental impact in space, or reduced by using modular, complementary technologies. This could be remedied by „on-orbit operations", in which satellites are repaired, recycled or reassembled in Earth orbit, which would reduce both space debris and emissions in the Earth's atmosphere (Storm 2020).

6.4.2 Monitoring space debris

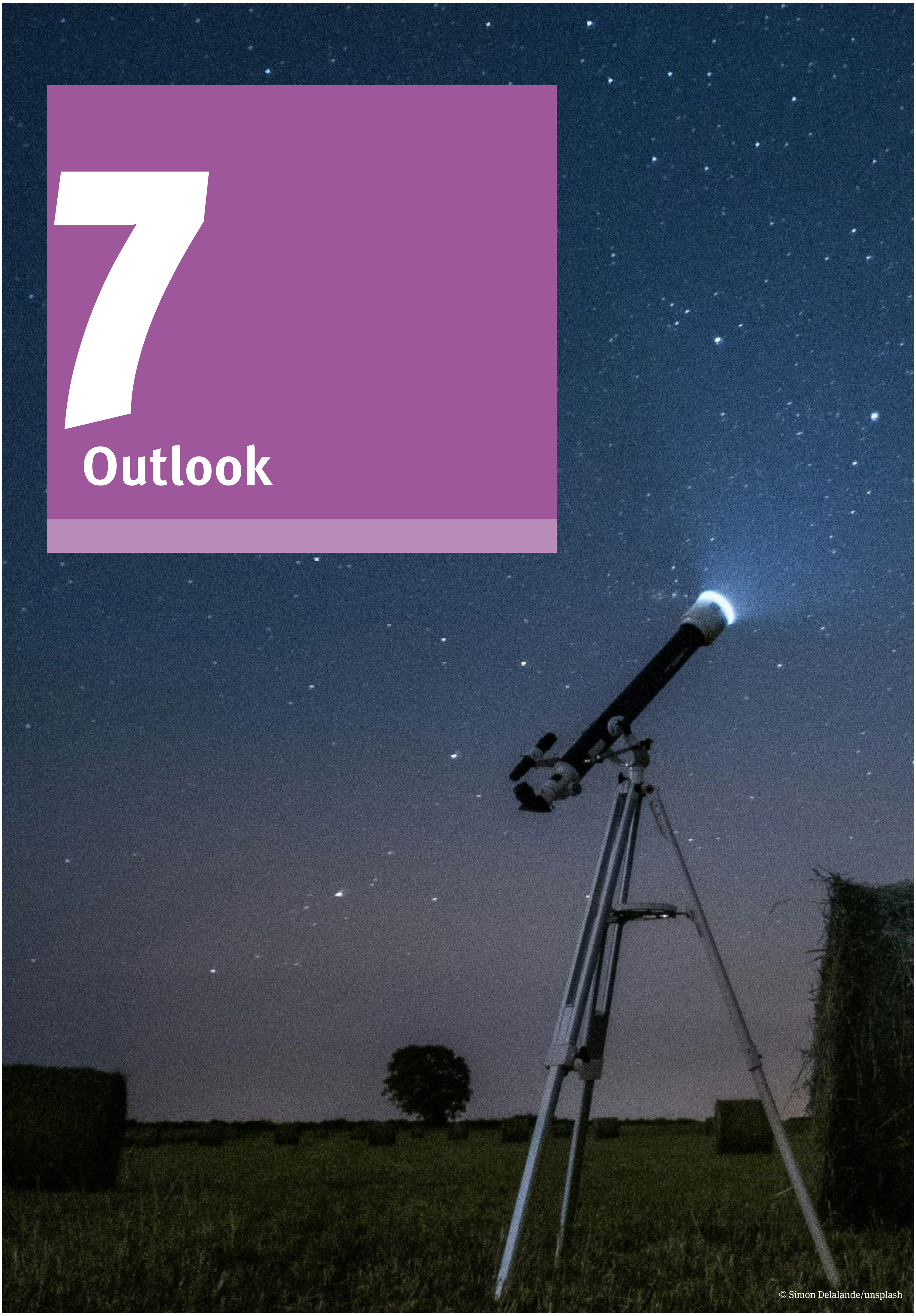
Existing space debris must continue to be monitored in order to avoid collisions. International co-operation is essential in this area, as a complete overview of all systems and objects launched into space is required. As described in chapter 3.2.3, the current regulations are not strict enough to enable comprehensive monitoring, as the reporting of objects in space is often considerably delayed. In the meantime, there are a growing number of objects in orbit whose presence is unknown to other actors - a security risk that the existing regulatory framework must be adapted to combat. Monitoring that is as complete as possible also enables better attribution of space debris, i.e. residues can be better traced back to the respective originator.

6.4.3 Disposing of space debris

In addition to the prevention of new space debris, the reduction of existing space debris is a key task facing humanity with regard to the continued usability of the Earth's orbit. The COPUOS Space Debris Mitigation Guidelines recommend that satellites in low-Earth orbit should be removed after 25 years at the latest in order to prevent collisions - a requirement that many operators do not comply with due to the non-binding nature of the guidelines. The strong commercialisation of the geostationary orbit, on the other hand, ensures that the majority of the players operating there take steps to clean up the orbit (see chapter 4.2.4).

Political approaches could pursue various strategies. By adapting the existing requirements, regulation is possible to the effect that satellites must be categorically removed from orbit at the end of their life cycle. This can be combined with improved methods for tracking operators in order to sanction non-compliance more effectively (see chapter 6.4.2). In addition, the stakeholders' own interest in continued unrestricted access to space can be utilised to encourage more responsible handling of the space debris they generate, e.g. by creating incentives. Last but not least, stepping up research into space debris disposal systems such as ClearSpace-1 can help to reduce the amount of space debris already in circulation (see chapter 4.2.4). However, if the Earth's orbit is cleaned up through targeted de-orbiting and burning up of space debris in the atmosphere, the negative consequences for the upper atmosphere, in particular the ozone layer (see chapter 4.2.4) must also be taken into account. Further research is also needed to enable the disposal of small pieces of debris, which also pose a risk to active spacecraft.

7 Outlook



This trend report summarises current and expected developments in the use of space and shows a clear increase in the commercialisation and privatisation of the sector. Falling costs for rocket launches are enabling more and more private players to become involved in space activities. Large private players such as SpaceX and Amazon are also expanding their activities and pursuing efforts to launch small commercial satellites (SpaceX: Starlink project, Amazon: Kuiper project). Government activities are also increasing significantly: around 90 countries are currently financing their own space programme.

In Germany, the Federation of German Industries (BDI) called for a spaceport in the North Sea, and the German Offshore Spaceport Alliance (GOSA) originally announced it for 2020. Plans are now progressing: the offshore spaceport is to be built more than 400 kilometres off the coast in the form of a special ship with a launch pad and will be able to launch small satellites into space using microlaunchers. The rockets with satellites and the launch pad are to be transported from Bremerhaven to the launch site by a cargo ship (Ilina 2023). The first launch is scheduled for 2023, but has not yet been announced (as of September 2023). As Germany already has secure European access to space as a member of ESA, the need to establish a German spaceport in a sensitive ecosystem (see chapter 5.1.1) should be viewed critically.

New developments in satellite navigation and communication enable improved control of mobility systems. The trend analysis shows that this is particularly relevant for transport and logistics, for example for the development of autonomous logistics concepts and robotic navigation. Internet coverage can be expanded globally with the help of mega-constellations of small satellites and a fusion with terrestrial 5G technology. Other areas of application include environmentally friendly and resource-saving precision agriculture and smart cities.

Opportunities for combating and adapting to climate change on Earth also arise from applications in the field of Earth observation: information from Earth observation satellites can support measures against the loss of biodiversity through detailed data, for example by documenting habitat changes, deterioration in soil, air and water quality and climatic changes. In addition, the creation of digital twins of the Earth could help to monitor natural and human processes and to model and test scenarios for the use of climate protection measures.

Sufficiency must be a fundamental and important guiding principle in space travel. Sufficiency involves carefully weighing up space missions, limiting unnecessary activities in space and promoting sustainable alternatives in order to ensure a balanced and responsible use of our planet‘s limited resources and protect the ozone layer. Even before innovative technologies are used to reduce the environmental impact of space travel, there should be a fundamental discussion and decision on the extent to which the utilisation of space is necessary for people and the environment and the associated risks are acceptable.

The mining of raw materials in space is the subject of controversial debate, as although it could potentially solve resource scarcity on Earth and resource problems in space travel, it can also harbour considerable risks. Possible, irreversible damage is not yet foreseeable from today‘s perspective, meaning that potential resource extraction in space must urgently be subject to the precautionary principle. This trend report shows that the growth of the space sector is associated with numerous environmental impacts and risks, including chemical (e.g. greenhouse gases and air pollutants) and physical impacts (e.g. noise, resource consumption through production, operation and disposal) as well as the effects of space utilisation on satellite communication and Earth observation (light pollution) and the accumulation of space debris in Earth’s orbit.

Innovations in space travel and the increasing utilisation of outer space have the potential to improve the livelihoods of future generations, but also to further degrade them. In order to counter the possible consequences, a binding regulatory framework for the utilisation of space is necessary. The environmental impact of space activities must play a central role in this framework. At present, many initiatives are voluntary and are based on the idea that increased co-operation between the various players from industry, science and government will create potential for environmental protection. New regulations for space utilisation must be binding, but also innovation-friendly and in line with environmental and climate goals.

It is therefore urgently recommended to update the political framework and develop an international sustainability strategy for the utilisation of outer space. To this end, international cooperation must be expanded and deepened both in research and in the regulation of space utilisation, which can be based on the principles of the 2030 Agenda. If extraterrestrial resource extraction becomes feasible, even taking into account the concept of sufficiency, the goal should be the equitable, sustainable extraterrestrial utilisation of resources. Other important measures include the promotion of technological innovations and the greater consideration of sustainability criteria in space travel, e.g. the production of environmentally friendly fuels, resource savings through reusability or sharing systems and environmental assessments of structural infrastructure for the utilisation of space.

This trend report shows that space travel in Germany and worldwide must become a greater focus of environmental policy. Space should be given greater consideration in the environment ministry in order to harmonise future trends in space travel with national and global sustainability efforts. In particular, because many fields of space applications are associated with high resource consumption, environmental issues must not be passed on to future generations, but must be proactively addressed today. The basis for this must be an informed, society-wide discourse on the goals of space travel, which takes into account not only the opportunities but also the risks and sustainability aspects. Many developments, such as space tourism, are still in their infancy and, without countermeasures, their expansion and thus their environmental impact will increase significantly in the near future.

We need to anticipate these developments and create a framework in which space as well as planet Earth and its orbits can be protected. This report is intended to be a starting point for this. Due to the dynamic and multifaceted nature of the topic, several further research approaches and needs arise from this report. In particular, the report shows that sustainability aspects must play a central role in space research if space and planet Earth are to be equally usable for future generations. Anchoring this topic in legislation and society is the major task facing the environment department in relation to space.

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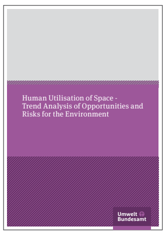

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